New Type of Short High-Frequency VLF Patches (“VLF Birds”) Above 4–5 kHz

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Abstract The new type of daytime natural very low frequency (VLF) whistler mode emissions of the magnetospheric origin was found in the VLF observations at Kannuslehto station (L ~ 5.5) in Northern Finland. The events occurred at the frequencies above 4–5 kHz even up to 15 kHz. These emissions have never been observed earlier in the spectrograms because they were hidden by strong impulsive atmospherics (sferics) in the same frequency range originating in lightning discharges. After filtering out the sferics, we surprisingly discovered completely new types of high frequency right-hand polarized peculiar VLF emissions with various unusual dynamic spectra. These new VLF emissions typically occur as a sequence of a number of short (~1–3 min) burst-like structures or single short patches with the total duration up to a few hours. The spectral peculiarities of several long-lasting VLF events as well as individual short VLF patches are discussed. The dynamic spectra of these new VLF patches raise the question of the temporal and spatial details of the wave-particle interactions in the magnetospheric plasma. These emissions are observed only under quiet or weakly disturbed space weather conditions, but during small negative values of the Dst index, indicating the presence of a certain excess of the radiation belt electrons. Note, these high frequency VLF patches are observed at the frequencies much higher than the half of the equatorial electron gyrofrequency which is equal to ~5.5 kHz at L ~ 5.5. It seems that these emissions are generated deep in the magnetosphere, but the detailed nature, generation region, and propagation behavior of these newly discovered VLF emissions remain unknown. An appearance of high frequency VLF patches could be an indirect indicator of a local enhancement of electron fluxes in the radiation belt that are not directly measured and may occur even in the absence of visible ground-based geomagnetic disturbances. Further researches may shed new light on wave-particle interactions occurring in the Earth’s radiation belts.

1. Introduction

The main feature of the magnetosphere consists in its filling with a large variety of waves at different frequency scales with different characteristics and of different origins. The natural electromagnetic waves at the audio range of frequencies (3–30 kHz) termed very low frequency (VLF) emissions are typical for the magnetospheric plasma as well. They are whistler mode waves of magnetospheric origin at the frequencies between the ion and electron gyrofrequency, that have propagated through the ionosphere to the ground.

The natural VLF waves known as chorus, hiss, and quasiperiodic (QP) emissions have been widely studied more than 50 years since the classical monograph by Helliwell (1965). The majority of these emissions are usually generated at or near the geomagnetic equator in the magnetosphere through resonant cyclotron interactions with energetic (~hundreds of keV) electrons of the Earth’s radiation belts (e.g., Kennel & Petschek, 1966, Rycroft, 1972, 1991; Trakhtengerts, 1963; Trakhtengerts & Rycroft, 2008). The frequency of these waves is controlled by the electron gyrofrequency $f_{\text{geo}}$ at the geomagnetic equator. Thus, these whistler mode waves represent one of the most important agents controlling the dynamics of trapped electron into the magnetosphere.

It is well known that VLF whistler mode waves, which are generated near the magnetic equator in the magnetosphere, propagate to the ionosphere in the waveguide (Inan & Bell, 1977), that is, guided by density gradients that extend along the geomagnetic field lines and are called “whistler ducts.” Only the ducted VLF...
whistler wave which penetrate through the ionosphere with low wave normal angles, can be observed on
the ground in the vicinity of the footprint of the ionospheric exit point of the wave (Helliwell, 1965). Theo-
retically (Smith et al., 1960) and experimentally (Carpenter, 1968), it was found that the ducted propagation
of VLF waves is only possible at the frequencies lower than half of the equatorial electron gyrofrequency
\(f_{\text{He}}/2\) of the given \(L\)-shell. At higher frequencies \(f > f_{\text{He}}/2\), the waves can propagate in a nonducted way,
that is, obliquely with respect to the local magnetic field lines (e.g., Demekhov et al., 2020; Martinez-Cal-
deron et al., 2016; Némec et al., 2013; Titova et al., 2017).

Leaving the duct, the right-hand elliptically polarized whistler waves penetrate into the Earth-ionosphere
waveguide and suffer many reflections from its anisotropic upper boundary on their rather long path, up to
\(\sim 800\) km and even more (e.g., Strangeway et al., 1983), to the ground-based receiver. But with increasing
the distance (up to 300–400 km) between the ionospheric exit point of the wave and its receiver, the right-
hand polarization of the wave becomes the left-hand one (e.g., Yearby & Smith, 1994). Thus, the right-hand
polarization of the wave indicates that the wave receiver is located in vicinity of the ionospheric exit point,
no further than 300–400 km.

Among the natural VLF waves, the chorus emission is one of the most known. It is generally accepted that
due to wave-particle interaction, chorus emissions can control the state of trapped energetic electrons and
its acceleration or scattering (e.g., Bortnik et al., 2007; Hayosh et al., 2010; Meredith et al., 2001).

The second type of the widely known VLF emissions is auroral hiss generating via Cherenkov instability
of streams of precipitating soft auroral electrons along the magnetic field lines during the substorms (e.g.,
Jørgensen, 1966; Laaspere & Hoffman, 1976; LaBelle & Treumann, 2002).

Another type is QP emissions (e.g., Helliwell, 1965; Sazhin & Hayakawa, 1994 and many others) which
characterized by periodic or QP repetition of a sequence of noise bursts, in which each burst may consist of
a number of discrete events at the frequencies below 4 kHz (e.g., Engebretson et al., 2004). The repetition
periods vary from several seconds to several minutes. These emissions are usually observed during the
daytime under quiet geomagnetic conditions. The discrete QP emissions could be a result of self-oscillating
processes in the plasma magnetospheric maser (Bespelov, 1982; Bespalov & Trakhentverts, 1976; David-
son, 1986; Pasmanik et al., 2004; Trakhentverts & Rycroft, 2008). The frequency of the self-oscillations
corresponds to the alternating stages of accumulation of charged particles in the magnetosphere and their
precipitation into the ionosphere during the electromagnetic wave generation.

Despite the importance of direct VLF measurements in the space with satellite instruments, the continu-
ous ground-based observations can provide the unique possibility to study the temporal dynamics of the
waves. In particular, still now many findings of properties and dynamics of different types of natural VLF
emissions such as chorus, hiss, long series of QP emissions, have been found basing on the ground-based
observations at Kannuslehto station (KAN) in Northern Finland (e.g., Bezděková et al., 2020; Demekhov
et al., 2020; Kleimenova et al., 2015, 2019; Manninen et al., 2013, 2014, 2015, 2016, 2017, 2020, 2012;
Martinez-Calderon et al., 2019; Shklyar et al., 2020; Titova et al., 2017, 2015).

However, the ground-based studies of VLF emissions at frequencies above \(\sim 4–5\) kHz were difficult because,
even at auroral latitudes, strong atmospherics (sferics) completely shielded all natural high-frequency VLF
emissions. Sferics are electromagnetic pulses originating in low latitude lightning discharges (e.g., Ohya
et al., 2015) and propagating to thousands of kilometer in the Earth-ionosphere waveguide. To reject off the
parasite signals like sferics, we have to apply special digital programs which filter out the strong impulsive
sferics with a duration of less than 30 ms. This method has been briefly described in Manninen et al. (2016).

After filtering out the sferics, we surprisingly discovered completely new types of peculiar high-frequency
daytime VLF emissions with various unusual spectral structures that have never been seeing before (Man-
ninen et al., 2016, 2017).

In this study, we present and discuss the spectral characteristics and temporal dynamics of these new natu-
ral electromagnetic emissions of the magnetospheric origin with frequencies above 4–5 kHz. The used data
and the instruments are described in Section 2, and the observation results are presented in Section 3. In
Section 4, the geomagnetic conditions during the considered VLF events are discussed. Section 5 presents
our conclusions.
2. Data

Our study was based on the VLF observations in Northern Finland at Kannuslehto station (KAN) with the geographic coordinates 67.74°N, 26.27°E; and MLAT = 64.4°N, L = 5.46. The VLF receiver in the frequency band from 0.2 to 39 kHz comprised of two orthogonal magnetic loop antennas oriented in the geographical north-south and east-west directions. This allows to calculate polarization characteristics of the signal and to estimate the azimuthal orientation of the wave arriving with an ambiguity of 180° as the direction of the small axis of the polarization ellipse (here we term it the angle of arrival). The receiver sensitivity is about 0.1 fT (i.e., 10^{-14} nT^2Hz^{-1}). The wide dynamic range of the receiver (up to 120 dB) allows to detect both very weak and strong signals. Data has a sampling frequency of 78.125 kHz (the details of the equipment see in Manninen, 2005). The magnetic field intensities are calibrated using the method described by Fedorenko et al. (2014).

Several wintertime VLF campaigns (2006–2020) have been carried out at this low noise site located ∼40 km northward of the Sodankylä Geophysical Observatory. The results of the primary processing (Fast Fourier Transform) of VLF observations at KAN in the form of minute, hour, and daily colored wave dynamic spectra (spectrograms at 0–16 kHz) are on the website (https://www.sgo.fi/pub_vlf/).

3. Observations

In the current study, we study the spectral peculiarities of new discovered high frequency (above 4–5 kHz) short (few tens of seconds) patches of VLF emissions that were for the first time described by Manninen et al. (2016, 2017). These signals were discovered after the digital filtering out sferics. We called these peculiar daytime VLF patches “birds” because the radio speaker of VLF receiver sounds were like a bird chirping. These VLF emissions were observed at frequencies above ∼4–5 kHz and were predominantly a dayside phenomenon, with a broad maximum near local noon.

Three examples of nonfiltered (upper plots) and filtered data (bottom plots) are given in Figure 1 as the 1-h total power spectrograms (frequency-time dynamic spectra) on different days. The upper panels show how the strong sferics hide all VLF signals at the frequencies above ∼5 kHz. The bottom panels demonstrate different kinds of strange VLF natural emissions appearing after filtering. In the given time scale, these emissions look like some vertical sticks due to their short duration. Three white horizontal lines around 12 kHz and about 15 kHz in the bottom panels are the removed traces of radio navigation transmitter signals. Sometimes the “bird” emissions are observed simultaneously with VLF chorus or hiss at the lower frequencies. In Figure 1,
that is shown during the event on 5 January 2015 when the short high frequency VLF patches were recorded simultaneously with strong hiss emissions at the frequencies below \( \sim 4 \text{ kHz} \).

We found (Manninen et al., 2016) that these newly discovered high frequency VLF patches (“VLF birds”) are observed in the local daytime. These VLF emissions have always been right-hand polarized waves. During five Finnish local winter VLF campaigns (2006–2016), they were observed almost every day. But the recent time (2018–2020) has not been so rich of these signals.

3.1. Long Lasting High-Frequency VLF-Patch Events

The “VLF birds” usually occur as a sequence of a number of discrete signals or single short patches with the total duration from tens of seconds to a few hours. Here we present two examples of the long-lasting events on two different consecutive days: December 25 and 27, 2014.

3.1.1. Event on December 25, 2014

Figure 2 presents an example of the “VLF bird” event with duration of about 8 h observed on December 25, 2014 as a long series of the short high frequency VLF patches. Figure 2a demonstrates the total power spectrogram in the frequency band of 2–12 kHz (left panel) and its right-hand part of the circular polarization (right panel). The bottom frequency (2 kHz) is used to avoid the local power line harmonic radiations (PLHR) which is seen as bottom strong red area in Figure 1.

Very many short signals looking as thin sticks are seen in Figure 2a, particularly as right-hand polarized VLF patches. One can see that before \( \sim 07 \text{ UT} \) the signals were observed at the frequencies above \( \sim 6 \text{ kHz} \), later on they suddenly shifted to lower frequencies. The wave frequency change demonstrates the variation of the position of their source associated with the location of the resonant electrons. Strange and complicated spectral structures of some selected VLF patches are plotted in Figure 2b as the 60-s total power spectrograms.

Figure 2b shows that the first event (#1, starting at \( \sim 06:08:25 \text{ UT} \)) consisted of two very short (\( \sim 10 \text{ s} \)) simultaneous spots of hiss-like emissions in the frequency bands of \( \sim 7.0–8.5 \text{ kHz} \) and \( \sim 9–11 \text{ kHz} \) supporting the existence of two simultaneous sources of the VLF generation located at the different L-shells. The second event (#3, starting at \( \sim 08:26:25 \text{ UT} \)) represented the complicated multiband VLF emissions at the frequencies from \( \sim 3 \) to \( \sim 8 \text{ kHz} \). The individual signal duration was \( \sim 10 \text{ s} \) at the higher frequencies and of \( \sim 30 \text{ s} \) at lower frequencies. The middle hiss-like band demonstrates a superposition of noise waves with very short discrete impulsive signals at the same frequencies. The third event (#5, starting at \( \sim 09:27:20 \text{ UT} \)) has very strange three-band structure, but in the frequency range of \( \sim 4–9 \text{ kHz} \), that is, a little higher than in the previous event. The middle spot lasted only \( \sim 5 \text{ s} \), but two others were of \( \sim 20 \text{ s} \) duration. One may conclude that the location and temporal dynamics of the source of this complicated VLF spot should be very complicated as well. The next event (#6, starting at 12:24 UT) with duration of \( \sim 40 \text{ s} \) is looking like a monochromatic narrow hiss band with the central frequency \( \sim 6.5 \text{ kHz} \).

Figure 2c displays two 2-min VLF spectra of the VLF patches starting at 07:51:35 UT (#2) and 08:48:50 UT (#4). The spectral structure of the VLF patch #2 completely differed from the event #1 (Figure 2b), the signal duration strongly increased and the frequency band decreased. That can indicate that the source of this VLF patch moved to the higher \( L \)-value. The VLF patch #4 in Figure 2c has occurred about 20 min after the VLF patch #3 shown in Figure 2b. The dynamic spectra and the frequency band of these events were relative similar indicating the similar location of their sources but with the different duration.

3.1.2. Event on December 27, 2014

Two days later, on December 27, 2014, relatively similar long-lasting high-frequency VLF patch event took place lasting about 6 h. Figure 3 shows that the emissions started about at 05 UT as a series of VLF signals looking like thin “sticks” at the frequencies above \( \sim 4 \text{ kHz} \). As it is seen in Figure 3a, after 08 UT, the dynamic spectrum of the signals changed. That is demonstrated in Figure 3b where the total power spectra of VLF patches present for two intervals: 05–06 UT and 08–09 UT. In these intervals, the signal spectra were totally different, the thin VLF “sticks” replaced by some VLF “tatters,” that is, by the signals with more complicated spectra. The total power spectra of the selected VLF patches are shown in Figure 3c.
In the first interval (05–06 UT), the emissions were observed as short (∼20–40 s) VLF patches in two frequency ranges decreasing over time: ∼6–7 kHz and ∼4–6 kHz. That may support the idea that in this time there were two different narrow sources of cyclotron emissions located at the different L-values in the magnetosphere. In the second time interval (08–09 UT), the signals were observed at the similar frequency band.
Figure 3. The event on December 27, 2014: (a) the 8-h VLF total power spectrogram in the frequency band of 1–10 kHz at KAN; (b) the 1-h VLF spectrograms of the 05–06 UT and 08–09 UT intervals; (c) the 3-min VLF spectrograms of the total power of some VLF patches shown by the arrows; (d) the AL index variations during these events (marked by the blue bars); (e) the global maps of the magnetic disturbance vectors obtained by ground-based magnetometer stations of the SuperMAG network during the first and the second intervals. VLF, very low frequency.
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3.2. Temporal Variability of Spectrum Shapes of the Short VLF Patches

The different dynamic spectra of the separated VLF patches have been obtained by VLF records at KAN. In Figure 4, we demonstrate several examples of the 3-min dynamic spectra of the VLF patches (total power) observed at KAN during different days. The analysis of the variability of dynamic wave spectra is an important tool for the development of theoretical ideas about the details of the interaction of waves and particles in the magnetosphere leading to the generation of these previously unknown types of high-frequency VLF patches.

Figure 4a displays three examples of the VLF patches at the frequency above ∼ 5 kHz with different temporal spectral shapes observed in the local afternoon on December 10, 2013. Some of the signals were resembling flowing birds. The waves in the first (at 10:10 UT) and second (at 11:21 UT) panel in Figure 4a are characterized by a very sharp low frequency cutoff near ∼ 5.5 kHz. The VLF emissions represent a superposition of almost continuous narrow band around this cutoff frequency and the bursts of emissions with the central frequency near 7 kHz. The impulsive wave generation is observed at 10:10:30 UT. At 10:12 UT, two short spots at the frequencies of ∼ 5.5 and ∼ 7.0 kHz followed each other giving the impression that their excitation is somehow connected. The similar sequence of VLF spots at different frequencies are seen as well at 11:33:20 UT (last plot in Figure 4a). Figure 4b demonstrates the typical shape of “VLF bird” emissions as short hiss-like spots at different frequencies between 5 and 10 kHz.

Figure 4c shows the examples of three different shapes of the 3 min dynamic spectra observed on different days: December 9, 2016, February 20, 2018, and February 3, 2020. Figures 4d and 4e demonstrate the fine spectral structure of these events as their zoom-ins by the scaling in 60 s (Figure 4d) and 10 s (Figure 4e). The very complicated dynamic spectra of the VLF patches are seen accompanying by the short period QP modulation of the signal intensity at different frequencies under the absence of geomagnetic pulsations with the similar periods. The modulation was very strong, up to 100%. In the VLF spectrum on December 9, 2016 (the left panels in Figures 4c–4e), there were two frequency bands of emissions observed with the similar QP modulation of the intensity. Since the different VLF frequencies of the cyclotron emissions are generated at the different L-values, the occurrence of the simultaneous QP modulation of the different frequency bands supports the source of the modulating driver being in the magnetosphere in the relatively vast area of the L-shells.

The ∼ 2 s signal repetition period as a very clear QP modulation of the VLF patch intensity at the frequency around 9 kHz is also seen in the middle panels in Figures 4c–4e (the event on 18 February 2018). The event on February 3, 2020, shown in the right panels in Figures 4c–4e, presents the simultaneous occurrence of the complicated VLF patches with the different duration and different frequency bands (from ∼ 4 to ∼ 10 kHz) and its frequency-time evolution demonstrating that in different domains of the magnetosphere, different regimes of plasma instabilities can develop simultaneously.

Figure 4 demonstrates only very small part of the huge collection of different spectrum shapes of the high frequency VLF “bird emissions.”

3.3. Strange QP Dot-Like High Frequency VLF Spots

The high-frequency VLF patches sometimes may exhibit the characteristic feature of a QP repetition of the individual signal occurrence. Two examples of such unusual events are shown in Figure 5.

The first event on December 5, 2014 (left panel in Figure 5a) represents the simultaneous generation of two frequency bands of QP VLF patches: the lower band with the central frequency gradually decreasing from ∼ 6.8 to ∼ 6.2 kHz and the higher band with the slowly varying central frequency at around ∼ 8.0 kHz. The signal repetition rate of ∼ 2 min was constant within the time when the signals have been observed (about 30 min). Figure 5b demonstrates that the strongest QP elements, detected at lower frequency band, consisted of short spots of hiss-like emissions with the duration of about 20 s. The QP elements, detected at higher frequency band, demonstrated the dash-like narrow-band VLF emissions lasting about 1 min each with...
Figure 4. The examples of the spectral structure of the VLF patches at KAN showing different shapes: (a) the 3-min spectrograms of the VLF patches with a sharp low frequency cutoff on December 10, 2013; (b) the typical spectral shapes of the VLF patches; (c) the very complicated 3-min spectra of the VLF patches on three different days; (d) the 1-min spectra scaling the above 3-min events; (e) the same with the time scaling of 10 s. KAN, Kannuslehto station; VLF, very low frequency.
Figure 5. The VLF events on December 5, 2014 (left panel) and December 27, 2015 (right panel): (a) the 30-min VLF total power spectrograms in the frequency band of 5–12 kHz at KAN; (b) the example of the 6-min spectrogram for the first event and the 9-min spectrogram for the second one; (c) the variations of the $B_z$ IMF and AL index during these events (marked by the blue bars); (d) the global maps of the magnetic disturbance vectors obtained by the ground-based SuperMAG network during the first and the second time intervals. KAN, Kannuslehto station; VLF, very low frequency.
the repetition rate of ∼2 min as well. However, there were no geomagnetic pulsations with the periods of ∼2 min. It is interesting to note that the VLF patches at lower frequency band exited at the end of the higher frequency band spots, that is, the VLF emissions arose at high and low frequency band by rotation. Probably, the generation of the individual signals of the lower and higher bands could be causally depended.

The second strange VLF event was observed on December 27, 2015 (right panel in Figure 5a). The VLF emissions were looking like a dotted line at the central frequency of ∼9 kHz and with the periodicity of about 1 min which did not vary considerably over the time. As in previous event, there were no geomagnetic pulsations with the similar periods. Figure 5b demonstrates that this high frequency VLF event represented a sequence of small spots of hiss-like emissions with the duration of about 30 s.

Figures 5c and 5d show some details of the geomagnetic situation during this event, they will be discussed later in Section 4.

3.4. Simultaneous VLF Observations at Two Longitude Separated Stations

The VLF observations at KAN were compared with those obtained at the Russian Lovozero station (LOZ, geographic coordinates 67.97°N, 35.02°E), which is located almost at the same geomagnetic latitude as KAN, but at a distance of about 400 km eastward (see geographic map in Figure 6a). The receivers of both stations have identical characteristics within the 30–16,000 Hz frequency band. More detailed description of the VLF recording at LOZ is given in Fedorenko et al. (2014). The receiver antennas at LOZ and KAN were calibrated by the same method. The preliminary filtering of sferics is applied at both points.

Note, that in addition to KAN, the LOZ equipment is completed with a recording of the vertical electrical field component to determine both the azimuth and angles of the VLF wave arrival. The dipole antenna is used to register the electric component at LOZ. Comparing the KAN and LOZ registration of a given event, we can remove the 180° uncertainty in determination of the direction of the wave arrival at KAN because as it was found previously (e.g., Manninen et al., 2014, 2020), the VLF emissions at KAN and LOZ are usually of the same origin. Knowing the measured angle of arrival of waves in LOZ, it can be assumed that the signals arrived in KAN roughly from the same direction, and not from the opposite direction.

As examples we will discuss some morphological peculiarities and direction of the signal arrival of three selected events of the high-frequency VLF patches observed simultaneously at KAN and LOZ.

3.4.1. Event on January 5, 2015

The event was observed on January 5, 2015 from 05 to 14 UT as several hours lasting daytime VLF noise emission burst (“the VLF noise storm”) during the late recovery phase of the moderate magnetic storm. This event displayed in Figure 6b was described in detail in Manninen et al. (2020). The similar VLF emissions were recorded simultaneously at LOZ with the similar spectrograms (do not shown here). The “body” of the event (Figure 6b) consisted of hiss-like emissions at below ∼4 kHz. Since the shape of the event somewhat resembles the configuration of a reclining elephant, we called this event “an elephant.” It should be noted that in the beginning of the “elephant” (at 05–07 UT) as well as in the middle (at ∼09:30–10:30 UT) and in its end (12–14 UT), high-frequency VLF patches appeared at the frequencies above ∼5 kHz. Figure 6c displays the total power VLF spectrogram at KAN during the “elephant’s trunk” at 06–07 UT.

Several strong high-frequency VLF patches are seen above ∼4 kHz, that is, above the hiss-like VLF emissions. Two of these high-frequency VLF patches (at 06:10 UT and at 06:30 UT) are shown as the 3-min spectrograms in Figures 6d and 6e correspondently. Both patches occurred simultaneously at KAN and LOZ with very similar dynamic spectra. At 06:10 UT, the signal intensity at KAN was stronger than at LOZ, however, at 06:30 UT the signal at LOZ became stronger than at KAN.

Figure 6d demonstrates that the first event (06:10–06:12 UT) represented the sequence of two short (∼20 and ∼40 s) noise bursts in the decreasing frequency bands from ∼6.5–9.0 kHz to ∼5.0–7.0 kHz. The right panels in Figures 6d and 6e display the distribution of the angles of the wave arrival at KAN and LOZ. At KAN, the red color indicates that the waves arrived at KAN almost along the meridian N-S, but due to uncertainty of 180°, it is not known whether from north or from south. According to the LOZ measurements, both bursts arrived at LOZ from the southwest. Based on the KAN and LOZ spectrogram similarity, we
Figure 6. The comparison of the VLF data at KAN and LOZ on January 5, 2015: (a) the map of KAN and LOZ location; (b) the 10-h VLF total power spectrogram in the frequency band of 1–10 kHz at KAN; (c) the 1-h VLF spectrogram in the event beginning; (d) the 3-min VLF total power spectrograms and the angles of the wave arrival at KAN (upper panels) and LOZ (lower panels) starting at 06:10 UT; (e) the same as in (d) starting at 06:30 UT. The arrows show the direction to the ionospheric wave exit area of the VLF wave observed at KAN and LOZ. KAN, Kannuslehto station; LOZ, Lovozero station; VLF, very low frequency.
suppose that the VLF patches recorded at these points had a common source and ionospheric exit point. Therefore, we can assume that the studied waves came to KAN from the south and not from the north. According to the LOZ data, this source was located southwestern LOZ.

The spectrogram of the second VLF patch at 06:30–06:32 UT is shown in Figure 6e. This event was a noise burst with the slowly increasing frequency within \( \sim 5.0–8.0 \) kHz and with a duration of \( \sim 80 \) s. Figure 6e demonstrates that the VLF waves of this burst came to LOZ from the south and to KAN from the northwest or the southeast. By analogy to the previous arguments, we assume that at 06:30–06:32 UT, the VLF waves arrived at KAN from the southeast.

One can suppose, that in the first event, at 06:10–06:12 UT, the VLF wave source was located near the KAN meridian but much farther southern KAN; therefore, the waves arrived at LOZ from the southwest. During the second event, at 06:30–06:32 UT, the source of the VLF waves was located southward LOZ, and the VLF waves arrived to KAN from the southeast.

Thus, comparing the VLF measurements at KAN and LOZ, we specified the direction of the wave arrival at KAN, that is, got rid of 180° ambiguity. Then we found that wave exit area was located southward KAN and LOZ, but the direction of VLF wave arrival at KAN and LOZ was different.

### 3.4.2. Event on December 31, 2018

The second example of the different direction of the VLF wave arrival at KAN and LOZ is given in Figure 7 were the long-lasting series of the high-frequency patches is shown. These VLF emissions were recorded on December 31, 2018 from \( \sim 06 \) to \( \sim 09 \) UT (Figure 7a) at the frequencies between \( \sim 4 \) and \( \sim 8 \) kHz. There is our own calibration signal at the frequency of 6 kHz seeing on the spectrograms as a thin horizontal line. In Figure 7a, the individual VLF patches look like separated vertical sticks above 4 kHz. Three examples of the 2-min spectrograms of such VLF patches are shown in Figure 7b. Since the spectrograms at KAN and LOZ during this case were very similar as well as in the previous event (on January 5, 2015), we present here only KAN spectrograms.

The high frequency VLF patch of the event #1 lasted about one minute as a band of hiss-like emissions at the frequencies within \( \sim 4.2–7.0 \) kHz with the gradually declining upper frequency (Figure 7b). As we believe that the waves under study arise due to cyclotron instability in the magnetosphere, the constancy of the lower frequency of the event can be interpreted as the constant location of the region where the generation of waves did end (the highest \( L \)-value) during the given one minute. In this case, a decrease in the upper frequency of the patch indicates a displacement of the wave generation region toward the higher \( L \)-values.

The event #2 in Figure 7b lasted about 2 min. The strongest emissions were recorded in the first 40 s of the patch generation beginning, there the bottom and upper frequencies of the emissions remained rather constant (\( \sim 5 \) and \( \sim 7 \) kHz) demonstrating the rather constant source location. The event #3 lasted about 35 s with the constant frequency band as well, but within little higher frequencies.

Figure 7c demonstrates the calculated directions of the wave arrival at both stations of three VLF patches shown in Figure 7b. One can see that during all considered events, the wave exit area was located southward KAN and LOZ, and the direction of the wave arrival at KAN and LOZ were different. In the event #1, the wave exit area was located between the longitudes of KAN and LOZ, but closer to the KAN meridian. In the event #2, the wave exit area was located between the longitudes of KAN and LOZ at the almost same distance from KAN and LOZ. In the event #3, the wave exit area was located eastward both stations, but closer to the LOZ meridian.

Three examples of the 2-min spectrograms shown in Figure 7b demonstrate that the noise-like VLF patches actually had the same discrete structure. The 10-s spectrograms, displayed in Figure 7d as the total power and its right-hand polarized part, demonstrate that, in fact, each VLF patch is a dense sequence of very closely repeated risers. There were about 50 very short risers within 10 s. All these signals were right-hand polarized waves.

Previously one case (on July 27, 1972, between 14:55 and 15:30 UT) of the rising structure of VLF emissions at frequency of \( \sim 6.5–9.0 \) kHz was reported by Francis et al. (1983) based on the VLF recording at Halley station (\( L \) = 4.3) in Antarctica. The authors observed \( \sim 10–20 \) short irregular risers within 10 s which were
Figure 7. The VLF event on December 31, 2018: (a) the 4-h VLF total power spectrogram in the frequency band of 0–10 kHz at KAN; (b) the 2-min spectrograms in the frequency band of 2–10 kHz of the VLF patches at KAN shown by the thin black arrows; (c) the calculated directions to the ionospheric wave exit area of the VLF patches observed at KAN and LOZ; (d) the 10-s VLF spectrograms in the frequency band of 4–9 kHz of the total power and its right-handed polarized part of some selected events at KAN. KAN, Kannuslehto station; LOZ, Lovozero station; VLF, very low frequency.
looking similar to a riser structure of VLF chorus. Several explanations have been discussed by Francis et al. (1983), but no one was reasonable. Thus, the plausible source of such peculiar rising structure of the high frequency short VLF patches remains unknown.

3.4.3. Event on February 3, 2020

One spectacular VLF event of strange high-frequency patches was observed recently on February 3, 2020. The event lasted from ~14:40 UT to ~16:40 UT as a sequence of short signals with the repetition of about 5–6 min. The spectrogram of this event is given in Figure 8a.

The event started with a strange VLF patch at the frequencies from ∼3.5 to ∼7.0 kHz with very sharp low frequency cutoff. The 2-min spectrograms of this VLF patch as the wave total power and distribution of the angles of wave arrival at KAN and LOZ are displayed in Figure 8b. The very complex dynamic spectrum of this VLF patch was the same at KAN and LOZ. At LOZ, the waves arrived from the northeast, at KAN, the feature is more complicated, but it seems, that the waves arrived mainly from the same direction. The VLF emissions within ∼4–6 kHz exhibited the 100% intensity modulation with the QPs of few seconds observed at both stations in the absence of geomagnetic pulsations with the similar periods. Such short period (few seconds) modulation has often been previously observed both in the ground-based and satellite VLF observations at the frequencies below 4 kHz (e.g., Bespalov et al., 2010; Demekhov et al., 2020; Manninen et al., 2020; Martinez-Calderon et al., 2019) and can be explained by the auto-oscillation regime of the cyclotron instability of the Earth radiation belts (Bespalov, 1982; Trakhtengerts & Rycroft, 2008). However, such modulation of the high frequency VLF emissions above 4 kHz was found for the first time.

Figure 8c demonstrates the example of the 2-min spectrograms of one of the VLF patches in the middle of this event at 15:44–15:46 UT. It is seen that at KAN, the VLF emissions were recorded simultaneously in two frequency bands (∼4–6 kHz and ∼8–10 kHz), and the intensity of 8–10 kHz emissions was stronger than the intensity of 4–6 kHz emissions. However, at LOZ, there were no the remarkable high-frequency band emissions, only some very faint traces were seen. At both stations, the intensity of the low frequency emissions was modulated with QPs of a few seconds as it was in the event shown in Figure 8b. At KAN, the waves arrived roughly from the east-west direction, probably from the southeast because at LOZ the waves arrived from the south.

Since such nontypical case of the high frequency VLF patches was observed for the first time, it is not surprising that the physical conditions that caused such a complex dynamic spectrum of waves have not yet been established.

4. Discussion

Here we presented several examples of the different spectral shape and temporal behavior of the new discovered type of high frequency VLF patches ("VLF birds") observed at the ground-based stations KAN and LOZ at the auroral latitudes. As it was found previously (Manninen et al., 2016, 2017, 2020) these emissions were observed in the daytime under weak or moderately disturbed geomagnetic and interplanetary conditions. Our analysis of the considered here VLF events confirms this.

The first long-lasting VLF case examined here (Figure 2) has occurred on December 25, 2014, and has observed under the rather quiet geomagnetic conditions with Kp = 1–2 and Dst = −(10–15) nT. Figure 2d shows that during this event, the IMF Bz was small and positive. But in the beginning of the event, at ∼05–07 UT, the small magnetic substorm with AL index of about 100 nT was recorded. In this time, the high frequency VLF patches were observed. After the substorm the VLF frequency suddenly decreased to ∼4–8 kHz. Under the assumption of the cyclotron nature of the VLF waves, this can mean shifting of the wave source to higher L-values.

The second long-lasting VLF case shown in Figure 3 has occurred on December 27, 2014 and has similarly observed under the rather quiet geomagnetic conditions (Kp = 1–2, Dst = −(10–20) nT). In this case, there were no substorm in the beginning of the event (Figure 3d) when the VLF patches were very short (Figures 3b and 3c). Later, during the development of magnetic substorm (Figure 3d) with the intensity about 300 nT, the shape of the wave spectrum of the same frequency band became more complicated (Figure 3b), and the angle of the wave arrival changed significantly. Figure 3e demonstrates two global maps of the
Figure 8. The event on February 3, 2020: (a) the 2.5-h VLF total power spectrogram in the frequency band of 2–12 kHz at KAN; (b) the 2-min spectrograms of the total power and the angles of the wave arrival in the frequency band of 1–10 kHz at KAN (upper panel) and LOZ. KAN, Kannuslehto station; LOZ, Lovozero station; VLF, very low frequency.
magnetic disturbance vectors (http://supermag.jhuapl.edu/) obtained from about 300 globally distributed ground-based magnetometer stations of the SuperMAG project (Newell & Gjerloev, 2011) during the first and the second time intervals shown in Figure 3b. It is seen that there was no magnetic activity in the beginning of the event, but the strong magnetic disturbances occurred later. Then the dynamic spectra of the VLF patches became complex.

Two unusual VLF events looking like dotted lines shown in Figure 5 also were observed under the quiet geomagnetic conditions as in the previous cases. But, during the VLF event on December 5, 2014, the geomagnetic conditions were more disturbed, as it is seen in Figure 5c: the IMF Bz was negative, and the AL index variations indicated a magnetic substorm with the intensity of about 300 nT. The map in Figure 5d showed night side magnetic disturbances. This event demonstrates that under the more disturbed conditions, two frequency bands of the high frequency VLF emissions were generated simultaneously.

The VLF event on December 27, 2015 looking like one dotted line at ∼9 kHz has occurred under very quiet space weather conditions: the positive IMF Bz and the absence of magnetic substorms (see Figure 5d). The VLF patch event on January 5, 2015 (Figure 6) was observed in the late recovery phase of the small magnetic storm. In this time the Kp index dropped down to the value Kp = 2, the value of IMF Bz became positive, and magnetic substorms were over. But the Dst index remained rather high: about −40 nT.

The VLF event on 31 December 2018 (Figure 7) was also observed under the quiet space weather conditions: Kp = 2, Dst = −15 nT, AL = −100 nT. A similar situation was noted during the VLF event on February 3, 2020 (Figure 8): Kp = 0, Dst = −15 nT, AL = −100 nT, IMF Bz was slightly positive or negative. But, Figure 8c shows that the VLF patches at the frequencies above 7 kHz in Figure 8a appeared only after the small jump in the solar wind dynamic pressure (Psw).

So, we found that the high-frequency VLF patches (“VLF birds”) are observed at the ground-based station only under the quiet space weather conditions, but during the small negative values of the Dst index, indicating the presence of a certain excess of the radiation belt electrons. They could be a source for the cyclotron instability leading to the VLF wave generation. It should be noted that the development of the magnetic substorm at the nightside of the Earth, that is, the electron injection into the magnetosphere, resulted different changes of the properties of the VLF patches: in the frequency as in Figures 2 and 8, in the duration as in Figure 3, in the shape of the dynamic spectrum as in Figures 3 and 5. Hence, an appearance of the high frequency VLF patches could be an indirect indicator of a local enhancement of radiation belt electrons that are not directly measured and may occur even in the absence of visible geomagnetic disturbances.

Note that, at KAN, the considered high frequency VLF patches are observed at the frequencies much higher than the half of the equatorial electron gyrofrequency (f_{He}/2) which is ∼2.7 kHz at L ∼ 5.5. So, they could not be emissions generating near the equatorial plane of the magnetosphere at the correspondent KAN L shell (L ∼ 5.5) and propagating in a ducted way. Thus, we assume that the studied high-frequency VLF patches (“VLF birds”) are exited deep in the magnetosphere at L-shells much lower that the value of the L-shell correspondent to KAN.

We have to note, that recently in the papers Titova et al. (2017) and Demekhov et al. (2020), studying the QP emissions at 3–6 kHz detected simultaneously by two Van Allen Probes (RBSP) spacecrafts, located in the equatorial plane of the magnetosphere, and at the KAN station on December 25, 2015 at 11–13 UT, there was mention about two high frequency (above 8 kHz) VLF patches observed at 12:38 and 12:50 UT, both on the ground and the RBSP-B spacecraft. These VLF patches were almost monochromatic emissions with the slowly increasing frequencies: from ∼8.5 to ∼9.0 kHz in 12:38 UT event and from ∼8.7 to ∼9.8 kHz in 12:50 UT event. The Poynting vector direction of both events was of aligned direction, indicating the mostly field-aligned wave normal. Simultaneously with these VLF patches occurrence (at L ∼ 3.5, where f_{He} is equal to ∼20.4 kHz), an enhancement of the plasma density (a duct) was also recorded by RBSP-B spacecraft.

The waves at frequencies below f_{He}/2, that is, below ∼10 kHz, may be trapped in the duct which directs the waves to the ionosphere at L-shell much lower than the location of KAN. However, still now, it is poorly understood how these waves propagate to the ground-based station like KAN to be observed there as the right-hand polarized VLF emissions.
Anyway, our results are confident with the papers by Titova et al. (2017) and Demekhov et al. (2020), where it was directly confirmed that high-frequency VLF waves could generate in the magnetosphere at $L \sim 3.5$, that is, as we supposed, at the $L$-shells much lower than the value of the $L$-shell of KAN.

Thus, the collection of the different spectral structure of new discovered high frequency VLF patches could provide the experimental base for future theoretical ideas of the physical interpretation of the wave-particle interactions into the magnetospheric plasma.

5. Conclusion

The new, totally unexpected type of daytime high frequency VLF emission was discovered in the VLF observations at the Kannuslehto station ($L \sim 5.5$) at the frequencies above 4–6 kHz after the filtering out strong atmospherics (sferics) which hid like a curtain all natural VLF emissions at the same frequencies. These new high-frequency VLF emissions typically occur as a chaotic sequence of a number of short ($\sim 1–3$ min) burst-like right-hand polarized structures or single short patches with the total duration up to few hours.

A rich collection of different spectral shapes of these new high-frequency VLF patches is shown. Sometimes they were very complex, sometimes they exhibited a strange feature of a about 1–2 min QP repetition of the individual signal looking like a dotted line. The dynamic spectrum of the high-frequency VLF patches became more complex if there was a small magnetic substorm observed on the night side of the Earth in the same time. The spectral peculiarities of the dynamic spectra of the new VLF patches and its variability arise the questions of the temporal and spatial details of the wave-particle interactions in the magnetosphere.

The studied VLF patches were observed only under quiet or weakly disturbed space weather conditions, but during small negative values of the Dst index, indicating the presence of a certain excess of the radiation belt electrons.

The VLF observations at KAN were compared with those obtained at the Lovozero (LOZ) station, located at similar geomagnetic latitude, but about 400 km eastward. The results showed the common source of the individual VLF patches, and the location of its ionospheric exit area can change with time.

We suppose that these new discovered high-frequency VLF patches are generated deep in the magnetosphere at much lower $L$ values than the observation site. The details of the mechanism of generation and propagation of these waves remain unknown. However, these waves behavior represents an important subject for theoretical investigations of the plasma processes in the Earth's geomagnetic environment. An appearance of high frequency VLF patches could be an indirect indicator of a local enhancement of electron fluxes in the radiation belt that are not directly measured and may occur even in the absence of visible geomagnetic disturbances. Further researches may shed new light on wave-particle interactions occurring in the Earth's radiation belts.

Data Availability Statement

The filtered VLF KAN data are available at https://www.sgo.fi/pub_vlf/ as the power spectrograms in 24-h, 1-h, and 1-min intervals for all campaigns 2006–2019. The VLF LOZ data are available at http://aurora.pgia.ru:8071/.

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