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UNEXPECTED HIGH-FREQUENCY "BIRDS"-TYPE VLF EMISSIONS

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Abstract. The new type of daytime natural VLF whistler mode emissions of the magnetospheric origin was recently found in the VLF observations at Kannuslehto station (L ~ 5.5) in Northern Finland. These VLF events occurred at the frequencies above 4-5 kHz even up to 15 kHz. Here we present the different spectra of this peculiar daytime high-frequency VLF emissions observed under quiet geomagnetic conditions at auroral latitudes at Kannuslehto (Finland) and Lovozero (Russia) stations. These high-frequency waves cannot be attributed to typical well known VLF chorus and hiss. They became visible on the spectrograms only after the filtering out sferics originating by the lightning discharges and hiding all natural high-frequency signals. After this filtering, it was found a large collection of different natural VLF signals observed as a sequence of right-polarized short (less than 1-2 minutes) patches at frequencies above 4-5 kHz, i.e. at higher frequency than a half the equatorial electron gyrofrequency at the L-shell of Kannuslehto and Lovozero. These emissions were called "birds" due to their chirped sounds. It was established that the "birds" are typically occur during the daytime only under quiet space weather conditions. But in this time, small magnetic substorms were could be observed in the night sector of the Earth. Here we also show the recently observed series of the "bird-mode" emissions with various bizarre quasi-periodic dynamic spectra, sometimes consisting of two (and even more) frequency bands. The "birds" occur simultaneously at Kannuslehto and Lovozero with similar spectral structure demonstrating their common source. It seems that the "birds" emissions are generated deep inside the magnetosphere at the low L-shells. But the real nature, the generation region and propagation behavior of these VLF emissions remain still unknown. Moreover, nobody can explain how the waves could reach the ground at the auroral latitudes like Kannuslehto and Lovozero as well as which magnetospheric driver could generate this very complicated spectral feature of the emissions.

Introduction. The very-low-frequency (VLF) emissions 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 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., *Trakhtengerts*, 1963; *Kennel and Petschek*, 1966; *Rycroft,* 1972; *Trakhtengerts and Rycroft*, 2008]**.** The frequency of these waves is controlled by the electron gyrofrequency f_{He} at the geomagnetic equator**.** Despite the importance of direct VLF measurements in the space with satellite instruments, the continuous 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.

However, the ground-based studies of VLF emissions at frequencies above ~ 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 km 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 [*Manninen et al*., 2016, 2017]. The example of non-filtered (left plot) and filtered data (right plot) is given in Fig. 1. It is seen that a series of new unusual signals appear after filtering. These VLF waves were observed as a sequence of right-polarized (these spectra do not show here) short (less one-two minutes) patches of emissions at the high-frequencies above 4-5 kHz, i.e. at higher frequency than a half of the equatorial electron gyrofrequency at the L-shell of Kannuslehto and Lovozero (L = ~ 5.5, $f_{He}/2$ = ~ 2.7 kHz). These emissions were called "birds" due to their chirped sounds.

The aim of this paper is to present some spectral characteristics and temporal dynamics of these new natural electromagnetic emissions (birds) of the magnetospheric origin with frequencies above 4-5 kHz.

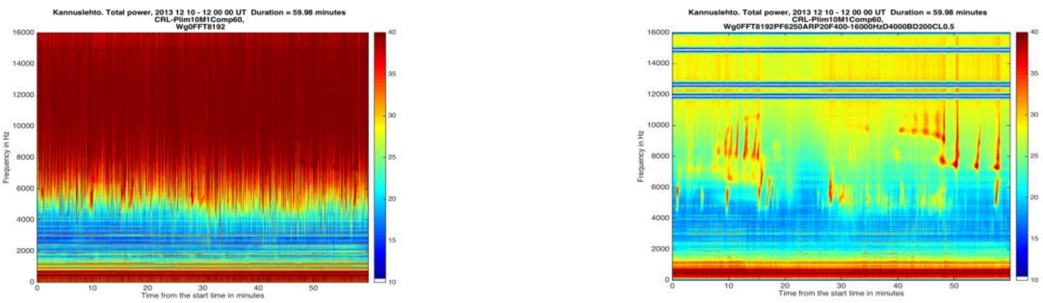

Figure 1. The example of 1-h spectrograms of VLF emissions at KAN: the non-filtered spectrogram (left panel) and the same spectrogram after sferics filtering (right panel). Three white high-frequency horizontal lines are the removed radio navigation transmitter signals.

Data. Our study was based on the VLF observations in Northern Finland at Kannuslehto station (KAN) with the geographic coordinates 67.74º N, 26.27º E; and MLAT = 64.4º 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 (the details of the equipment see in [*Manninen*, 2005]). 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 (*http://www.sgo.fi/pub_vlf/*). Since 2012, the similar VLF registration are carried out as well at Russian observatory Lovozero (LOZ), located at the similar L-shell ~400 km to the East.

Observation and discussion. The different dynamic spectra of the separated VLF patches have been obtained by VLF records at KAN. In Figure 2, we demonstrate several examples of the 3-min dynamic spectra of the VLF patches (total power) observed at KAN during different days. Some of the signals were resembling flowing birds. Figure 2b demonstrates the most typical shape of "VLF bird" emissions as short spots at different frequencies between 5 and 10 kHz.

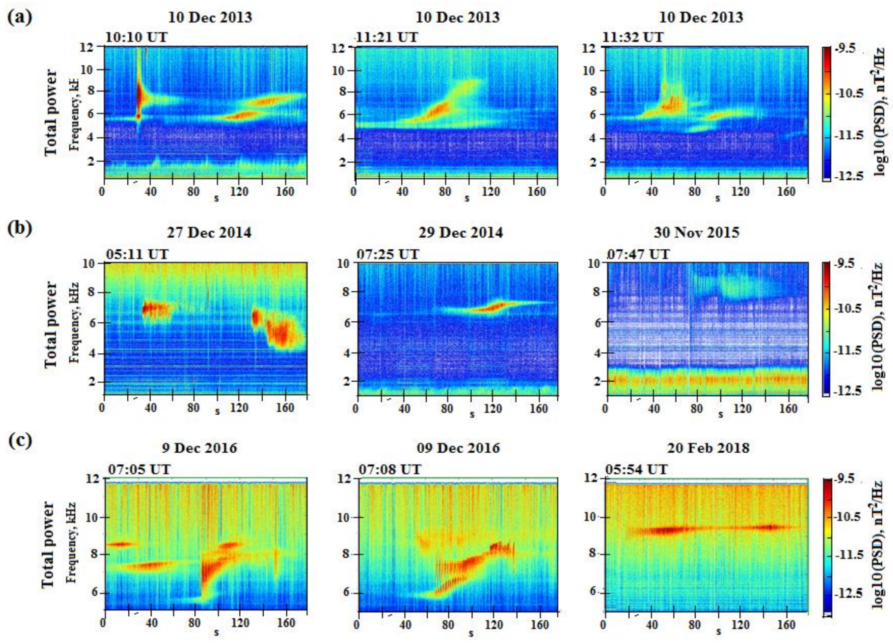

Figure 2. Examples of 3-min spectrograms of the VLF patches of different shapes at KAN: (a) VLF patches with sharp low frequency cutoff; (b) the most typical shape of VLF patches; (c) very complicated spectra of the VLF patches.

The high-frequency VLF patches sometimes may exhibit the characteristic feature of a quasiperiodic (QP) repetition of the individual signal occurrence. Two examples of such unusual events are shown in the left part of Fig. 3. The first event on 5 December 2014 represents the simultaneous generation of two frequency bands of quasiperiodic VLF patches. The QP elements, detected at higher frequency band, demonstrated the dash-like narrow-band VLF emissions lasting about one minute each with 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, i.e., 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 27 December 2015. 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.

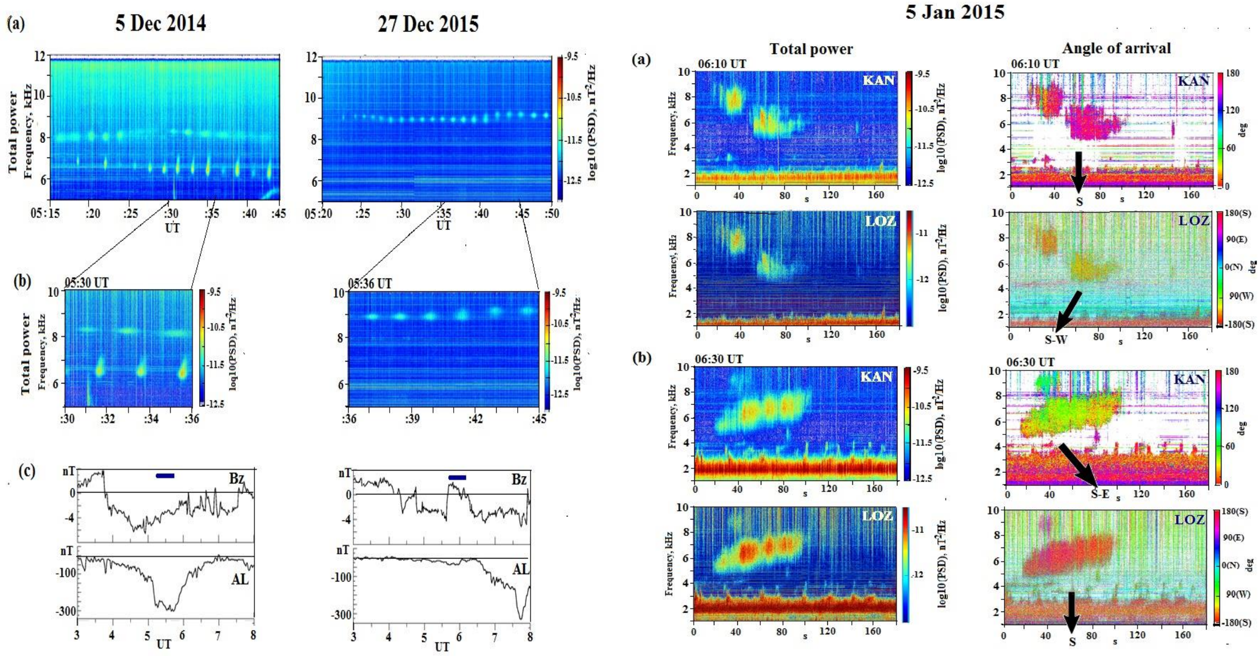

Figure 3. Left part – two VLF events with QP repetition and IMF Bz and AL-index variation during these events. The right part - two events of the "birds" at KAN and LOZ and the directions to their possible ionospheric exit areas.

It was established that the "birds" are typically occur during the daytime only under the quiet space weather conditions [*Manninen et al.*, 2017] as it is seen in Fig. 3 during the VLF event of 27 Dec 2015 under the positive IMF Bz. But simultaneously small or moderate magnetic substorms could be observed in the night sector of the Earth as it is seen in the event of 5 Dec 2014 under the negative IMF Bz.

The "bird" event of 5 Jan 2015 (right part in Fig. 3) was observed during the late recovery phase of the moderate magnetic storm. Two high-frequency VLF patches (at 06:10 UT and at 06:30 UT) are shown as the 3-min spectrograms. The VLF patches occurred simultaneously at KAN and LOZ with very similar dynamic spectra, but the direction of VLF wave arrival at KAN and LOZ was different. Based on the KAN and LOZ spectrogram similarity, we suppose that the VLF patches recorded at these points had a common source and ionospheric exit point. According to the LOZ measurements, the first event (at 06:10 UT) arrived at LOZ from the southwest, but at KAN from south. The second event (at 06:30 UT) arrived at LOZ from the south, but at KAN from the southeast. One can suppose, that in the first event, 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, the source of the VLF waves was located southward LOZ, and the VLF waves arrived to KAN from the southeast.

It is well known that 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. The ducted propagation of VLF waves is only possible at the frequencies lower than a half of the equatorial electron gyrofrequency ($f_{He}/2$) of the given *L*-shell [*Smith et al.*, 1960; *Carpenter*, 1968]. At higher frequencies ($f > f_{He}/2$), the waves can propagate in a non-ducted way, i.e., obliquely with respect to the local magnetic field lines. KAN is located at L ~ 5.5, where the half of the equatorial electron gyrofrequency ($f_{He}/2$) is ~ 2.7 kHz. Thus, we assume that the studied high-frequency VLF patches ("VLF birds") are exited at deep in the magnetosphere at L-shells much lower that the value of the L-shell correspondent to KAN and LOZ.

However, if these waves are generated and ducted at the L-shell much lower than the location of KAN and LOZ, then after the wave leaves the duct, the wave-normal angle rapidly increases during the non-ducted propagation and such wave cannot pass through the ionosphere. Still now, it is unknown how these waves can propagate to the ground-based station like KAN and LOZ to be observed there as the right-hand polarized VLF emissions.

Summary. A rich collection of different spectral shapes of the new high-frequency VLF patches is shown. Sometimes they were very complex, sometimes they exhibited a strange feature of a about 1-2 min quasiperiodic 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 plasma.

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 sites. The details of the mechanism of generation and propagation of these waves remain unknown. However, these waves behaviour 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.

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