We thank both referees for their valuable and interesting comments. We appreciate very much that they were willing to spent their time helping us to improve our paper. We did our best to use all the comments and suggestions to improve the manuscript.

- We have changed ‘Unknown’ to ‘New’ in the title. (RC1)

- We have corrected everywhere the upper frequency to ’12 kHz’. (RC1)

- The end of the emission is not a consequence of the filtering method. Unfortunately, we could not find a plausible source of such strong signal rejection. Some speculation could be attributed to a sudden drop of the flux of trapped electrons at the geomagnetic flux tube, where the wave-particle interaction is taking place. (RC1 and RC2) (New lines 100-107)

- A possible explanation why the second set of “bullets” is only observed at lower frequencies could be that it is as a result of a time-shift of the wave generation region to higher L-shells. (RC2) (New lines 85-86)

- The size of the ionospheric exit points is not possible to determine with only two-component (magnetic NS and EW) receiver. We would need either the third component (Z, electric) or one or two similar receivers within a couple of hundreds of kilometres from KAN. Based on the polarisation and ellipticity of the waves we can estimate an ionospheric exit area roughly. (RC2) (New lines 119-121)

- All technical corrections have been made according to referees’ suggestions. (RC1 and RC2)

New high-frequency (7-12 kHz) quasi-periodic VLF emissions observed on the ground at L ~ 5.5

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Abstract. We reveal previously unknown quasi-periodic (QP) VLF emissions at the unusual high-frequency band of ~**7-12** kHz by applying the digital filtering of strong sferics to the ground-based VLF data recorded at Kannuslehto station (KAN). It is located in Northern Finland at L~5.5. The frequencies of QP emissions are much higher than the equatorial electron gyrofrequency at L~ 5.5. Thus, these emissions must have been generated at much lower L-shells than KAN. Two high-frequency QP emission events have been studied in detail. The emissions were right-hand polarized waves indicating an overhead location of the exit area of waves in the ionosphere. In one event, the spectral-temporal forms of the emissions looked like a series of giant "bullets" with the very abrupt cessation. Unfortunately, we could not explain such **a strange dynamic spectral** shape of the waves. In the second event, the modulation period was about 3 min under the absence **of simultaneous** geomagnetic pulsations. The studied emissions lasted about 4 hours and were observed under the very quiet geomagnetic activity. The adequate mechanisms of the generation and propagation of the revealed high-frequency QP emissions have not yet been established. We speculate that studied QP emissions can be attributed to the auto-oscillations of the cyclotron instability in the magnetospheric plasma maser.

Keywords. Magnetospheric physics (magnetosphere-ionosphere interactions; plasma waves and instabilities, energetic particles)

1 Introduction

The whistler mode VLF emissions, observed on the ground and onboard satellites, can exhibit a quasi-periodic (QP) occurrence of the separated signal patches in the frequency range of about 0.5-4 kHz, and due to that, they are termed QP-emissions (e.g., Carson et al., 1965; Kitamura et al., 1969; Sato et al., 1974; Morrison et al., 1994; Sazhin and Hayakawa, 1994; Engebretson et al., 2004; **Němec** et al., 2016). **QP emissions** were measured by satellites over a large **volume of geospace** (e.g., **Pasmanik et al., 2004; Němec** et al., 2013, 2014; Titova et al., 2015; Hayosh et al., 2016). A series of expressive long-lasting QP emissions, observed at ground station at the auroral latitudes, have been shown by Manninen et al., (2012, 2013, 2014). Note, the ground-based recordings provide important information about the temporal properties of the studied waves.

However, even **at auroral** latitudes, the ground-based VLF measurements are mostly covered by strong atmospherics (sferics) (e.g., Yamashita, 1978; Yedemsky et al., 1992; Volland, 1995) which hide all natural emissions with weaker amplitudes. Tweek atmospherics are electromagnetic pulses with duration of ~ 10–100 milliseconds originated from lightning discharges and propagating over distances of a few thousands km in the Earth-ionosphere waveguide (e.g., Ohya et al., 2015). To study the waves of the magnetospheric origin, we applied the special method of digitally filtering out the strong impulsive atmospherics with duration less than 30 ms. This processing allowed us to discover completely new types of high-frequency VLF emissions (Manninen et al., 2016). **Beside separated** discrete emissions, discussed by Manninen et al. (2016), we found also some previously unknown unusual high-frequency quasi-periodic VLF-emission lasting up to several hours. Such emissions have not been reported earlier.

The aim of this paper is to present the spectral feature of the revealed emissions at the frequency higher than 7 kHz. Our study was based on the VLF measurements (Manninen, 2005) at the auroral latitudes (L ~ 5.5) in Northern Finland at Kannuslehto (KAN, the geographic coordinates are 67.74°N, 26.27°E). To reject the influence of the strong narrow-band navigation transmitter signals, we analyzed the VLF emissions at the frequencies less than 12 kHz.

2 Observation results and its discussion

Here we present the analysis of two events of the unusual high-frequency QP emissions observed on 25 December 2011 and 5 January 2014 both at 16-20 UT (19-23 MLT). Two-hour non-filtered spectrograms, shown in the upper panels of Figure 1, demonstrate that the strong sferics **hide** all other weaker waves at the frequencies higher than 5-6 kHz. The same spectrograms, obtained after the filtering out sferics, are shown in the bottom panels of Fig. 1. Unexpectedly, after this filtering, the strange QP emissions were detected at the frequency band of **about 7 - 12** kHz. **A rather** similar event was recorded also on 10 December 2012 (not studied here). All considered VLF emissions were the right-hand polarized waves indicating the ionospheric exit point location to be approximately overhead. It is unlike the sferics which characterized by the left-hand polarization (e.g., Yedemsky et al., 1992; Haykawa et al., 1994). Some behavior of waves such as the temporal dynamics of the right-hand polarized part of the QP missions and its arriving direction of both studied events are given in Figure 2 in frequency band of 6-12 kHz.

Description of the VLF receiver is given by Manninen (2005). Sampling frequency was 78125 Hz and the noise level of the receiver is **10^{-14} nT^2/Hz**. The FFT size is 8192 in all spectral analysis.

2.1 Event of 25 Dec 2011

The spectrogram of the first studied event (25 Dec 2011, the left panels in Fig. 1) demonstrates the strange spectral-temporal forms look like a chain of giant “bullets” with a very sharp end of each element. The 4-hours total power spectrogram of this event as well as the right-hand (RH) polarized power of the waves in frequency band of 6-12 kHz and the angles of arrival of the waves are given in Fig. 2a. It is seen that the RH polarized waves represented two separated frequency bands: the strongly modulated band of 7.0-8.5 kHz and almost continuous hiss-like band of 9.0-10.5 kHz. Two strong “bullets” are observed in the beginning of the high-frequency band. It is interesting to note that the first “bullet” occurred at the higher frequency band, the second “bullet” appeared at both frequency bands and later the “bullets” were observed only at the lower frequencies. **That could be interpreted as a result of a time-shift of the wave generation region to higher L-shells.**

The direction-finding analysis showed that the high-frequency band arrived mostly along the meridian during the whole event, but the angles of arrival of the low frequency ‘bullets” changed with time deviating from the meridian (Fig. 2a, two lower panels). The angle of arrival has an uncertainty of 180 degrees (or ambiguity) due to only two orthogonal magnetic loop antennas oriented in the north-south and east-west directions are used in this study. The angle of arrival is determined as the direction of the minor axes of the wave polarization ellipses. In order to remove the ambiguity, an additional vertical electric antenna would be needed.

Attributing the emission generation to the electron cyclotron instability (e.g., Trakhtengerts and Rycroft, 2008), we may suppose the different location of the generation regions responsible for the high-frequency hiss and for the "bullets". The higher frequency band was originated at the smaller L-shells than the lower frequency band, and, the source of the "bullets"-like emissions removed in course of time. Although these two bands may have different source location, the sharp ends of every burst occur simultaneously in all frequencies.

The spectrogram of one separated "bullet" is presented in Fig. 3 both in 20 min (Fig. 3a) and 2 min (Fig. 3b) time scales. **Totally new observation was a very** abrupt cessation of the "bullet" which is clearly seen in Fig. 3a near **17:29 UT. It is really steep in the time scale of several** seconds (Fig. 3b). It is important to note that there were no such remarkable changes of the higher frequency (9.0-10.5 kHz) band. **This suggests that the end of the emission is not a consequence of the filtering method.** Unfortunately, we could not find a plausible source of such strong signal rejection. **Some speculation could be attributed to a sudden drop of the flux of trapped electrons at the geomagnetic flux tube, where the wave-particle interaction is taking place.**

2.2. Event of 5 Jan 2014

The second studied event (5 January 2014, right panels in Fig. 1) represents a series of quasi-repeated short patches with rather constant low frequencies and gradually increasing upper ones. The analysis of this QP event (Fig. 2b) demonstrated that the behavior of the event is much more visible in RH wave power spectrum than in its total power spectrum (upper plot). During first two hours, the band of emissions gradually shifted to the higher frequencies. At the beginning, the upper frequency limit increased from ~ 9 kHz to ~ 11 kHz within 1.5 hours. After ~18:30 UT, it began to decrease down to ~ 10 kHz (at ~19:30 UT). As well as during the 25 Dec 2011 QP event (Fig. 2a), the angle of arrival of this QP event quickly changed deviating from the north-south direction. At about 17:30 UT, the angle of arrival got settled approximately along the east-west direction as if in a daily rotation of the Earth the receiver is removed away from the source of wave generation. Note, that at this time, the waves remained RH polarized, so, we may conclude that all this time, the VLF receiver was **located not very far from the** ionospheric exit area of waves.

The detailed structure of the quasi-repeated patches is shown in Figure 4 as the temporal variation of total (T) and right-handed (RH) wave power spectra. The bottom panel represents the variations of the integrated wave intensity in the frequency band of 7-10 kHz demonstrating the average period of the VLF wave repetition of ~ 3 min. In addition, there were altogether 10 QP emission bursts with 3 s internal periodicity shown in the bottom panel in Figure 4. According to ground-based measurements at Scandinavian IMAGE magnetometer chain, there were no geomagnetic pulsations with similar periods.

Besides this 3-min periodicity, Figure 4 demonstrates an appearance of the strong impulsive packets of very short periods VLF emissions superposing the quasi-repeated VLF patches. An example of the fine structure of these impulses is shown in Figure 5 at 2-min time scale. It was found that its structure consists of the long series of the RH polarized QP emissions in the ~ 8.5-10.5 kHz frequency band with repetition period of about 3 s. The first six emissions were non-dispersive, but the following ones exhibited smaller intensity decreasing with time and positive time-frequency slope (df/dt > 0). The short period QP emissions having similar periodicity have been recorded previously on the ground and onboard satellites (e.g., Bespalov et al., 2010; Manninen et al., 2014). However, in these papers the QP emissions were at the frequencies less than 2.5 kHz, but in our case the QP emissions were observed at **frequencies** higher than 7 kHz.

During our events, the conditions in the solar wind and IMF were very quiet shown in Figure 6a. During the studied intervals, there were no geomagnetic disturbances and pulsations at SOD located 45 km south-east from KAN. The planetary geomagnetic activity was quiet with Kp ~ 0. However, some small Kp enhancements can be seen within preceding 24 hours (Fig. 6b), providing additional electrons in the radiation belts. This might be due to a small magnetic substorm in the night side (AL values up to 100 nT) before the 5 Jan 2014 event. There was no substorm before 25 Dec 2011 event. According to data of RBSP (A and B) satellites [http://enarc.space.swri.edu/PTP], KAN was mapped in the vicinity of the plasmapause (Fig. 6c).

There is no complete theory adequately **explaining** the generation of such high-frequency QP emissions because our finding is so new. **The studied QP events did not accompanied by ULF magnetic pulsations with any period comparable to the modulation period of QP emissions. So, a possible generation mechanism of such QP event could be the periodic wave generation in the relaxation oscillations of the cyclotron instability of the Earth radiation belts in the magnetospheric plasma maser** (Bespalov and Trakhtengerts, 1986, Trakhtengerts and Rycroft, 2008). **This model was also applied to explain some satellite observations of QP emissions (Pasmanik et al., 2004).** The excitation of these oscillations is possible only during low geomagnetic activity as it was observed during the studied events.

The revealed 7-10 kHz QP emissions could not be generated at L-shell corresponding to KAN location because the equatorial electron gyrofrequency at L~ 5.5 is ~ 5 kHz, and this value controls the upper frequency of the generation of whistler mode waves at given L shell. Moreover, the ducted propagation of the whistler mode wave in the magnetosphere is possible only at frequencies less than one half of this value (Carpenter, 1968). So, we suppose that the studied QP emissions propagated in unducted mode like it was discussed in the papers (**Němec** et al., 2013; Titova et al., 2015; Hayosh et al., 2016). We assume that the high-frequency QP emissions are generated at much lower L shells than KAN, probably even inside of the plasmasphere.

3 Summary

Applying the digital filtering of strong sferics to the ground-based VLF data at L~5.5 we reveal previously unknown quasi-periodic VLF emissions at unusual high-frequencies of ~7-11 kHz. These frequencies are much higher than the equatorial gyrofrequency of electrons at L~ 5.5.

Contrary to typical QP emissions, the discovered high-frequency waves, presented in this paper, were observed in the late evening. The emissions were right-hand polarized indicating that the ionospheric exit point of the waves was located approximately overheard. In the first event, the spectral-temporal forms of the emissions looked like a series of giant "bullets" with the very abrupt cessation. There were no any geomagnetic nor absorption events, which could explain the sharp stop of generation of the "bullets" on 25 Dec 2011. Maximum variation in geomagnetic field was only 4 nT and riometer absorption was at the background level. Unfortunately, we could not explain such strange feature of the emissions. In the second event, the repetition period was about 3 min with the absence of the simultaneous geomagnetic pulsations. Thus, the source of such modulation remains unknown.

The high-frequency QP emissions were observed under very quiet geomagnetic activity. Apparently, the studied emissions can be attributed to the auto-oscillations of the cyclotron instability in the magnetospheric plasma maser (Bespalov and Trakhtengerts, 1986; Trakhtengerts and Rycroft, 2008), and we speculate that the studied waves propagated in the unducted mode. The source of studied QP emissions could be located at low L-values into the plasmasphere. However, the adequate mechanism of the generation and propagation of QP emissions at untypical high frequencies is not yet established.

Acknowledgements

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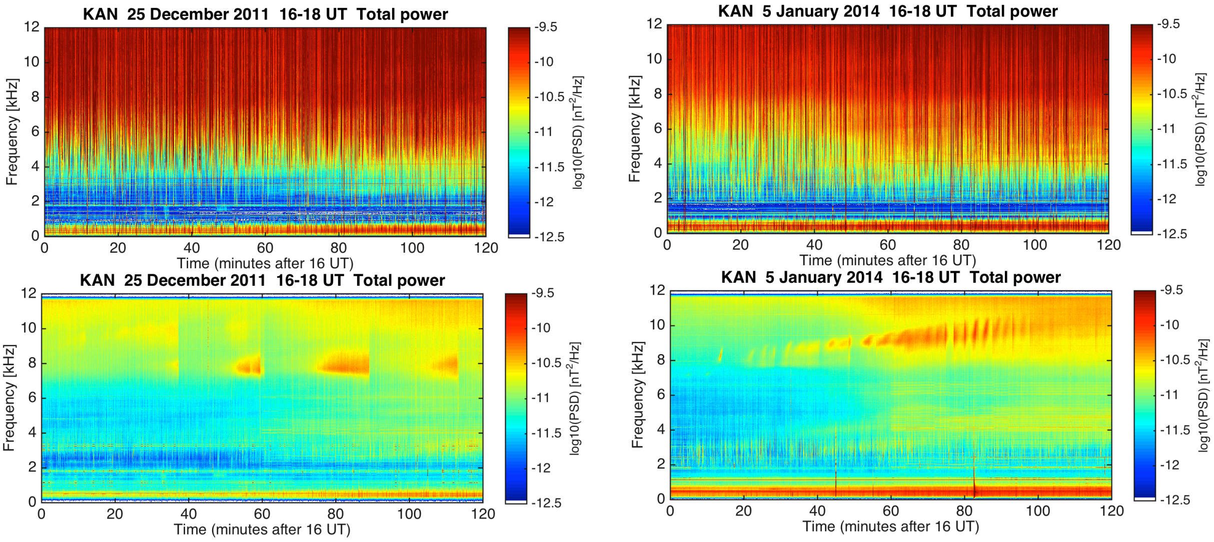

Fig. 1. The 2-hour spectrograms of QP events observed on 25 Dec 2011 and 5 Jan 2014. Upper panels show 0-12 kHz spectrograms without sferics filtering demonstrating that intense sferics hided all natural VLF emissions at frequencies above 4 kHz. The bottom panels show the same intervals after filtering out the sferics, and previously unknown events revealed. Colour bars shown in the right side represent the signal power (in log10(PSD) [nT^2/Hz]).

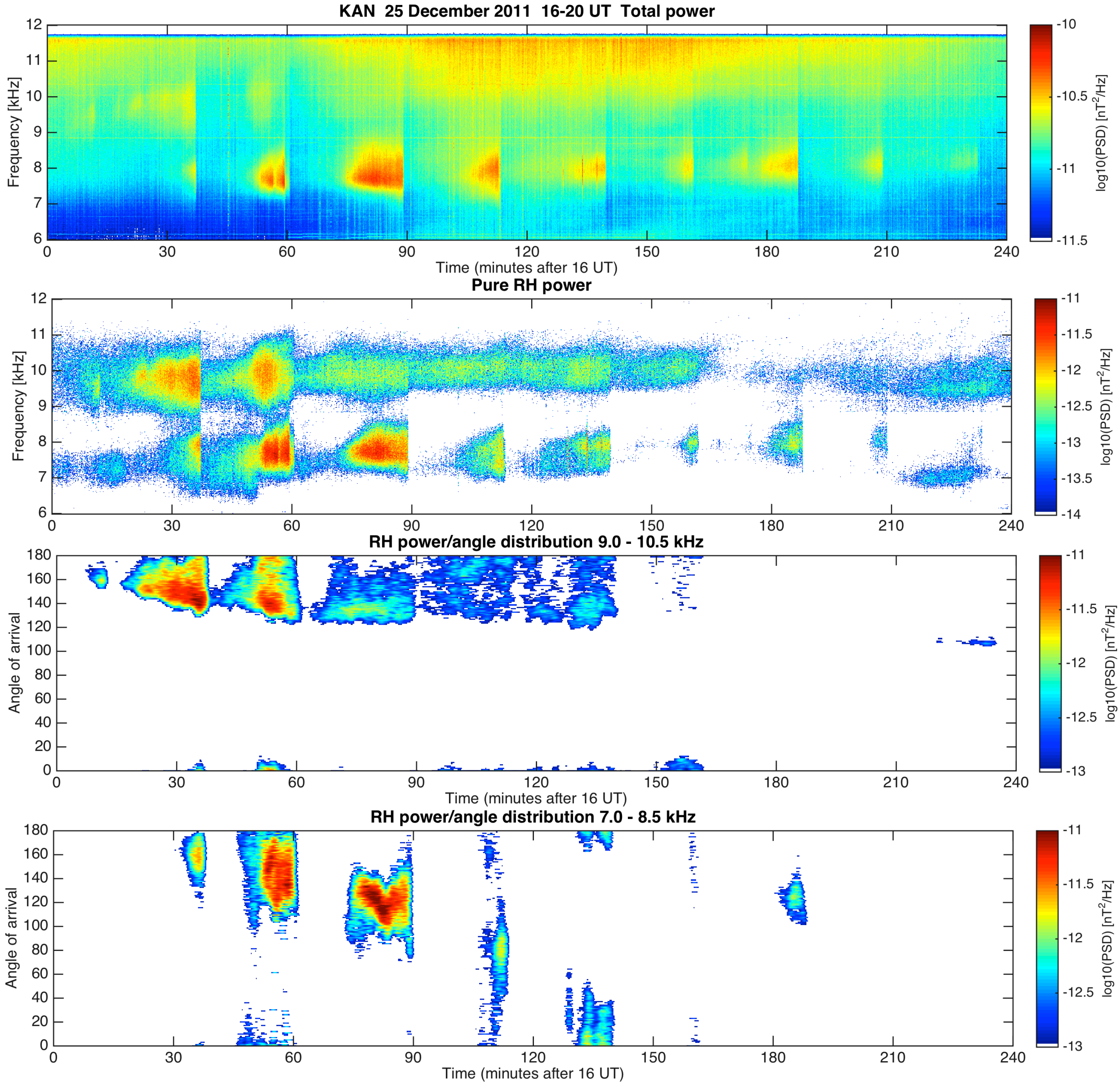

Fig. 2a. The 4-hour VLF spectrograms at 6-12 kHz: total power (uppermost panel), right-handed power (second panel), the wave power/angle distribution based on pure right-hand power at 9.0-10.5 kHz (third panel) and 7.0-8.5 kHz (lowermost panel) on 25 Dec 2011. Colour bars represent the signal power (in log10(PSD) [nT^2/Hz]).

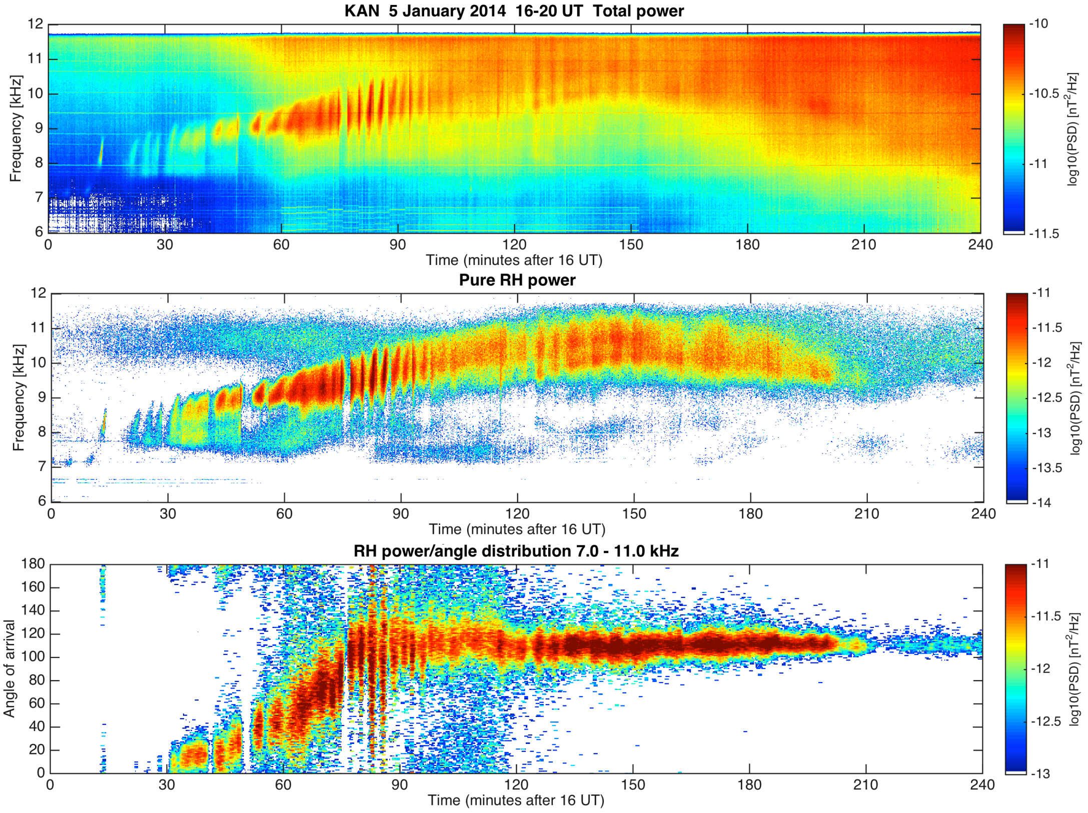

Fig. 2b. The 4-hour VLF spectrograms at 6-12 kHz: total power (uppermost panel), right-handed power (middle panel), the wave power/angle distribution based on pure right-hand power at 7.0-11.0 kHz (lowermost panel) on 5 Jan 2014.

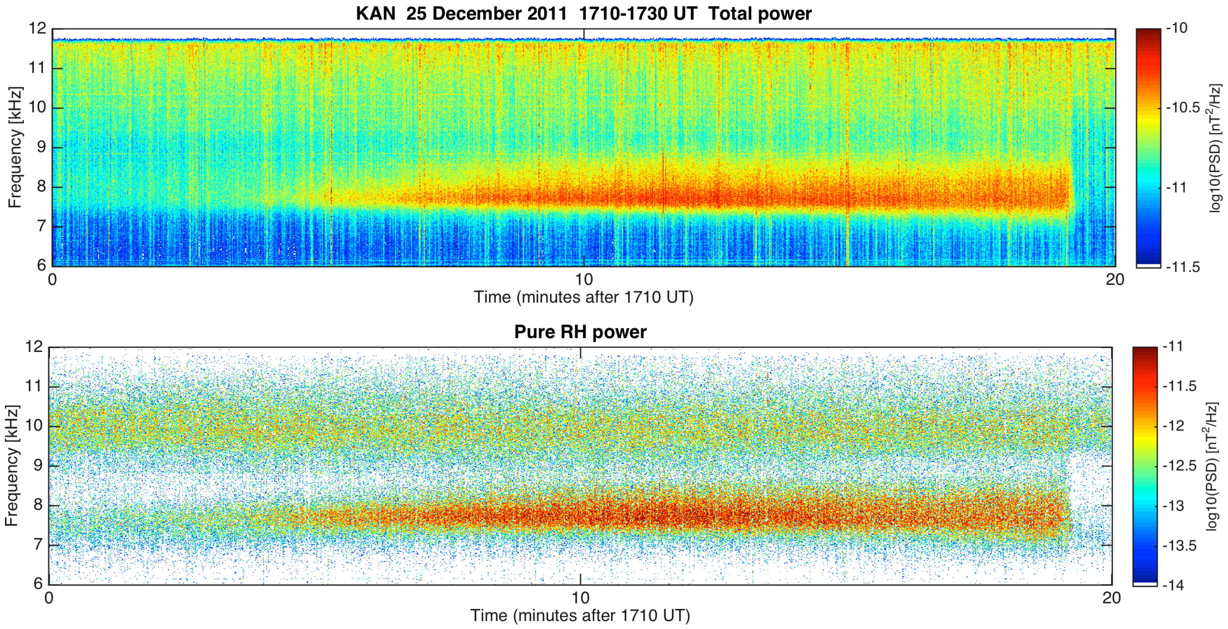

Fig. 3a. The 6-12 kHz VLF spectrograms (total and right-handed powers) of one individual element ("bullet") of QP emissions at 1710-1730 UT on 25 Dec 2011.

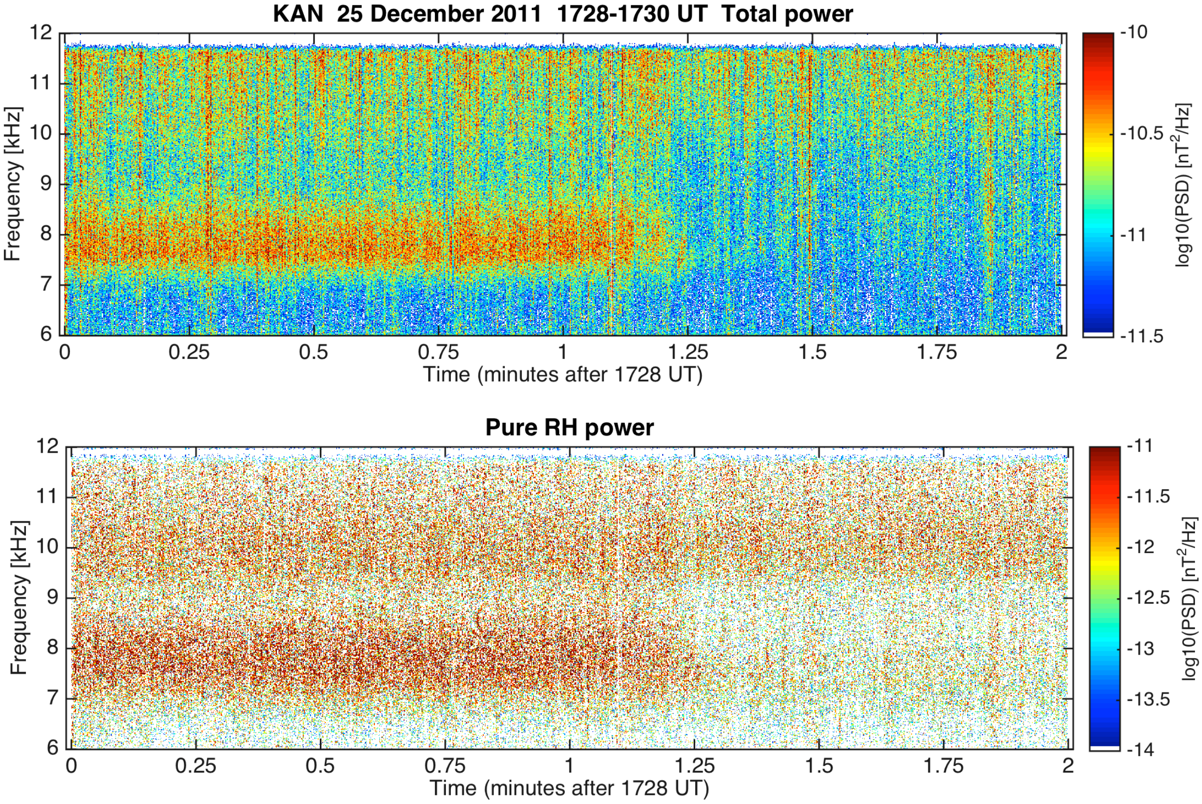

Fig. 3b. Same event as in Fig 3a., but only last 2 minutes (1728-1730 UT).

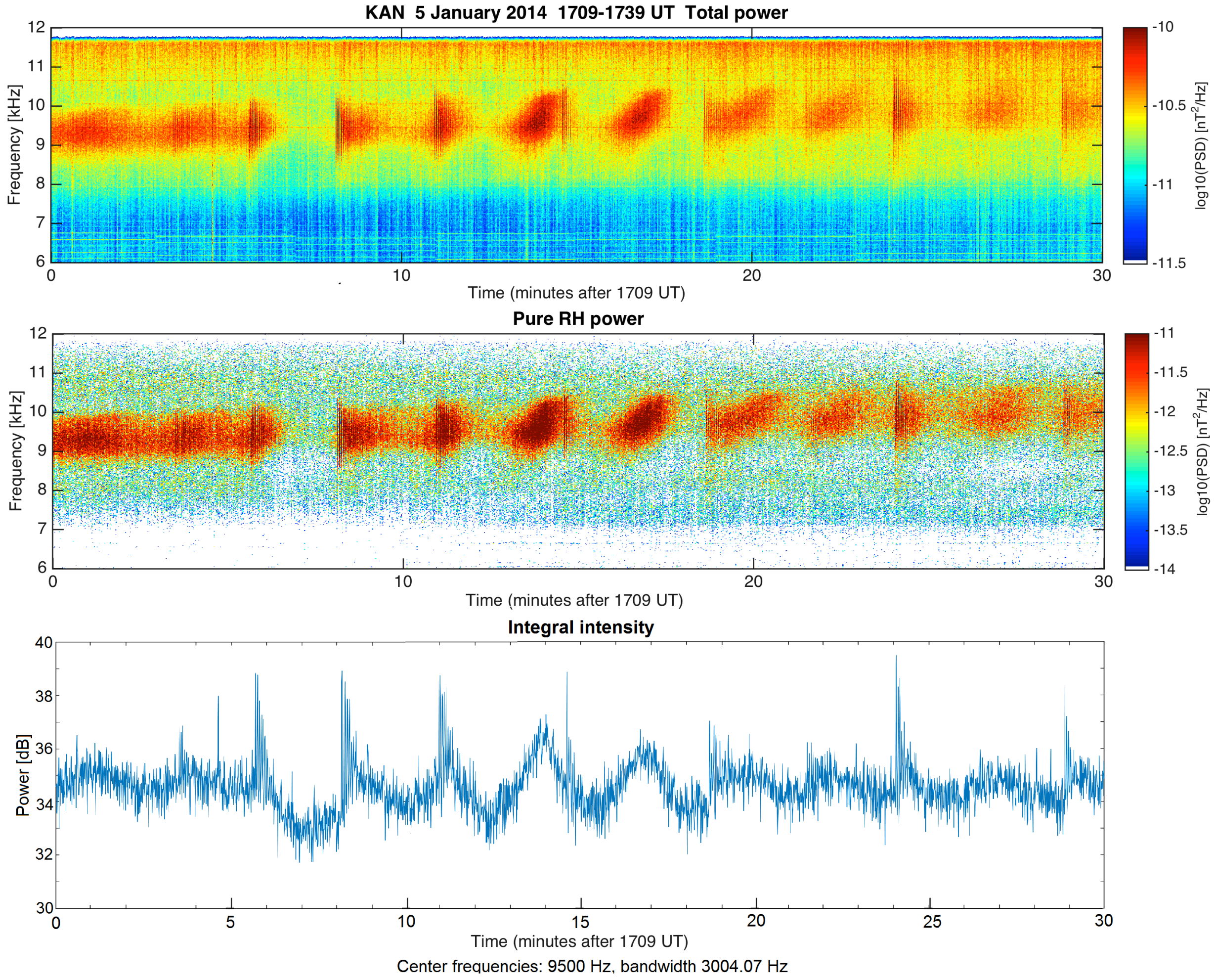

Fig. 4. The 6-12 kHz VLF spectrograms (total and right-handed powers) and the variation of the integrated wave intensity in frequency band of 8-11 kHz on 5 Jan 2014.

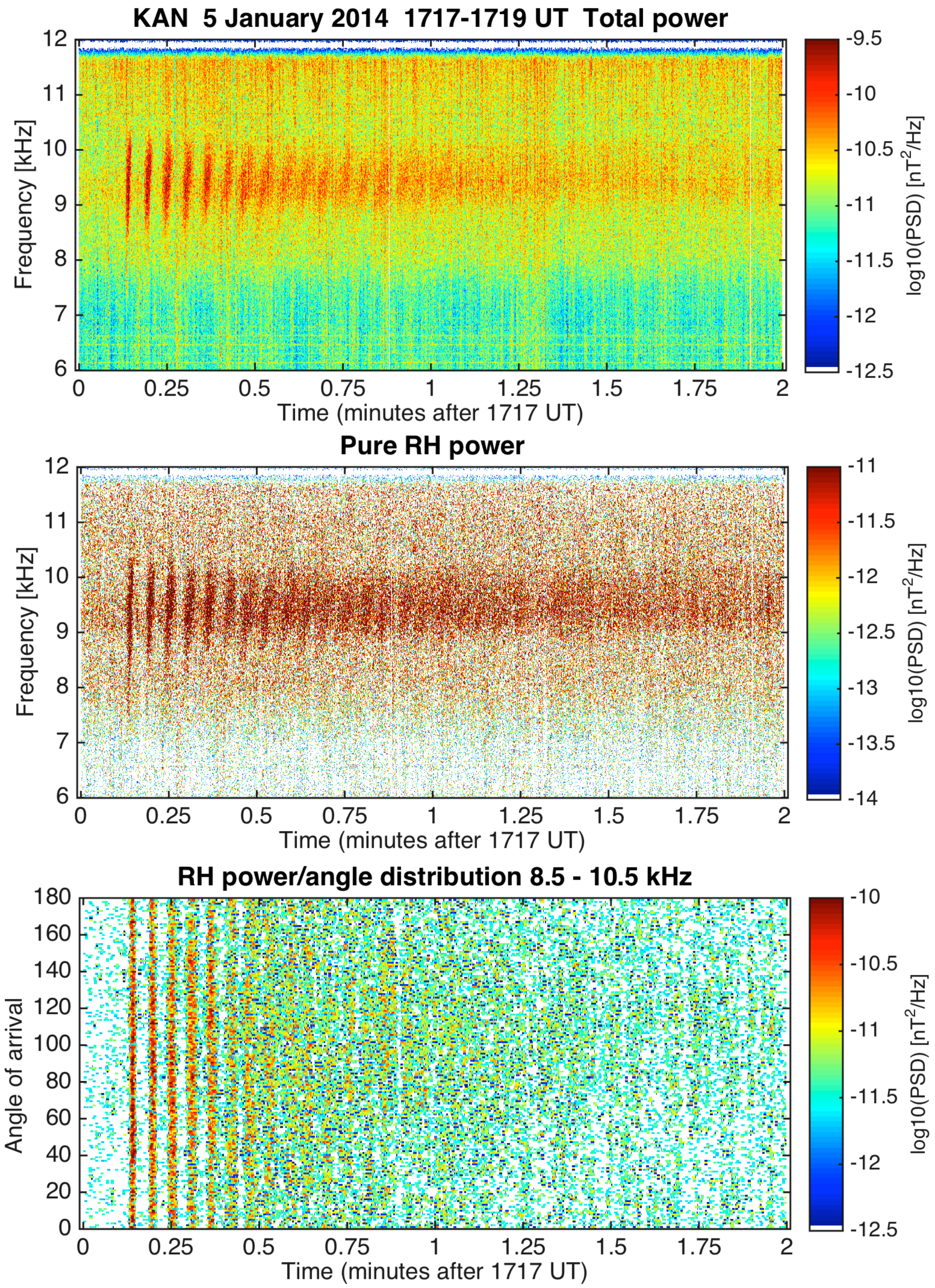

Fig. 5. The 6-12 kHz VLF spectrograms (total and right-handed powers) of two-minutes duration and the wave power/angle distribution based on pure right-hand power at 8.5-10.5 kHz of the short-period QP emissions on 5 Jan 2014.

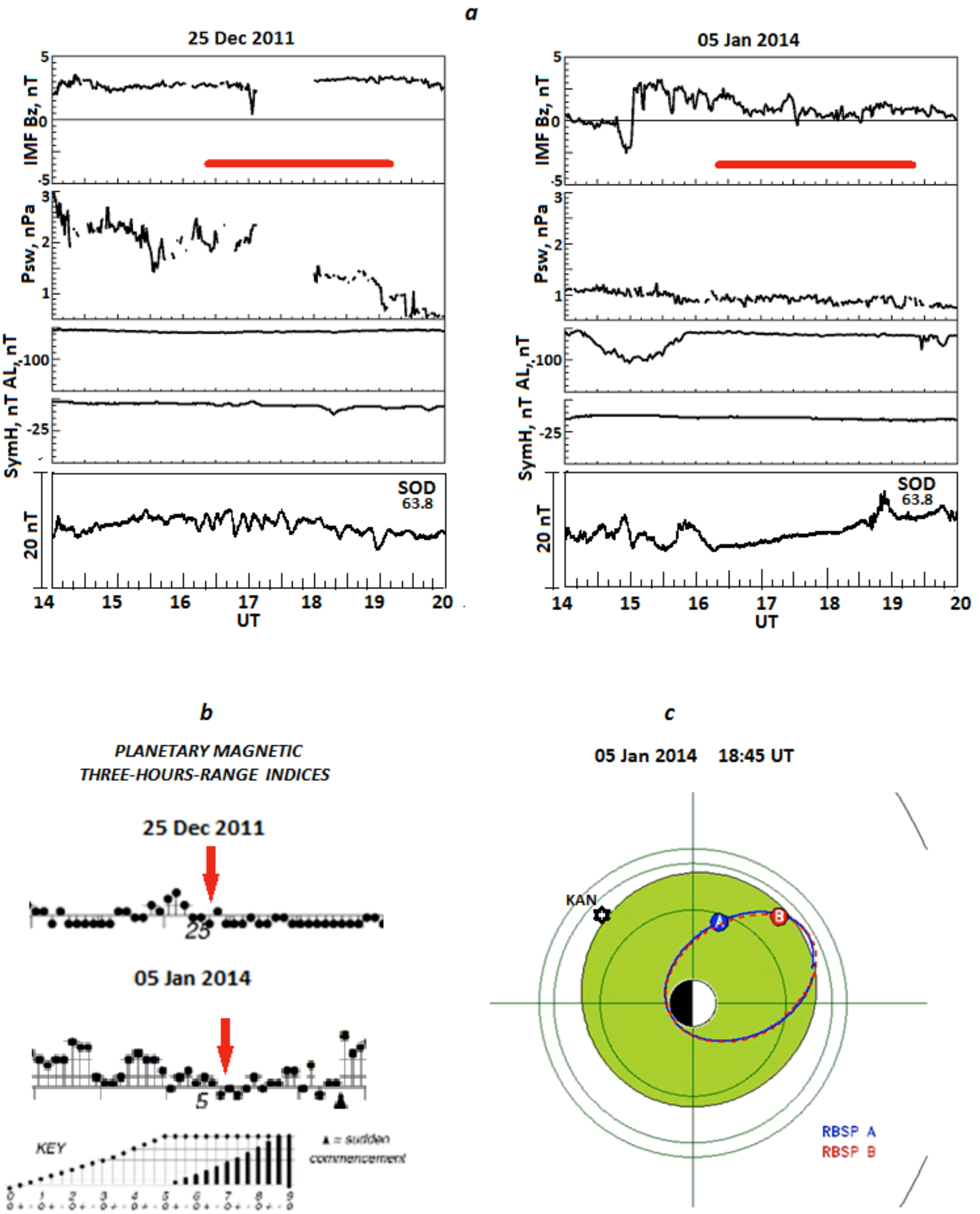

Fig. 6. Geophysical situation during two considered events: (*a*) – OMNI data (IMF Bz and Psw), the *AL* and *SymH* geomagnetic indexes, and the magnetograms from **SOD**; (*b*) – the variation of the planetary Kp –index; (*c*) – the plasmapause location according to measurements on satellites RBSP (A and B) [http://enarc.space.swri.edu/PTP]