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New results of structured VLF emissions observed simultaneously at two closely located stations near $L \sim 5.5$

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Abstract. Simultaneous records of VLF (very low frequencies) emissions have been carried out at two ground-based stations located at similar geomagnetic latitudes near $L \sim 5.5$ and spaced in the longitude by ~ 400 km, Kannuslehto (KAN) in Finland and Lovozero (LOZ) in Russia, using quite similar VLF receivers with two calibrated orthogonal air-core loop antennas. We found that the general spectral properties of the VLF chorus emissions at these two stations were similar and typically have right-hand polarization. Contrary to VLF chorus, the short-period VLF emissions (periodic emissions, PE) in which separated spectral elements are repeated with the periodicity of 3–4 s were mostly left-hand polarized. Usually, these waves propagated in the north–south direction. We suppose that PEs are generated inside of the plasmasphere by the cyclotron instability under a quasi-linear relaxation of the energetic electron distribution function. However, sometimes PE occurred only at an individual station. We speculated that this could be due to the influence of the local inhomogeneities to the VLF waves during the propagation through the ionospheric trough to the ground. Unusual series of short-duration (10–100 s) bursts of VLF emissions, lasting several hours, were also found in the morning under very quiet geomagnetic conditions (Kp $\sim$ 0–1). Generally, these emissions were observed simultaneously at KAN and LOZ showing both right-hand and left-hand polarization, and different arrival directions provided the rather extended ionospheric exit area.

Keywords. Ionosphere (wave propagation) – magnetospheric physics (magnetosphere-ionosphere interactions; plasma waves and instabilities)

1 Introduction

Natural electromagnetic VLF (very low frequency) waves play an important role in the dynamics of energetic particles in the magnetosphere as well as in their local acceleration, and precipitation into the ionosphere (e.g. Trakhtengerts and Rycroft, 2008). In spite of a great significance of the satellite measurements, the ground-based VLF observations have an advantage because they allow studying a temporal behaviour of these emissions.

During recent years, several VLF campaigns have been carried out at a temporary station in Kannuslehto (KAN) in Finland, ($\varphi = 67.74°$ N, $\lambda = 26.27°$ E) by applying the high-sensitivity VLF receiver (Manninen, 2005). Some results of the quasi-period VLF emissions analysis have been published in Manninen et al. (2012, 2013). Furthermore, since the end of 2012, the continuous VLF recordings were started at Lovozero (LOZ) in Russia ($\varphi = 67.97°$ N, $\lambda = 35.02°$ E), located ~ 400 km to the magnetic east from KAN. Both stations are located at similar geomagnetic latitude near $L \sim 5.5$ (Fig. 1).

The aim of this paper is to compare the structured VLF emissions recorded at these two stations and reveal the similarities or distinctions at such short distance. This study can provide some new information of the dimension of the ionospheric exit area of VLF waves, and its temporal dynamics. As a first step we study (i) the morning VLF chorus, which is typical for moderate geomagnetic activity, (ii) the poorly known short-periodic VLF emissions with repetition period of $\sim$ 3–4 s (periodic emissions), which are also recorded under moderate magnetic activity, and (iii) isolated hiss-like

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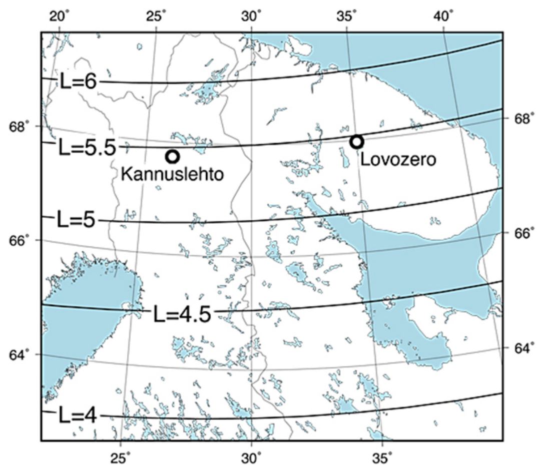

Figure 1. A map of the locations of the stations.

VLF spots lasting ∼ 10–40 s, observed under quiet geomagnetic conditions and sometimes revealing very complicated spectral shapes.

2 Instrumentation

The data studied in this paper were recorded at KAN and LOZ using quite similar VLF receivers. Both receivers have two orthogonal air-core loop antennas geographically oriented. Both stations were calibrated by injecting a fine-measured current into a toroidal coil wound in a single layer. The air-core loop antennas were threaded through the toroidal coil. Taking into account that the magnetic field was entirely confined to the space enclosed by windings, we calculated the magnetic flux through the plane of the air-core loops and then evaluated the calibration constant of the receivers. Furthermore, the receiver at LOZ includes a vertical dipole antenna to assess the vertical component of the electric field of VLF waves. This component is informative when one needs to differentiate between wave propagation directions that differed by 180° and that could not be performed using only horizontal magnetic components. The preamplifiers are located near the antennas, and a line receiver and data-recording system is located about 100 m from the antennas to reduce the 50 Hz harmonics from industrial power lines. The preamplified signals are sampled by 24 bit AD (analog-to-digital) converters. The sampling rate at LOZ was of 16 kHz while at KAN it was of 78.125 kHz. Both data-recording systems were synchronized by GPS time modules.

The spectrograms of total spectral density power, pure right-hand and pure left-hand polarized power presented in this paper were acquired using a polarization matrix of horizontal magnetic field components (Means, 1972). The elements of the polarization matrix were calculated by the FFT (fast Fourier transform) of the input signals B_x and B_y. Calibration curves were implemented into the analysis before calculating polarization matrix elements. The pure right-handed polarization represents the signals polarized similarly to whistler mode waves in magnetized space plasma.

All spectrograms in this paper are shown in the same scale, in decibels, where $0\,\mathrm{dB} = 1\,\mathrm{fT}^2\,\mathrm{Hz}^{-1}$, the wave intensity is colour-coded according to the colour bar on the right side.

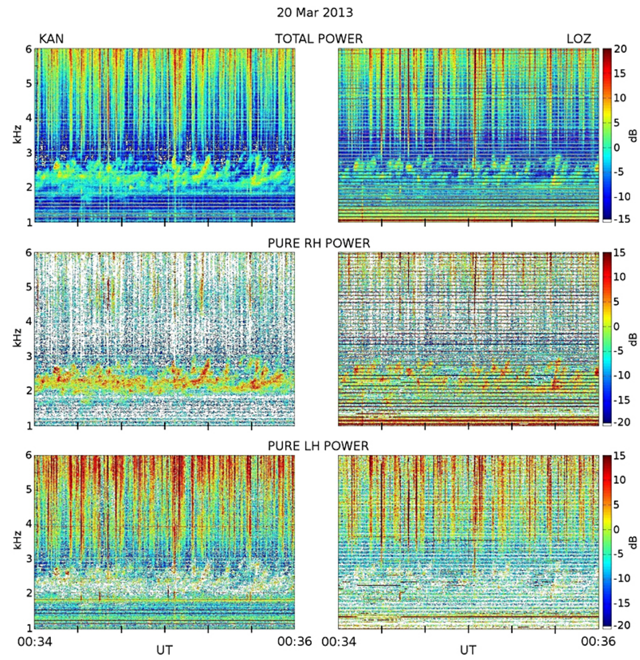

Figure 2. An example of simultaneous dynamic spectra of a VLF chorus observed at KAN and LOZ at 00:34–00:35 UT on 20 March 2013.

3 Observations

The preliminary analysis of VLF recordings at KAN and LOZ (in February, March and December 2013) shows that the typical morning chorus occurs simultaneously at both stations in the same frequency band (usually at the frequencies less than 3 kHz), with similar spectral structure, and with the right-hand (R) polarization (see an example in Fig. 2). The analysis method used in this paper has been described in Manninen (2005). According to Yearby and Smith (1994), we may conclude that both stations are located within the same ionospheric exit area of waves (not further than ∼ 100 km). Strong horizontal lines in this and other figures are due to power line harmonics (PLH), which are multiples of 50 Hz.

Another type of structured VLF emissions, observed under moderate geomagnetic activity (Kp ∼ 2), were short-period VLF emissions representing a sequence of separated spectral events showing regular spacing with a typical periodicity of about 3–5 s (so called periodic emissions, PE). This type of VLF waves was theoretically studied by Bespalov (1984,

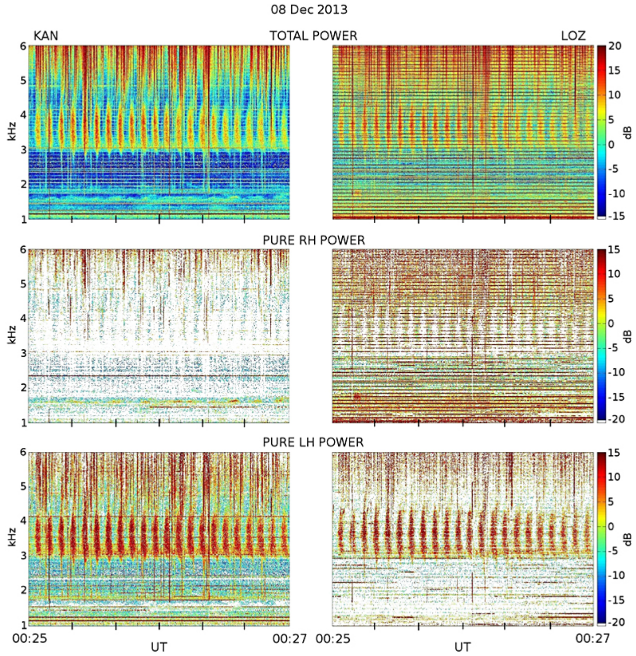

Figure 3. Dynamic spectra of left-hand polarized PE emissions observed at KAN and LOZ at 00:25–00:27 UT on 8 December 2013.

1993). Later it was found both in space (on board the DEMETER spacecraft) and on the ground at KAN (Bespalov et al., 2010). Earlier, the occurrence and seasonal variations of the similar short-period VLF emissions were studied by Engebretson et al. (2004) based on the observations at Antarctic stations. They showed that their repetition periods were similar to the two-hop travel time of echoing whistlers and that the signal occurrence was strong in the local winter.

We found that the PEs, as the VLF chorus, occurred simultaneously at KAN and LOZ, mostly recorded in the frequency band of ∼ 2–4 kHz but, contrary to chorus, showed the left-hand (L) polarization (Fig. 3) with a N–S direction of arrival (not shown here). These PEs are actually originally triggered by the whistler echo train. Based on these findings, we suppose that the ionospheric exit area of PE was located far away from KAN and LOZ, presumably inside of the plasmasphere. Sometimes the PEs were recorded only at one of these stations, as shown in Fig. 4. This event was observed in the night-time after a sharp drop in the solar wind density (from 30 to 5 cm^{-3}) under low solar wind velocity (∼ 350 $\mathrm{km\,s}^{-1}$) resulting in an expansion of the magnetosphere and plasmasphere. The considered PEs were accompanied by visible auroras. So, the ionosphere at this latitude was disturbed as it was indicated by the sporadic E layer (E_s) in the Sodankylä ionosonde data (not shown here). Similar ionosphere disturbances were recorded also during the PE shown in Fig. 3.

A very unusual series of short bursts of VLF emissions, lasting several hours, were observed in the morning of 22 and 31 March 2013 (Figs. 5 and 6 correspondently) under very quiet geomagnetic conditions (Kp ∼ 0–1) and quiet ionosphere above Sodankylä. The emissions looked like a sequence of short (lasting about 40–100 s) bursts of hiss-like emissions in the frequency range of ∼ 2.5–4.5 kHz. Their polarization was right-handed and they had different arrival directions. At both stations, these emissions were observed simultaneously with the similar properties. This confirms that both stations were located in the vicinity of the ionospheric exit area of the waves. An example of such VLF burst with a very complicated spectral structure is shown in Fig. 5. The burst was structured by multihop whistlers. The signal was a little stronger at KAN than at LOZ, where the arrival direction was mostly E–W directed (green colour in the picture). We conclude that LOZ was located farther from the ionospheric exit area than KAN.

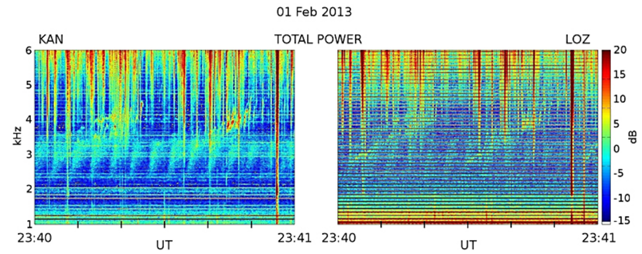

Figure 4. An example of periodic emissions (PE) that occurred only at KAN at 23:40–23:41 UT on 1 February 2013.

Moreover, on 31 March 2013, we found two events (04:32 and 08:12 UT, universal time) with temporal change of the wave polarization. The spectrogram of the first event (04:32 UT) is shown in Fig. 6. At KAN, in the first 20 s of the event, the polarization was mostly right-handed and then changed to strongly left-handed. The arrival direction at KAN also changed from being multidirectional (in the first part of the event) to approximately E–W (green colour in the picture). However, at LOZ, the VLF waves remained mostly right-hand polarized all the time and arrived from different directions (poorly seen in Fig. 6 due to strong PLHs at LOZ).

4 Discussion

First we noted that under quiet geomagnetic conditions (Kp ∼ 0–1) KAN and LOZ are located inside the plasmasphere or near the inner edge of the plasmapause, while under moderate geomagnetic conditions (Kp ∼ 2–3) outside of the plasmasphere.

It is well known, that chorus emissions are usually excited near the magnetic equator at $5 < L < 10$ at frequencies which are just below or just above half of the local electron cyclotron frequency $\omega_{BL}/2$ (Santolik et al., 2010). The plasmapause is an excellent waveguide channel (Inan and Bell, 1977) guiding the whistler mode waves to the ionosphere, where the light ions trough violates a layered structure of the

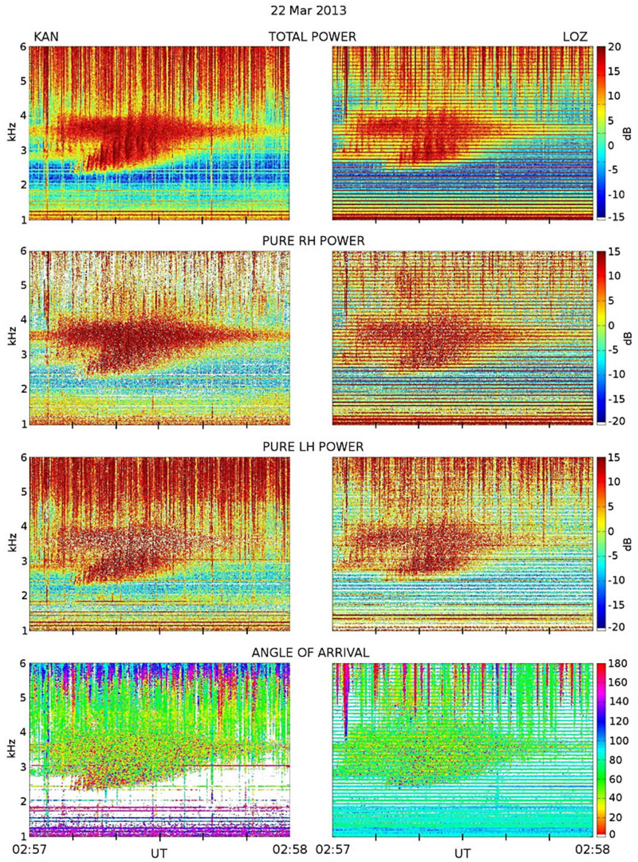

Figure 5. A VLF event with complex spectral structure observed at KAN and LOZ at 02:57–02:58 UT on 22 March 2013.

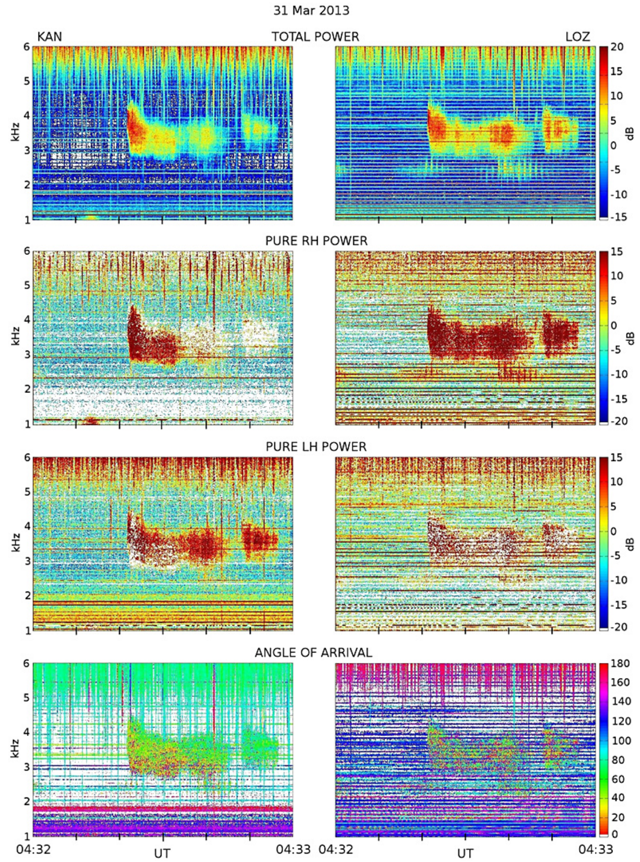

Figure 6. Short-lasting hiss-like VLF emissions observed at KAN and LOZ at 04:32–04:33 UT on 31 March 2013. There is a clear difference in the polarization of the event between our stations.

ionosphere. Penetrating to the ground under the ionospheric trough, chorus emissions show the right-hand polarization, which is typical for whistler mode waves (see Fig. 2).

An example of the short-period PE with the left-hand polarization at both stations is shown in Fig. 3. The frequency band of these emissions was higher than 2–3 kHz, i.e. higher than the cut-off frequency of the earth–ionosphere waveguide. We suppose that PEs can be excited inside the plasmasphere, where waves are guided by cold plasma ducts. In our opinion, the PEs are generated by the cyclotron instability under a quasi-linear relaxation of the energetic electron distribution function (Bespalov et al., 2010). The mean content of the energetic electrons in the magnetic tube has to be so low that the radiation belt is below the threshold of self-excitation for conventional cyclotron instability. Moreover, the power source of energetic electrons should have a suitable pitch-angular dependence.

These factors may provide the whistler mode wave packet (one or two), oscillating between the conjugate ionospheres without a dispersion. A repetition period of spectral forms is greater than two-hop travel time at the nose frequency $2t_{\mathrm{n}}$ for one packet or t_{n} for two packets. Note that all observed PEs show the packet repetition period longer than 3 s.

However, we also found some events in which the PEs were recorded only at one station. One example is shown in Fig. 4. This event occurred under Kp $\sim$ 2 when the both stations were located outside of the plasmasphere. In our opinion, the difference in VLF signals may occur due to the influence of the local ionospheric-trough inhomogeneities on the VLF waves' penetration to the ground. It should be kept in mind that the trough region is located at different magnetic latitudes depending on the magnetic longitudes at the given time and could vary with time (e.g. Rycroft and Burnell, 1970; Karpachev, 2003).

The morphological properties and the behaviour of short-lasting spots of VLF hiss-like emissions (Figs. 5, 6) observed under quiet geomagnetic conditions, as well as a state of magnetosphere during their generation, are not sufficiently investigated. We found that generally these emissions were observed simultaneously at both stations exhibiting the right-hand as well as the left-hand polarization, providing the rather large extent of the ionospheric exit area. We may speculate that these emissions are excited by the cyclotron wave-particle interactions inside of weak "clouds" of energetic electrons, drifting eastward in the magnetosphere and sometimes crossing the plasmapause in the morning side. As the result of the azimuthal movement of the "cloud", one of the stations may appear outside of the ionospheric exit area and the right-hand wave polarization changed to the left-hand.

5 Summary

The simultaneous observations of VLF emissions have been carried out at two stations located at the same geomagnetic latitudes ($L \sim 5.5$) and spaced in the longitude by ~ 400 km, Kannuslehto (KAN) in Finland and Lovozero (LOZ) in Russia, having quite similar VLF receivers. Both receivers employ two orthogonal air-core loop antennas oriented to measure the horizontal magnetic components of the wave field on the ground. The receivers at KAN and LOZ have been calibrated.

We found that the general behaviour of VLF chorus at the two sites was similar. The chorus was observed simultaneously with similar spectral variations and right-hand polarization. We concluded that both stations are located within the footprint of the ionospheric exit area, and consider this area as expanding along the longitude.

In contrast to the VLF chorus, the periodic VLF emissions (PE) with periodicity of 3–4 s were usually left-hand polarized waves. The PEs, as the VLF chorus, were recorded at KAN and LOZ simultaneously. We suppose that these PEs can be generated inside the plasmasphere by the cyclotron instability under the appropriate energetic electron distribution function as it was proposed by Bespalov et al. (2010). We also found some PE events, which occurred only at one station, and which we believe can be a result of the possible influence of local ionospheric inhomogeneities in the moderately disturbed (Kp $\sim$ 2) trough on the behaviour of the VLF wave propagation to the ground.

Some unusual series of short (10–100 s) bursts of VLF emissions, lasting several hours, were found in the morning under very quiet geomagnetic (Kp $\sim$ 0–1) conditions. Generally, these emissions were observed simultaneously at both stations with the right-hand and the left-hand polarization, providing a rather wide longitudinal expansion of the ionospheric exit area.

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