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FULL PAPER

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On the use of ELF/MLF emissions triggered by HAARP to simulate PLHR and to study associated MLR events

Michel Parrot^{1,2*} , František Němec^{3*}, Morris B. Cohen^{4*} and Mark Gołkowski^{5*}

Abstract

A spectrogram of Power Line Harmonic Radiation (PLHR) consists of a set of lines with frequency spacing corresponding exactly to 50 or 60 Hz. It is distinct from a spectrogram of Magnetospheric Line Radiation (MLR) where the lines are not equidistant and drift in frequency. PLHR and MLR propagate in the ionosphere and the magnetosphere and are recorded by ground experiments and satellites. If the source of PLHR is evident, the origin of the MLR is still under debate and the purpose of this paper is to understand how MLR lines are formed. The ELF waves triggered by High-frequency Active Auroral Research Program (HAARP) in the ionosphere are used to simulate lines (pulses of different lengths and different frequencies). Several receivers are utilized to survey the propagation of these pulses. The resulting waves are simultaneously recorded by ground-based experiments close to HAARP in Alaska, and by the low-altitude satellite DEMETER either above HAARP or its magnetically conjugate point. Six cases are presented which show that 2-hop echoes (pulses going back and forth in the magnetosphere) are very often observed. The pulses emitted by HAARP return in the Northern hemisphere with a time delay. A detailed spectral analysis shows that sidebands can be triggered and create elements with superposed frequency lines which drift in frequency during the propagation. These elements acting like quasi-periodic emissions are subjected to equatorial amplification and can trigger hooks and falling tones. At the end all these known physical processes lead to the formation of the observed MLR by HAARP pulses. It is shown that there is a tendency for the MLR frequencies of occurrence to be around 2 kHz although the exciting waves have been emitted at lower and higher frequencies.

Keywords: Ionospheric heating, Power Line Harmonic Radiation, Magnetospheric Line Radiation, HAARP, DEMETER

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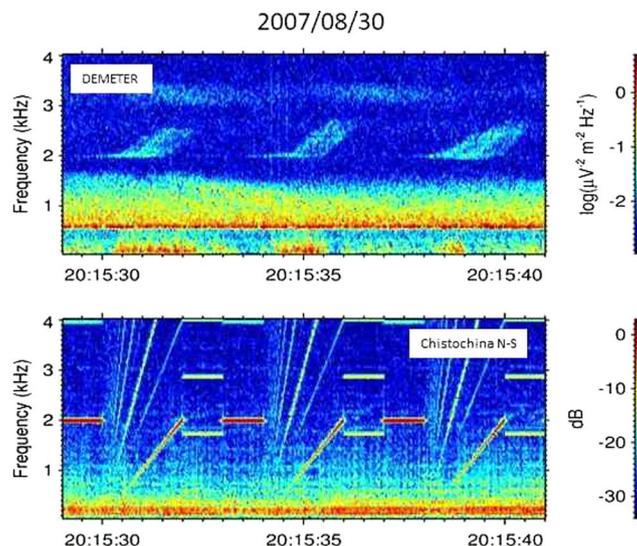
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Graphical Abstract

The HF carrier frequency emitted by HAARP is modulated to trigger in the bottom of the ionosphere (~ 80 km) pulses at ELF/VLF frequencies which are simultaneously recorded by the low altitude satellite DEMETER (660 km) and the ground station Chistochina.



Introduction

Power Line Harmonic Radiation (PLHR) are electromagnetic man-made waves at harmonic frequencies of 50 or 60 Hz. They have been observed on ground over many decades (Helliwell et al. 1975; Park and Helliwell 1978, 1981, 1983; Matthews and Yearby 1978; Yearby et al. 1983; Manninen 2005). Observations by satellite have been also done on a case basis (Bell et al. 1982; Koons et al. 1978; Tomizawa and Yoshino 1985; Rodger et al. 1995). In frequency–time spectrograms they look like a set of parallel lines with distances of 50/100 or 60/120 Hz. Using DEMETER data, Němec et al. (2006) have developed a procedure for an automatic detection of PLHR events between 500 Hz and 4 kHz. They have detected events with frequency spacing of spectral lines of 50/100 Hz and with frequency spacing of 60/120 Hz which very well correspond to the frequencies of electric power systems in the possible regions of generation below or in their magnetically conjugate areas. Other properties of PLHR occurrence observed by DEMETER can be found in Němec et al. (2008). Němec et al. (2010) did not find that the intensity of the natural electromagnetic waves measured over industrialized areas and magnetically conjugate regions is larger than elsewhere. PLHR observed at 50/60 Hz and low harmonics have been studied by Dudkin et al. (2015) and Němec et al. (2015), who were looking also for a weekend effect (Park and Miller 1979). Such an effect is possibly present above the European region, but it is very weak. They have further shown that the PLHR effects are less often detected in the summer, because on one hand the ionospheric absorption

increases, and on the other hand the PLHR are masked by lightning generated emissions. However, on a case basis Parrot et al. (2014) have related triggered emissions due to PLHR propagating in the magnetosphere and suffering wave–particle interactions in the equatorial region. There are rising tones or hooks with a starting frequency associated to a parent line at a frequency multiple of 50 or 60 Hz. These triggered emissions occurred more frequently at high latitudes ($3 < L < 6$).

However, different sets of lines not separated by 50/100 or by 60/120 Hz have been observed either with satellites (Rodger et al. 1995) or with ground-based experiments (Rodger et al. 1999, 2000a, b; Yearby 1982). These lines usually drift in frequency and they are called Magnetospheric Line Radiation (MLR). Their origin is not completely known and in particular their possible relation with PLHR has been extensively discussed for a long time. For example, Kostrov et al. (2017) claimed that the nature of the generation of MLR and PLHR is the same. They said that the only difference is that MLR passed through unstable plasma, while PLHR propagated in calm conditions.

Onboard DEMETER, MLR have been observed by Němec et al. (2007) who have compared their relative occurrence with PLHR. For example, PLHR events are more intense during the night than during the day, whereas no dependence of MLR peak intensities on magnetic local time was found. Other properties of MLR events seen by DEMETER are reported by Němec et al. (2009a). In particular, they have shown a remarkable daytime event where PLHR are observed in

the North hemisphere and MLR in the same frequency range are observed in the conjugate region in the South hemisphere half an hour later. Different features of MLR have been studied by Němec et al. (2012a, b). It includes a MLR event observed simultaneously on board DEMETER and CLUSTER 1 and 2 satellites during a perigee passage at a radial distance of about $4 R_E$. Although the two CLUSTER satellites are separated by ~ 0.7 L-shells, the wave pattern is identical on both. They have shown that the waves cross the geomagnetic equator over a significant range of L-shells (3.9–4.6). Considering that the DEMETER satellite was separated by about 1.8 h in MLT from the Cluster spacecraft this indicates a significant azimuthal extent of the source.

Comparisons between ground-based and DEMETER observations have been done. Large-scale MLR have been observed simultaneously on ground at Kannuslehto (67.74° N, 26.27° E, $L = 5.41$) in Finland and on board DEMETER which was flying just above (Parrot et al. 2007). This 2-h-long event was recorded over a large area in the Northern hemisphere and in the conjugate region. They claimed that these MLR could be due to PLHR propagating in the ionosphere and the magnetosphere, and undergoing a nonlinear interaction with particles when they cross the equator. A similar MLR event simultaneously observed on ground in the Northern hemisphere and in the conjugate region by DEMETER has been reported by Němec et al. (2009b). They have shown that the individual lines of the event are formed (at least for this particular case) by elements going back and forth between the Northern and Southern hemispheres.

MLR events and associated triggered emissions observed by DEMETER have been reported by Parrot and Němec (2009). They said that, on one hand some MLR events are due to PLHR which may suffer a nonlinear gyro-resonant interaction at the magnetic equator, but on the other hand quasi-periodic (QP) emissions are very often associated with the MLR, and then the origin of these waves is natural. In that case, the appearance of lines in the spectrograms is caused by the periodicity and the frequency band limits of the QP individual elements.

Using the whole DEMETER data set, Bezděková et al. (2015) have studied the occurrence of MLR events with solar wind parameters and geomagnetic indices. They have found that MLR events occur more often after periods of enhanced geomagnetic activity, and more often during the northern winter and spring than during the northern summer. Later on, Bezděková et al. (2019) searched for a possible relation between these electromagnetic waves having either a frequency modulation (MLR) or a time modulation (QP emissions). All in all, 1152 MLR events and 2172 QP emissions have been analyzed, but they have not found a relation between the

properties of QP and MLR events observed at the same times.

The purpose of this work is to use the waves triggered by High-frequency Active Auroral Research Program (HAARP) as a simulation of PLHR emissions with the aim to see their possible effects, to understand how MLR are formed, and to check the role of the QP emissions. In this paper, we first briefly present the experiments (HAARP and DEMETER) together with previous results from HAARP. Next, we describe five cases simultaneously recorded by ground-based receivers in Alaska and by the satellite DEMETER. Then, a wave propagation analysis of the triggered signals is done for a sixth case. Finally, discussions are displayed and conclusions are given.

The experiments

HAARP

HAARP uses powerful radio waves at HF (3–30 MHz) to heat the ionospheric plasma. It is located near Gakona in Alaska. Its geographic coordinates are 62.4° N in latitude and 145.2° W in longitude, its magnetic conjugate point is located at 56.67° S, 174.48° E (Gołkowski 2009), and its McIlwain parameter L is equal to 4.9. The ON-OFF modulation of the HF wave at ELF/VLF rates, allows HF energy to be converted into ELF/VLF radiation (see Sheerin and Cohen 2015 and references therein). Various configurations of the HF heating have been experimented to determine the best wave generation (Cohen 2009, Cohen et al. 2011, 2012). To study the induced ionospheric effects many ground-based experiments are associated to HAARP, and in particular, ELF/VLF data are registered with broadband high-sensitivity receivers which consist of two orthogonal air-core loop antennae, measuring the two horizontal components of the magnetic field between 300 Hz and 40 kHz. The N–S antenna is sensitive to TEM mode waves arriving from the north or the south, whereas E–W is for the east or west direction. Details of this experiment can be found in Cohen et al. (2010a). In our paper data from two receivers located at Chistochina (62.61° N, 144.62° W, 37 km from HAARP), and Juneau (58.59° N, 134.90° W, 704 km SE of HAARP) are used. Their data are available from a web server named WALDO which is presented in Cohen (2020).

Previous results from HAARP heating

In this section, previous results in relation with our study are briefly presented. Inan et al. (2004) have observed at Chistochina up to 10-hop multiple reflected ELF/VLF signals going back and forth between the Northern hemisphere and the Southern hemisphere. They noticed amplification and triggering of emissions at each

crossing of the equatorial interaction region. Cohen et al. (2008) have found that the orientation of the effective HAARP electric dipole is generally oriented in the magnetic east–west direction. They used data from two ELF/VLF receivers located at 700 km from HAARP (including Chistochina). To detect 1-hop signal, very important experiments have been implemented on the open sea at the conjugate point of HAARP (a ship-borne receiver and two autonomous buoy platforms) and results have been presented by Gołkowski et al. (2008). The observed signals are accompanied by triggered emissions and exhibit temporal amplification of 15–25 dB/s and spectral broadening to 50 Hz. The 1-hop propagation time was 4.2 s, very similar to the 4 s propagation time from previous observations of HAARP echoes made by Inan et al. (2004). They also noticed that only certain components of the frequency–time formats transmitted are amplified. Another work reported by Golkowski et al. (2010) shows that echoes were produced only for frequencies between 2.0 and 2.8 kHz although single-frequency signals between 1 and 3 kHz and frequency sweeps from 0.5 to 3.5 kHz were injected. They claimed that it is due to resonance with anisotropic electrons with energy of 5 to 10 keV. A comparison by Hosseini et al. (2017) indicates that there is a similar evolution between chorus risers and 2-hop echoes of a single-frequency signal which presents triggered emissions. The occurrence of sidebands around the carrier frequency of pulses is discussed in a review by Gołkowski et al. (2019) who additionally examine the frequencies of the observed echoes which are missing (see also “Discussions” later on). One can see additional results in review papers by Cohen and Gołkowski (2013), and recently by Guo et al. (2021). Overall, ELF/VLF magnetospheric wave injection experiments with HAARP show that the facility injects ELF/VLF waves into the magnetosphere primarily from directly above the heated portion of the ionosphere (Golkowski et al. 2011).

DEMETER

DEMETER was a low-altitude satellite (660 km) in operation between 2004 and 2010 onto a polar and circular orbit. It measured electromagnetic waves and plasma parameters all around the Earth (Parrot 2006). The orbit of DEMETER was nearly sun-synchronous. The upgoing half-orbits correspond to nighttime (2230 LT) and the downgoing half-orbits correspond to daytime (1030 LT). The instruments are operated in two scientific modes (i) a survey mode where spectra of one electric and one magnetic component are computed onboard up to 20 kHz with a frequency resolution of 19.5 Hz and a time resolution of 2 s; (ii) a burst mode where waveforms of one electric field component and one magnetic component are recorded up to 20 kHz. In this burst mode the

waveforms of the six components of the electromagnetic field up to 1.25 kHz are also recorded to allow a wave propagation analysis.

Due to technical reasons, data were only recorded at invariant latitudes less than 65° except for special campaigns over HAARP or its magnetically conjugate region. Several studies have been already done during these special campaigns for ELF/VLF generation experiments conducted by the HF heating facilities at HAARP (see, e.g., Platino et al. 2006; Piddyachiy et al. 2008; Piddyachiy 2012).

The cases

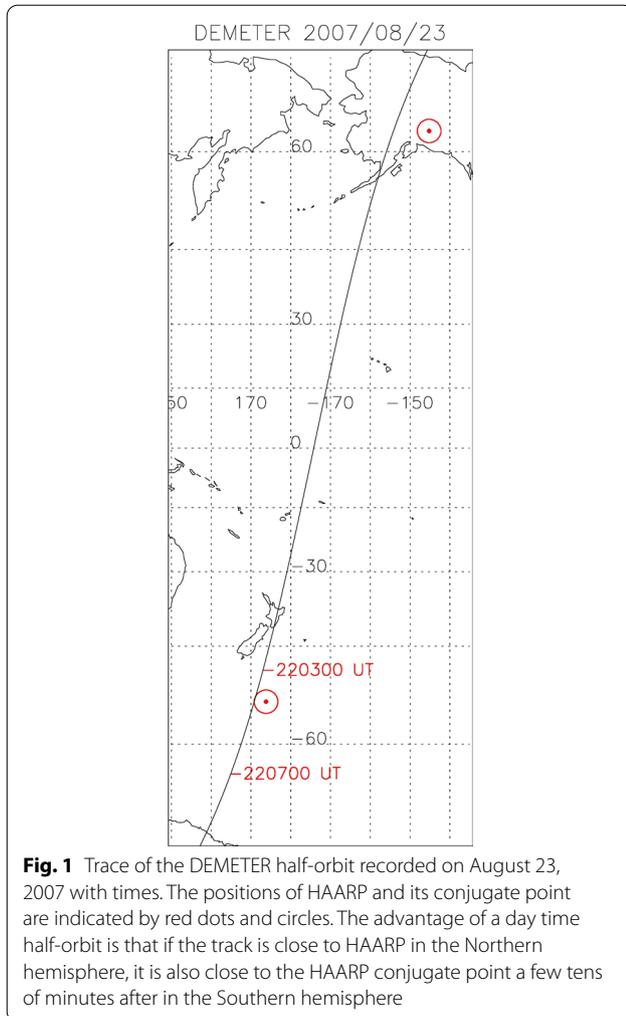
The cases are defined by the DEMETER half-orbit number and the date. For each case, we have several sets of data: (i) the parent emissions (pulses, ramps) which are scheduled, and then, which must be triggered by HAARP; (ii) the emissions really recorded by ground-based receivers close to HAARP (Chistochina and Juneau), and (iii) the emissions registered onboard DEMETER in the ionosphere close to HAARP or its magnetically conjugate point. One must say that the pulses of different lengths are emitted by HAARP in a frequency band where PLHR have been observed, but harmonics are sometimes also generated (see for example Gołkowski 2009).

For the ground station spectrograms, we used an FFT length of 16,384 points (the sampling frequency is 100 kHz) and an FFT length of 16,384/2.5 points for the DEMETER spectrograms (to achieve the same frequency resolution with the sampling frequency of only 40 kHz). We always used 50% overlapping and averaged over two subsequent spectra. To have spectrograms with a better time resolution, we use an FFT length of 3250 for ground stations and of 3250/2.5 = 1300 for DEMETER. By that we achieve the same frequency and time resolution (~31 Hz and 0.0325 s) for both the ground and satellite observations.

When it was necessary the Chistochina and Juneau data have been processed through a filter that removes the power line harmonic noise from the local power lines using a method described in Cohen et al. (2010b).

Case 1: 16781_0: 2007/08/23 daytime

This case 1 concerns data recorded when DEMETER is in the Southern hemisphere close to the HAARP conjugate point during day time. The corresponding half-orbit is shown in Fig. 1 and the recorded spectrogram by DEMETER between 0 and 4 kHz is shown in Fig. 2 (see also Fig. 2.8 of Gołkowski 2009, and Fig. 7.1 and 7.2 of Piddyachiy 2012). In this case, two 1-s pulses are simultaneously emitted at 2011 Hz and 1973 Hz followed by a 2-s ramp between 0 and 2 kHz and one 1-s pulse at 571 Hz (see Fig. 3). One can see pulses at the



specific frequency 1973 Hz with triggered emissions. As DEMETER is in the Southern hemisphere, they are 1-hop pulses. The complete time interval of pulse observation by DEMETER is between 22:03:00 and 22:07:00 UT (see Fig. 1). It is well around the HAARP conjugate point and this gives an evaluation of the zone illuminated by HAARP in the Southern hemisphere, i.e., between -50.01° S and -64.15° S in geographic latitude. One can see that the set of pulses at 1713 Hz (the third harmonic of 571 Hz) does not trigger emissions. Figure 4 displays more detailed spectrograms of data simultaneously recorded by DEMETER (top panel) and at Juneau (bottom panel). Juneau does not see the original pulses because they are perhaps too weak, but after an amplification at the equator Juneau sees 2-hop triggered emissions. It is possible to identify the same triggered elements on DEMETER and at Juneau and then to calculate the time for travel between hemispheres. There are 4.0 s between

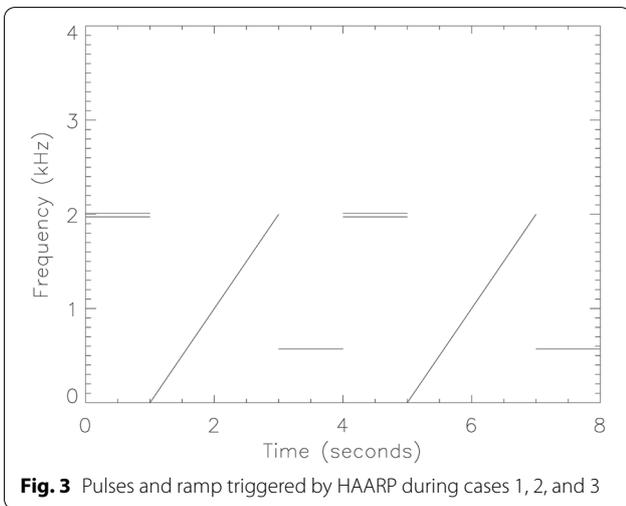
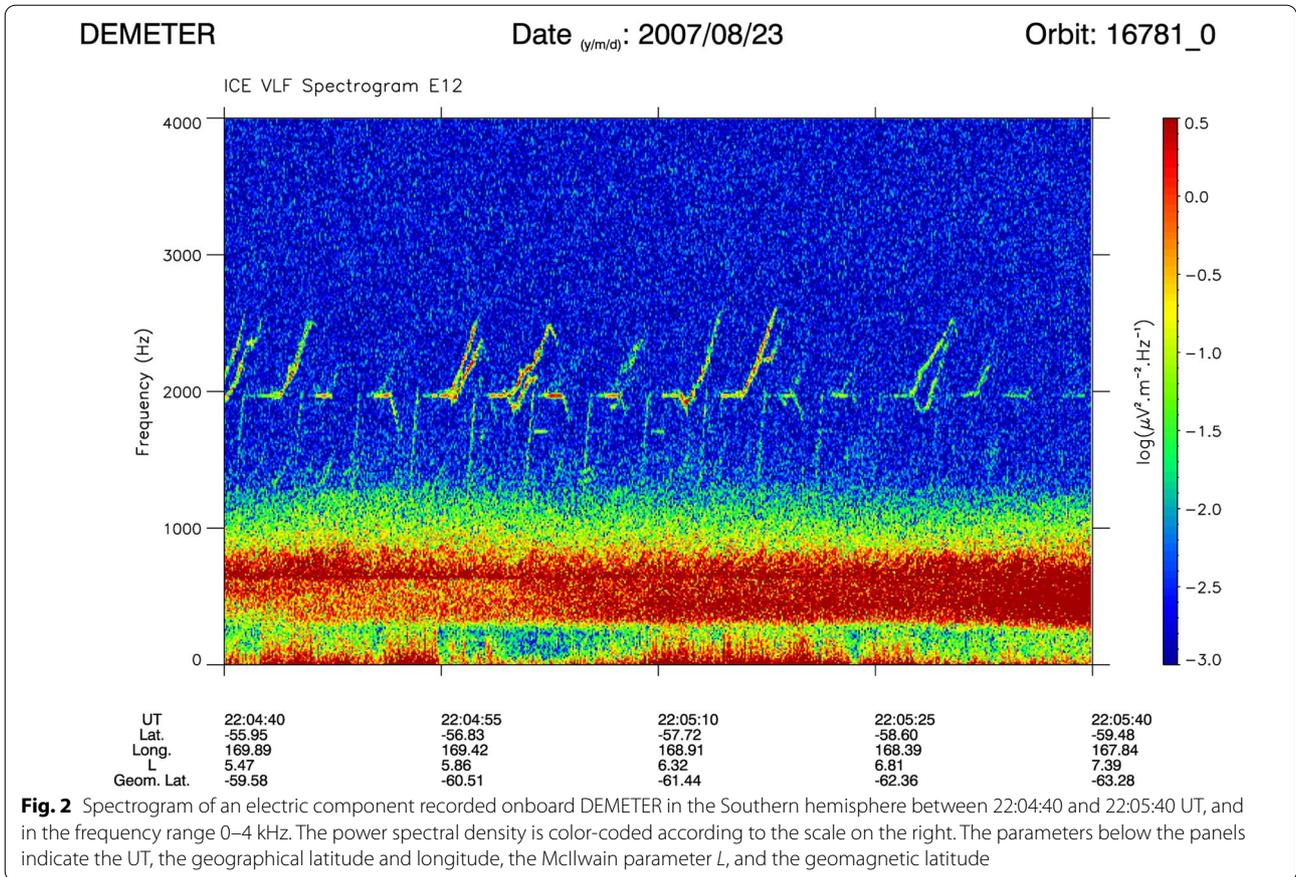
DEMETER and Juneau for the 3 triggered emissions indicated in Fig. 4. This is the expected time for a 1-hop travel (Gołkowski et al. 2008). No data were recorded at Chistochina.

This is a nice example with triggered emissions from pulses and also it is noticed that the pulses can trigger emissions only at a specific frequency (around 2 kHz). It is also interesting to note that the triggered elements seen by Juneau in the Northern hemisphere are very similar to the triggered elements observed by DEMETER in the Southern hemisphere. As the triggered elements seen by Juneau cross two times the equatorial interaction region, it means that the nonlinear triggering mechanism is less effective for emissions which are less coherent than the original pulses.

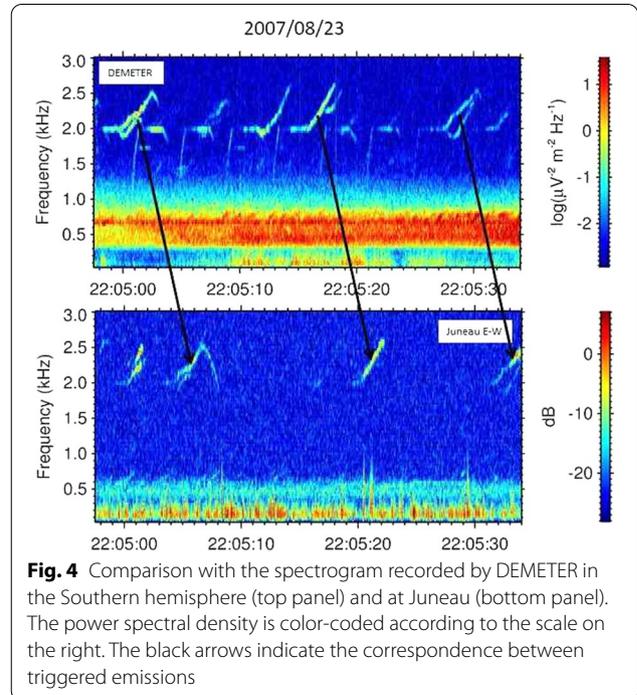
Case 2: 16883_0: 2007/08/30 daytime

The frequency pattern is similar to the previous one in case 1 (see Fig. 3). The spectrogram in Fig. 5 shows that pulses and triggered emissions are observed by DEMETER in the Northern hemisphere (see also Fig. 7.9 and 7.10 of Piddychiy 2012). In fact the pulses with triggered emissions are observed since 20:12:20 UT until 20:17:10 UT. A zoom of the emission observed by DEMETER and Chistochina in the Northern hemisphere is shown in Fig. 6. DEMETER in the North sees 2-hop triggered emissions. There are 9 s between the pulses on DEMETER plot and Chistochina plot. Pulses are elongated with triggered emissions. DEMETER does not see the direct emission as it is in the Chistochina plot because the orbit is not close to HAARP. Nothing is observed in the Juneau plot, although it is just below the DEMETER orbit.

In the Southern hemisphere pulses with triggered emissions are observed at different frequencies starting at 20:43:30 UT until the end of the DEMETER record at 20:46:30 UT (see the orbit in Fig. 7) but it is during survey mode, i.e., without good time and frequency resolution. The frequency pattern generated by HAARP at this time is three 3-s pulses at 1890 Hz, 2370 Hz, and 1710 Hz, followed by one 6-s ramp. Despite the bad resolution, it is possible to see on the DEMETER plot (not shown) that the pulses at 1710 Hz and 1890 Hz are accompanied by triggered emissions and that such triggered emissions are absent with the pulses at 2370 Hz. Except the frequency pattern nothing special is observed in the Chistochina plot (not shown). As it was when DEMETER was in the Northern hemisphere, nothing is also observed on the Juneau plot. This case is an important example of ELF/VLF nonlinear triggering by HAARP that is observed above the ionosphere, but not on the ground. The fact that the emissions are observed in both conjugate hemispheres suggests that the path is ducted at least near the equator. A possible explanation might be that the



emissions observed by DEMETER propagate in ducts that do not extend below 1000 km altitude, so that they are reflected from the bottom of the ionosphere and do not reach the ground.



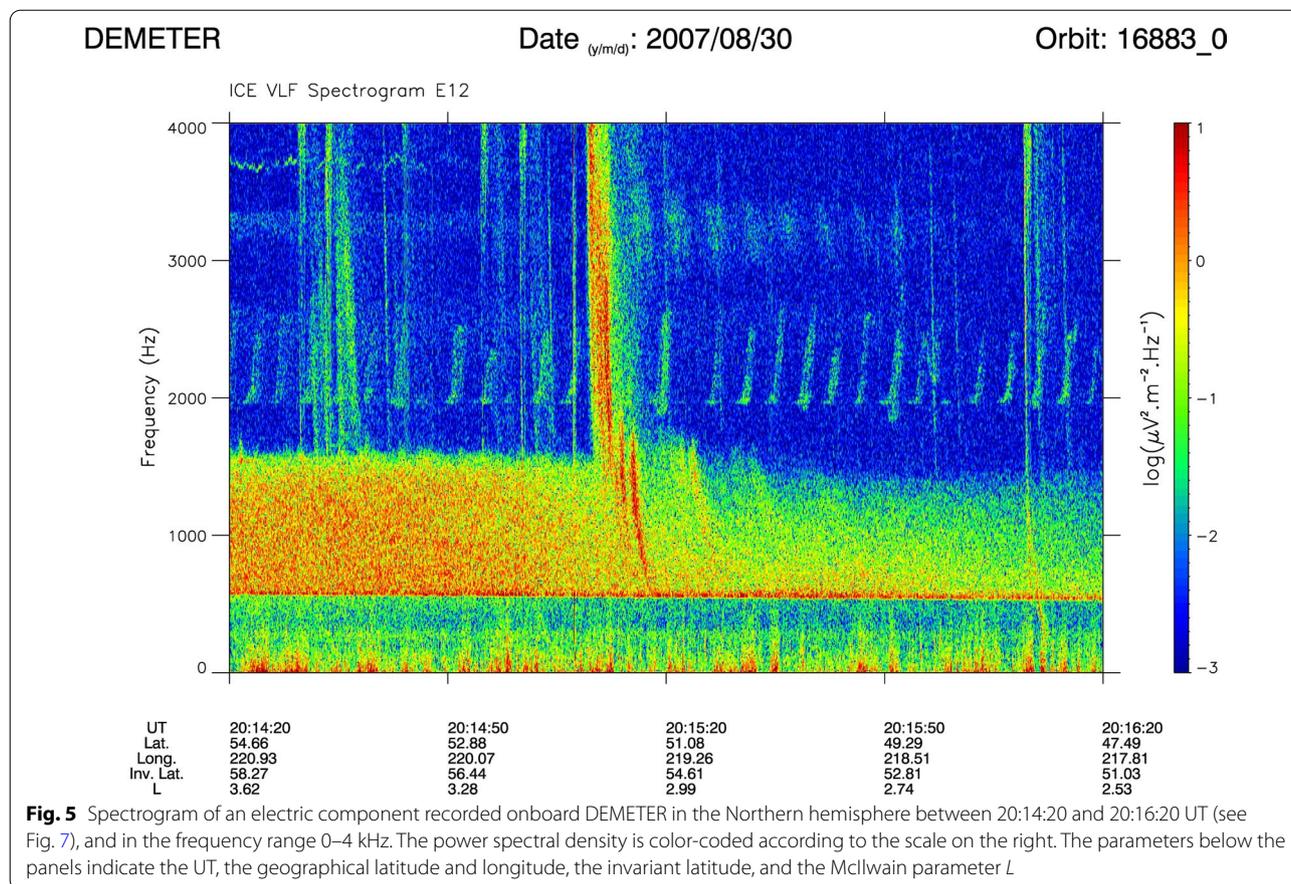


Fig. 5 Spectrogram of an electric component recorded onboard DEMETER in the Northern hemisphere between 20:14:20 and 20:16:20 UT (see Fig. 7), and in the frequency range 0–4 kHz. The power spectral density is color-coded according to the scale on the right. The parameters below the panels indicate the UT, the geographical latitude and longitude, the invariant latitude, and the McIlwain parameter *L*

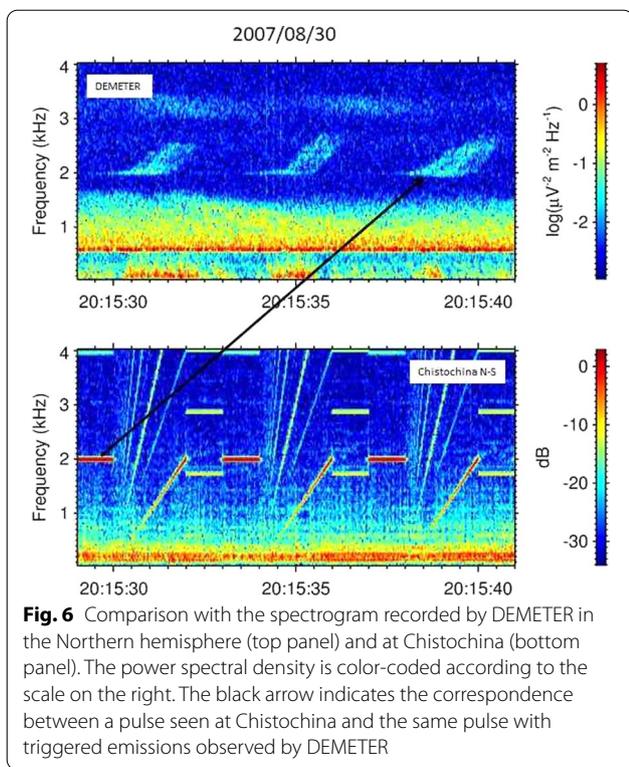
Case 3: 20534_1 2008/05/05 nighttime

In Fig. 8, the full time interval where magnetospheric emissions are observed by DEMETER in the Southern hemisphere is noticed. It is a nighttime orbit. Figure 9 shows the comparison between the spectrogram recorded by DEMETER in the Southern hemisphere, and the spectrograms recorded by the ground receivers at Chistochina and Juneau. One can see in the top panel (DEMETER spectrogram) a typical MLR event between 1.4 and 1.7 kHz. The frequency pattern emitted by HAARP is similar to the one emitted during the case 1 (see Fig. 3). On the Chistochina plot it is possible to see the frequency pattern, whereas on the Juneau plot weak magnetospheric emissions can be observed. A zoom is done in Fig. 10 where an interesting point is discovered. The magnetospheric emissions (falling tones) observed by DEMETER are completely not correlated with the pulses observed at Chistochina at 1713 Hz, although these magnetospheric emissions are around the 1713 Hz transmitted frequency. There is a time interval of 5.5 s between each element observed by DEMETER, whereas there is a time interval of 4 s between each pulse observed by Chistochina. A hypothesis is that one

pulse starts to trigger an emission and after this emission becomes a QP emission due to multi-hop. It must be noted that every 44 s an enhancement could be possible due to the match between one pulse and one QP element. The same QP emissions are also weakly observed on the Juneau plot with a time delay wrt DEMETER of ~3 s which correspond to a 1-hop travel. It is interesting to notice that only the third harmonic of the pulses at 571 Hz is able to initiate the emission although we see at Chistochina that the pulses at 1713 Hz have an intensity less than the 2011 Hz pulses.

Case 4: 20585_0 2008/05/08 day time

The DEMETER orbit of this case 4 is shown in Fig. 11. Data are recorded in the Northern hemisphere and in the Southern hemisphere during day time. The spectrogram recorded in the Northern hemisphere is shown in Fig. 12 together with the spectrogram simultaneously recorded at Chistochina. One can see on the DEMETER plot chorus elements at a frequency above 3 kHz around 21:24:30 UT followed by triggered emissions after 21:25:00 UT which corresponds to the closest approach to HAARP.



On the contrary, nothing is observed on the Chistochina plot except the pulses.

The frequency pattern of the pulses triggered by HAARP during this time is a repetition of the four 1-s pulses at 500 Hz, 3235 Hz, 2755 Hz, and 2575 Hz (see Fig. 13). The pulses at the three last frequencies can be clearly observed in the bottom panel of Fig. 14 together with a harmonic of the 500 Hz pulse at 4 kHz.

In the top panel of Fig. 14 one can see on the DEMETER plot several bursts of triggered emissions. They are around frequencies of the emitted pulses by HAARP at 2575 and 2755 Hz, but their period is slightly different. One can notice that the set of pulses at 3235 Hz has no influence although they have intensity similar to the pulses at 2575 and 2755 Hz.

When DEMETER is in the southern hemisphere, the corresponding spectrogram is displayed in Fig. 15 together with the spectrogram simultaneously recorded at Chistochina in the North. An important MLR event is observed on the DEMETER plot between 2 and 3 kHz, whereas only a weak emission is observed at Chistochina around the same frequencies.

The frequency pattern of the pulses triggered by HAARP during this time has been changed and now we have three 3-s pulses at 2555 Hz, 3035 Hz and 2375 Hz, followed by a ramp during 6 s (see Fig. 16). This can be seen in the bottom panel of Fig. 17 which is a zoom of

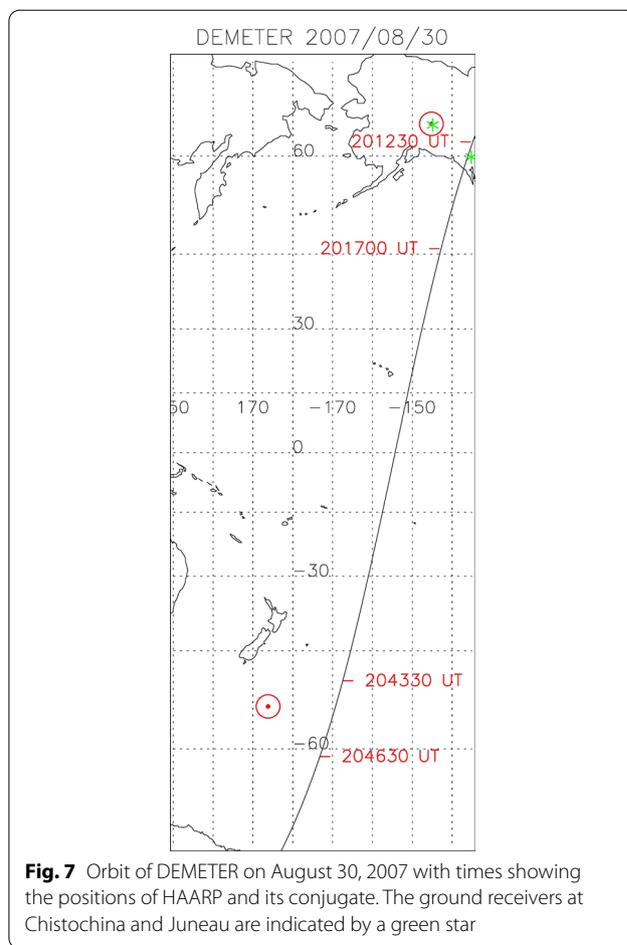
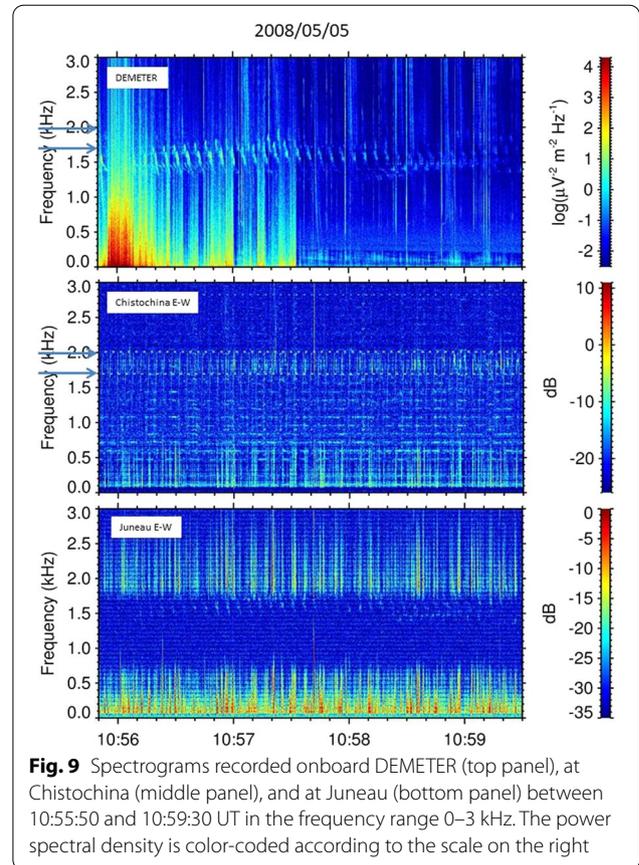
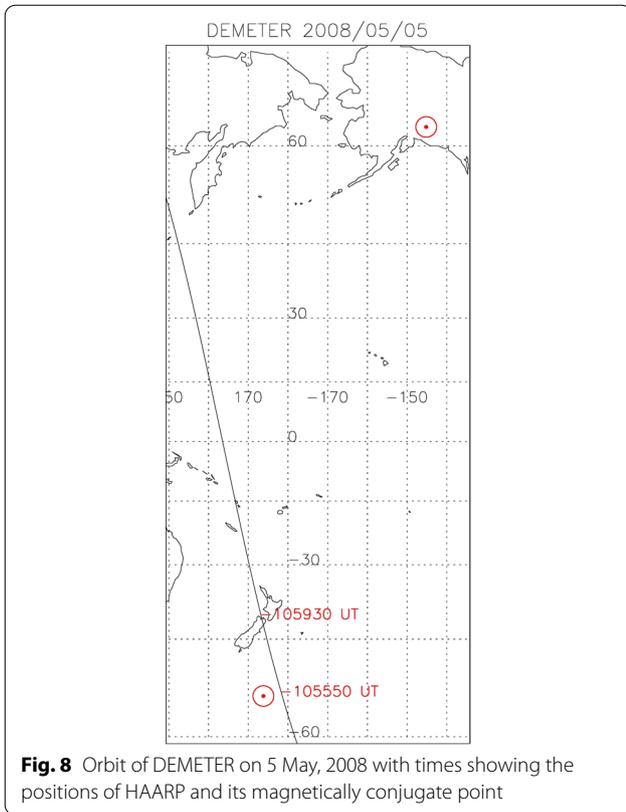


Fig. 15. We see in Fig. 17 the same bursts of triggered emissions on DEMETER and at Chistochina with a delay of 4 s because Chistochina sees the 2-hop emissions, whereas DEMETER sees the 1-hop emissions. But here also it is difficult to have a match between a pulse and a burst of triggered emissions although all these bursts of triggered emissions seen by DEMETER and Chistochina seem to be due to the two series of pulses at 2375 Hz and 2555 Hz. Once again nothing is seen for the set of pulses at 3035 Hz. As it has been observed before it seems that there is no more amplification in the second equatorial crossing for the triggered emissions which return in the Northern hemisphere and are seen by Chistochina.

Case 5: 20614_0: 2008/05/10 day time

This is an example of MLR recorded onboard DEMETER along the half-orbit shown in Fig. 18 during day time. Spectrograms recorded by DEMETER in survey mode in the Northern hemisphere as well as in the Southern hemisphere are shown in Fig. 19. These spectrograms exhibit in the North and in the South clear MLR between 1.3 and 2.3 kHz. In the North one can



even see two distinct MLR events around 1.5 kHz and around 2 kHz. It can be seen in Fig. 18 that these MLR are recorded close to HAARP and its conjugate point.

Ground data have been recorded at Juneau during the same day. The corresponding spectrogram is shown in Fig. 20 between 20:46:00 and 21:30:00 UT in the frequency range 0–4 kHz. One can also see a similar MLR event around 2 kHz. The time intervals delimited by double arrows indicate when DEMETER has simultaneously registered data in burst mode. A comparison between the spectrograms recorded by DEMETER in the Northern hemisphere, at Chistochina, and at Juneau is done in Fig. 21. Juneau sees exactly the same elements as DEMETER except the chorus event around 1 kHz but we see these chorus elements very weak on the Chistochina plot. This Chistochina plot also displays the set of pulses and ramps generated by HAARP. Every minute the frequency pattern is the following: five times there are three 2 s pulses at 1110 Hz, 1525 Hz, and 2125 Hz, followed by three 10 s ramps (see Fig. 22). Then the interval between 2 pulses at the same frequency is 4 s which means that every 6 s there is a pulse at this frequency followed by a gap during 34 s. Six seconds is close to a 2-hop travel and this is important for our observation. Between each set of

5 pulses there is a set of 3 ramps, the last one being a snake ramp.

A zoom of Fig. 21 is shown in Fig. 23. It appears now that there is a combination of two different sets of QP emissions which are inserted. One can see on the Chistochina plot 3 set of pulses at 1525 Hz, 2125 Hz, and 2220 Hz (it is in fact harmonics of the pulses at 1110 Hz). But on the DEMETER plot, we do not see all these pulses. Only the pulses at 2125 Hz seem to play a role in the triggered emissions as it corresponds to the higher frequency of the QP elements noted by red arrows. We only see 3 pulses at 2125 Hz and after they disappear. In fact we only see the pulses at a specific location when DEMETER is at the closest approach to HAARP (see Fig. 18). Even if it is weak, the fourth pulse of this series at 2125 Hz overlaps in fact with one element of the QP emissions noted by arrows. We see after an increase of these QP elements which are going back and forth in the magnetosphere. These QP elements are of dispersive type (negative slope) with lines at the lower frequencies. A rough estimation of the time interval between these QP emissions (noted by red arrows) is 6.3 s which corresponds to a 2-hop travel. The point is that it is close to the time interval between 2 pulses which is 6 s. This means that, at the beginning, the

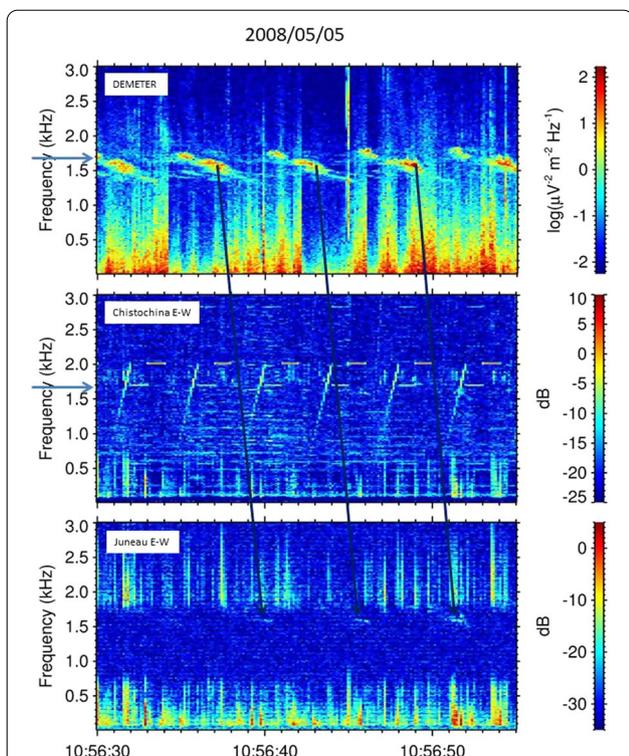


Fig. 10 Zoom of Fig. 9. Comparison between the spectrograms recorded by DEMETER in the Southern hemisphere (top panel), recorded at Chistochina (middle panel), and recorded at Juneau (bottom panel). The power spectral density is color-coded according to the scale on the right. The black arrows indicate the correspondence between emissions seen at Juneau and the same emissions observed by DEMETER

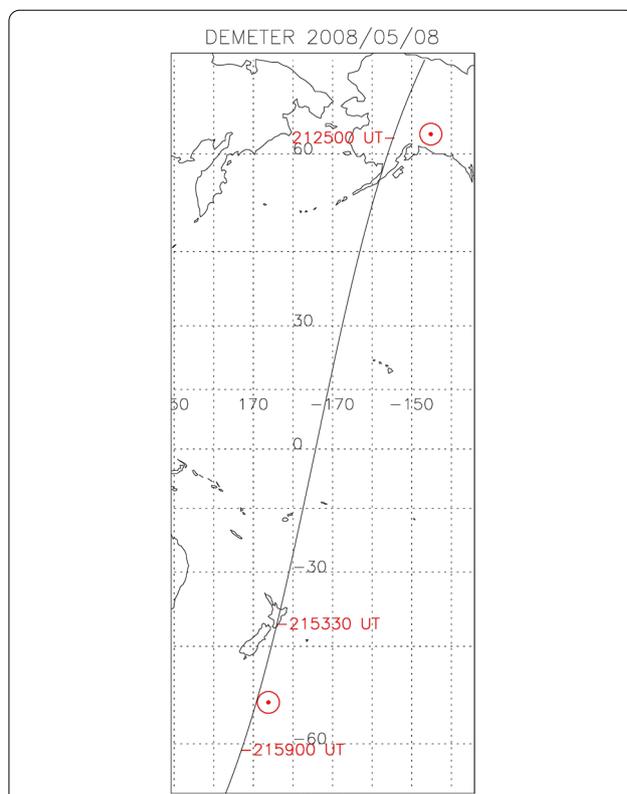


Fig. 11 Orbit of DEMETER on 8 May, 2008 with times showing the positions of HAARP and its magnetically conjugate point

first QP elements could have been enhanced by a previous set of pulses. These QP structures indicated by red arrows are in the form of inverse commas with increasing frequency dispersion as the time is going on. The intense triggering emissions at 20:48:25 UT start to occur when a low frequency part of one element of these QP structures overlaps with one of the elements indicated by the black arrows. These elements are formed by a ramp previously emitted which is amplified at the equator and which bounces between hemispheres with a period of ~11 s. It is very likely that it is due to the snake ramp as Gólkowski et al. (2008) found that a snake ramp can exhibit clear repeatable magnetospheric amplification and inter-hemisphere propagation even though other signals in the same frequency range were transmitted. At the end a second set of QP elements is formed. Juneau sees the same two sets of QP elements as DEMETER at the same time but does not see the parent emissions triggered by HAARP (pulses and ramps) that we have on the Chistochina plot.

Later on, in the zoom of Fig. 24 we see on the DEMETER plot pulses between QP emissions but they do not

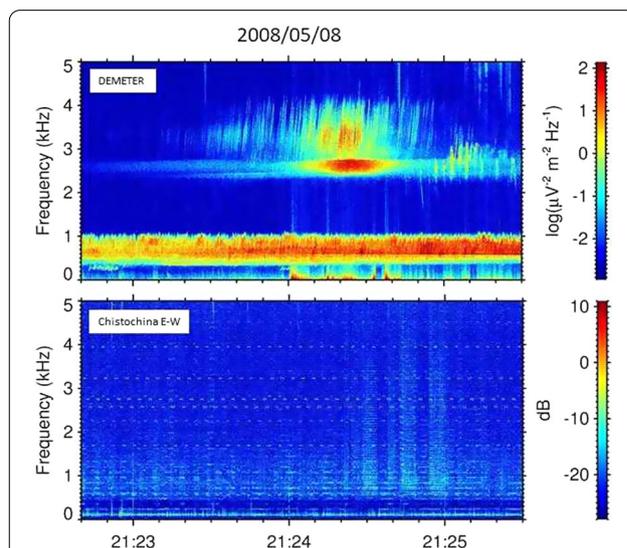
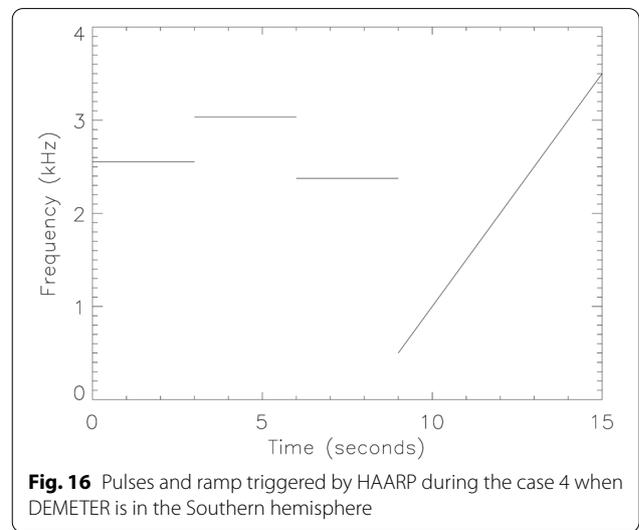
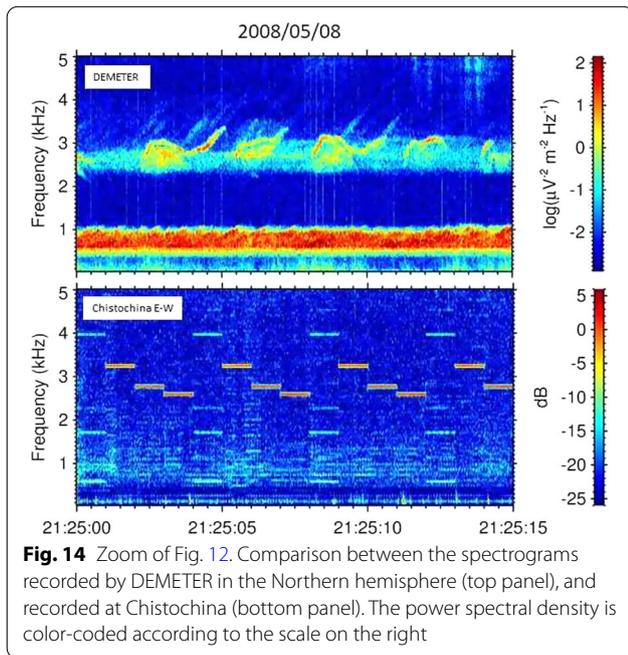
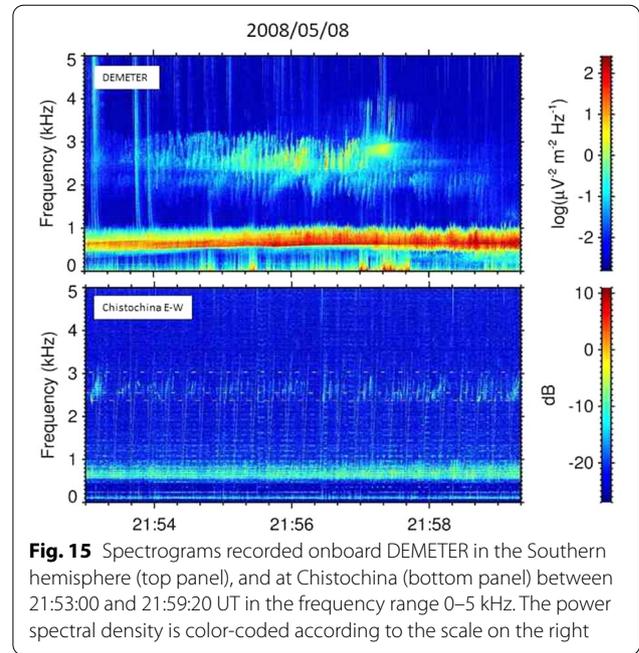
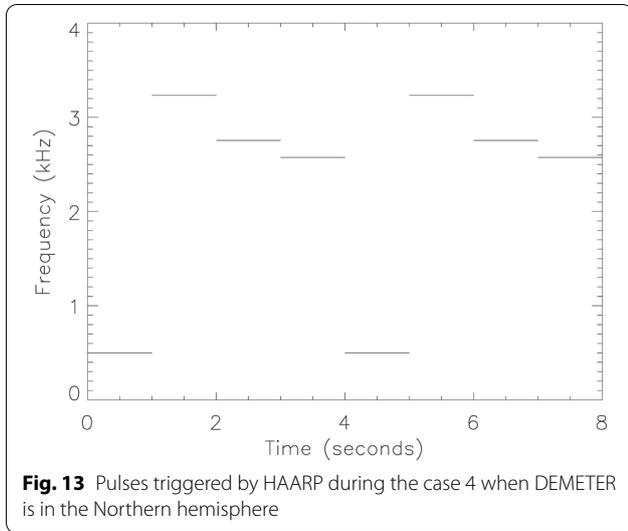


Fig. 12 Spectrograms recorded onboard DEMETER in the Northern hemisphere (top panel), and at Chistochina (bottom panel) between 21:22:40 and 21:25:30 UT in the frequency range 0–5 kHz. The power spectral density is color-coded according to the scale on the right



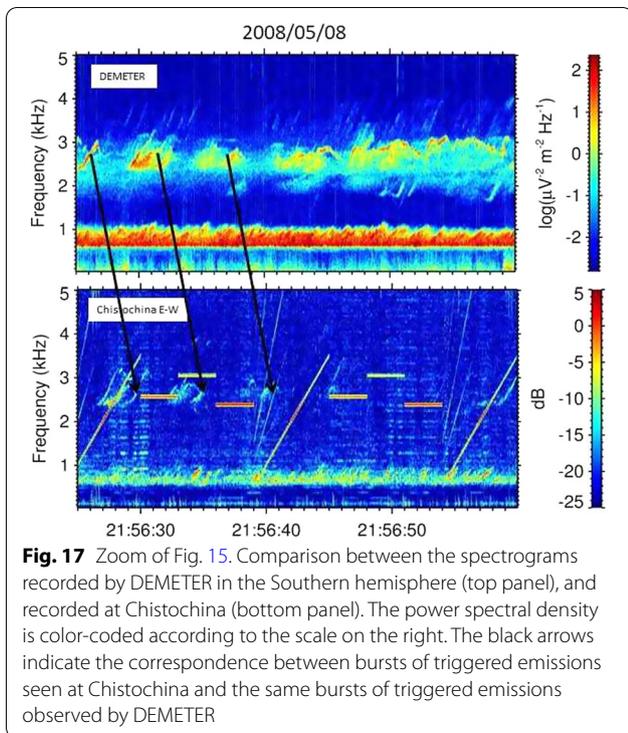
exactly correspond to the pulses seen by Chistochina at the same time because DEMETER is too far to observe the direct pulses. It could be 2-hop emissions generated by previous pulses because we see them even when there is a gap during which ramps are sent, or it is another QP emission which could be reinforced when they match the pulses as we said before.

In the plots in Figs. 23 and 24, there are additional sidebands (and/or spectral broadening) as far as multi-hops are going on. But only upper side bands seem to be triggered. For these QP elements there is a frequency

dispersion when the number of hops is increasing as it is for the whistlers.

It must be noted that the second MLR event between 1.5 and 1.8 kHz seen in Figs. 19 and 21 on the DEMETER plot is also observed on the Juneau plot but with a lower intensity. This distinct MLR event at lower frequency can be caused by the pulses at 1525 Hz as it was discussed above.

Figure 25 displays a spectrogram from DEMETER which is now in the South hemisphere (top panel), a spectrogram from Chistochina (middle panel), and a spectrogram from Juneau (bottom panel). A similar MLR

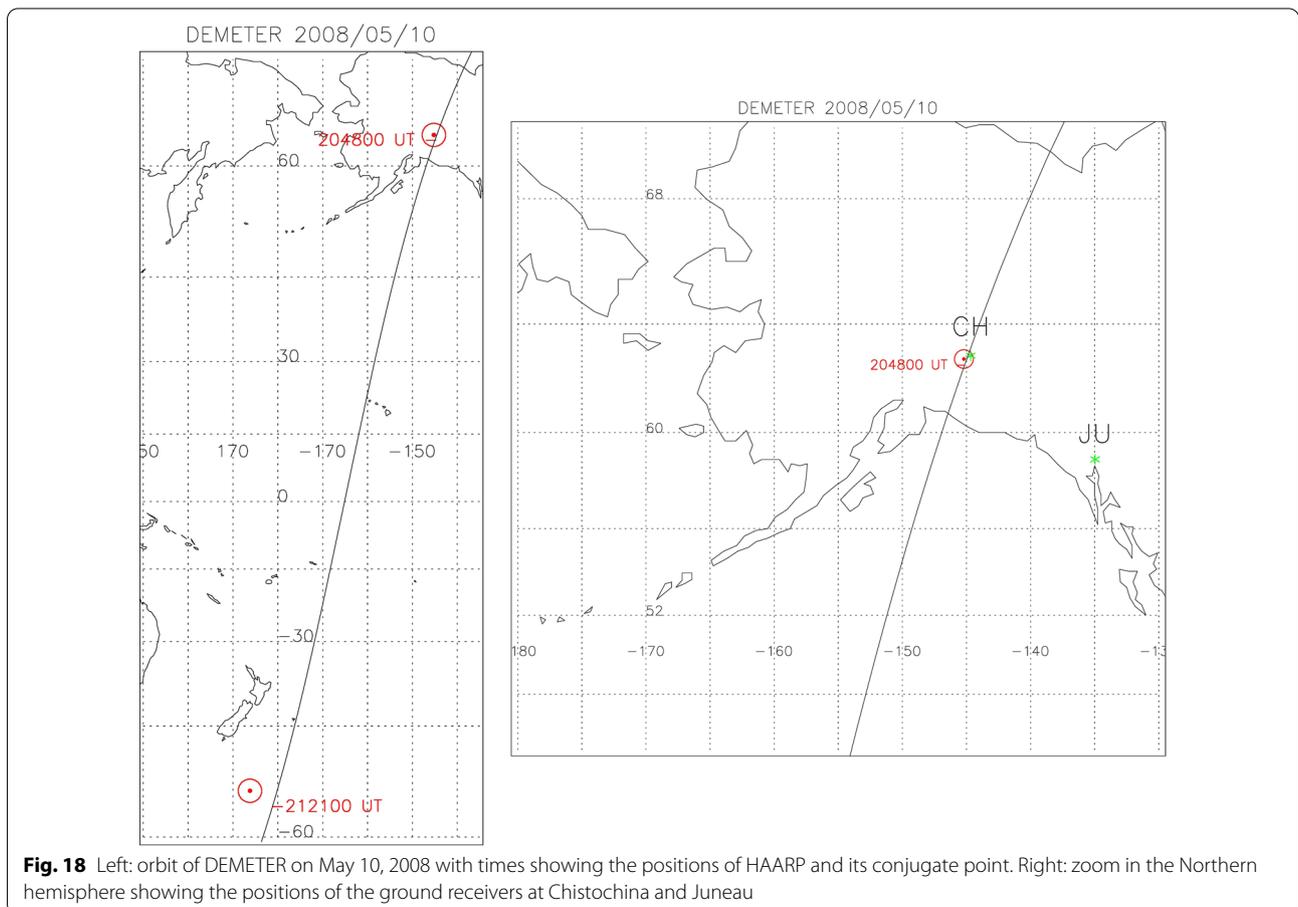


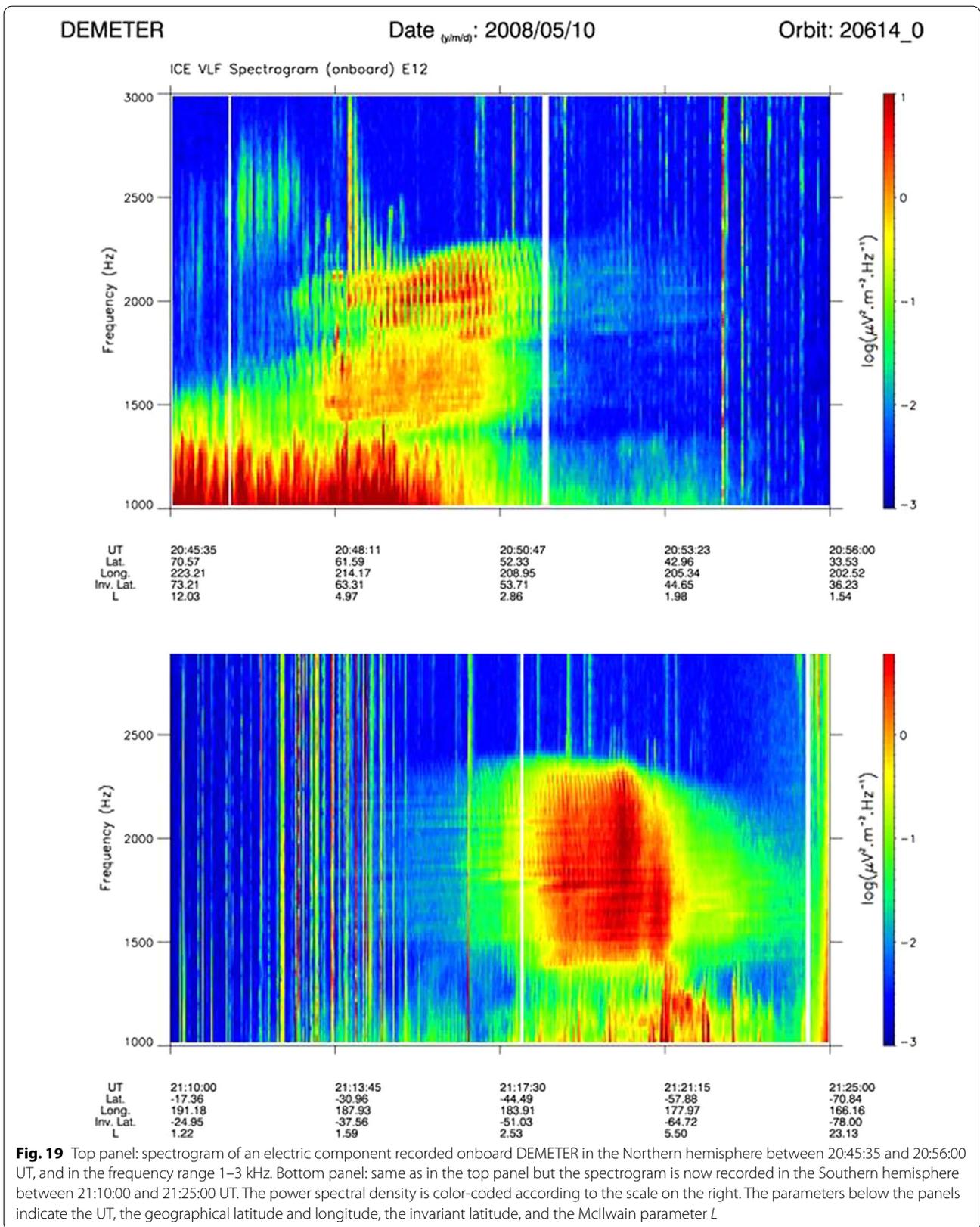
event is clearly observed in the DEMETER and Juneau plots. As it is seen in Fig. 20, it is the same event formed by QP elements which continues. The event is triggered at the beginning with the help of HAARP pulses and ramps, and it continues without other relation with the pulses observed on the Chistochina plot. This is confirmed by a change of the frequency pattern between 20:58:00 and 21:09:30 UT. It becomes three 3 s pulses at 755 Hz, 935 Hz, and 1415 Hz followed by a 6 s ramp (after 21:10:00 UT it returns to the previous one). No difference appears in the event during this time interval (see Fig. 20).

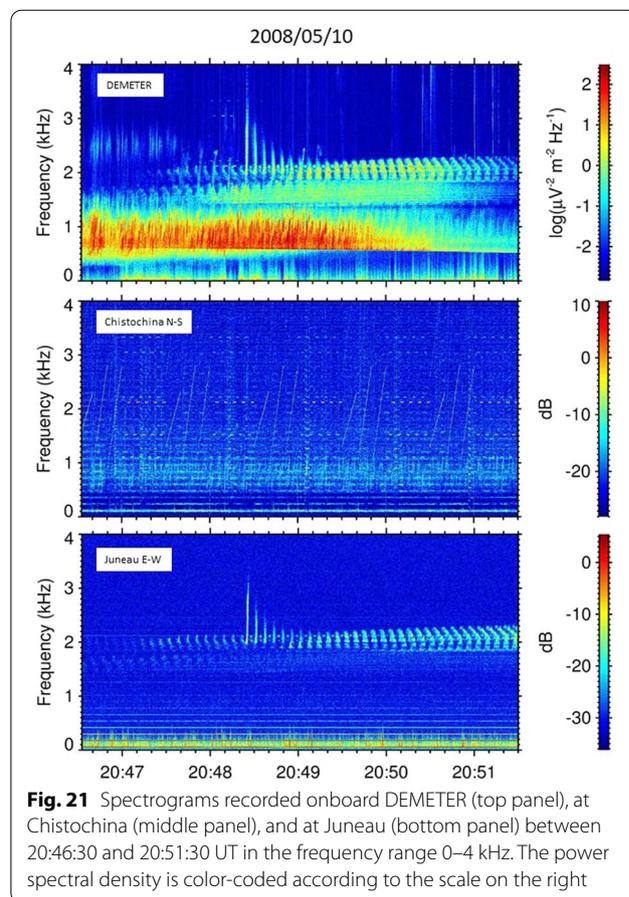
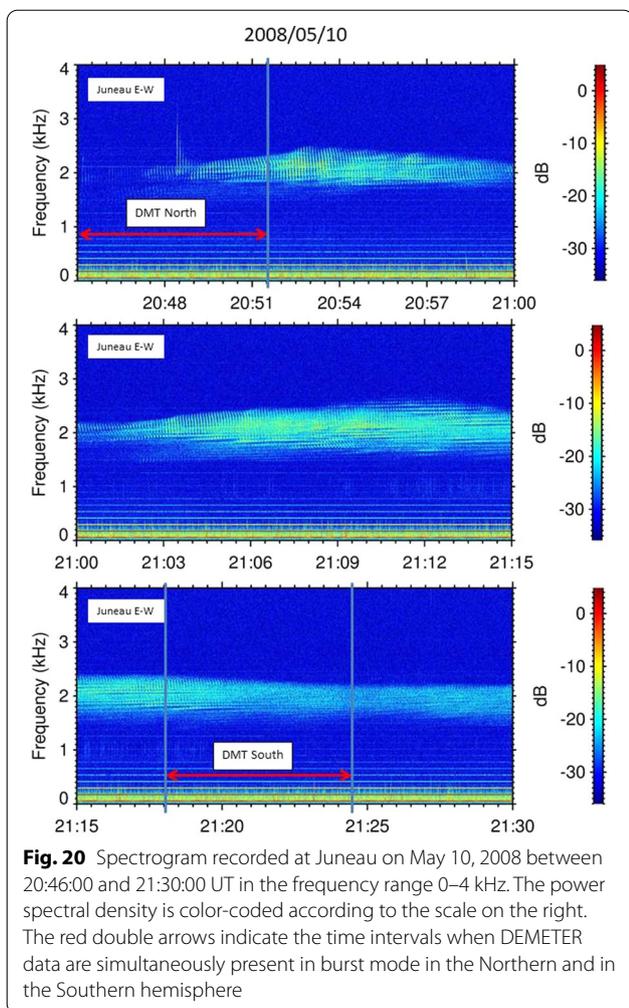
Figure 26 presents a zoom of Fig. 25. The time interval between each QP elements in the top panel of Fig. 26 is 6.24 s corresponding to 2-hop. The time delay between DEMETER and Juneau QP elements is of the order of 3.1 s.

Propagation analysis of single-frequency signals (case 6)

ELF/VLF emissions triggered by HAARP on April 5, 2010 and recorded by the satellite along the orbit shown in Fig. 27 are displayed in the top panel of Fig. 28 which

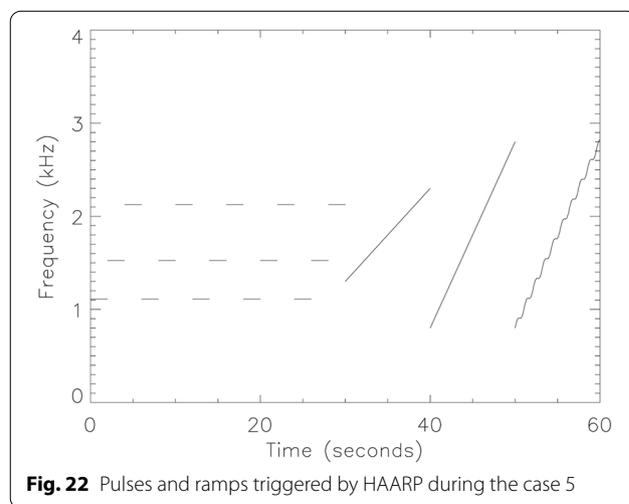




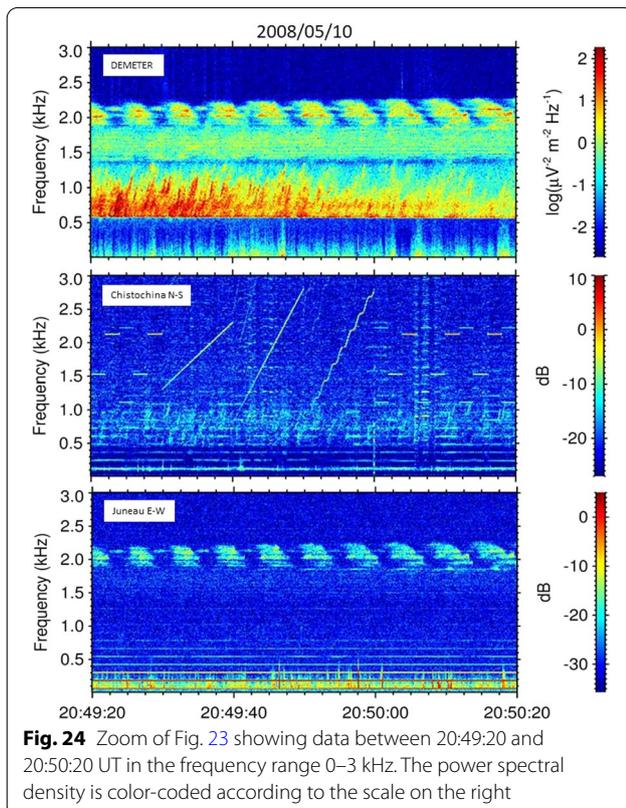
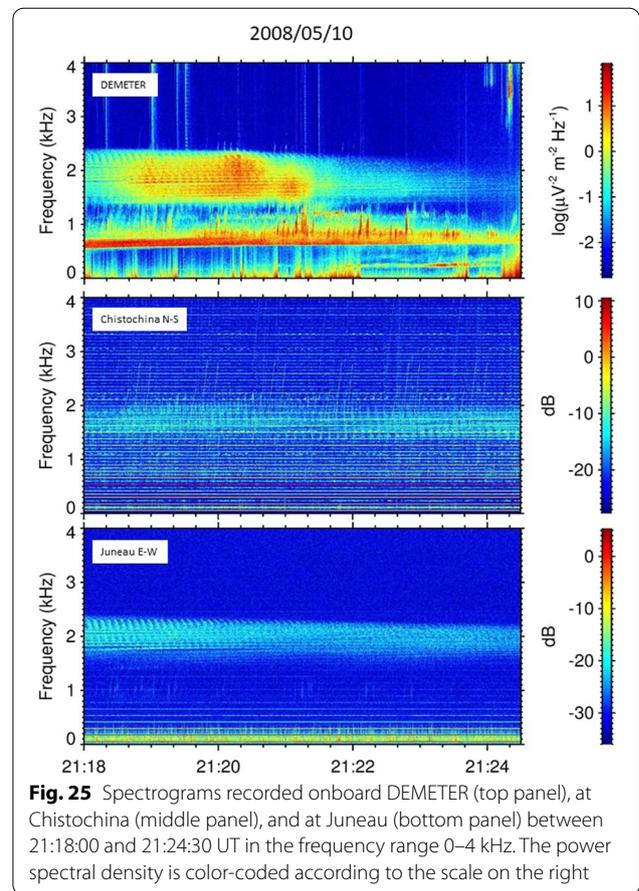
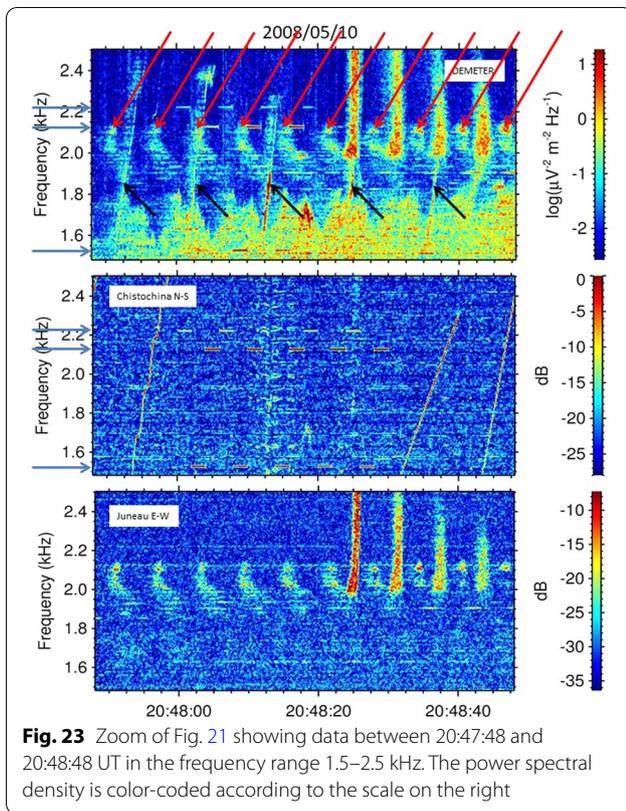


presents the spectrogram of an electric field component between 0 and 5 kHz. The HAARP frequency pattern is a 3-s pulse at 520.8 Hz followed by a 3-s pulse at 2083 Hz. In addition to these pulses at 520.8 Hz and 2083 Hz, one can see in the plot several series of pulses which correspond to harmonics. Intense electrostatic turbulence is also observed between 06:29:37 and 06:30:12 UT. It corresponds to a dramatic depletion of the electron density which is exhibited in the bottom panel of Fig. 28. This electron density depletion is known as the ionospheric trough which is very often observed at the latitude of HAARP (Pidyachiy et al. 2011). It can be noted in the spectrogram that there is a strong spectral broadening of the pulses at two specific frequencies (2083 Hz and 4166 Hz) due to the interaction with the electrostatic turbulence.

It is possible to determine the propagation characteristics of the two set of pulses observed at frequencies lower than 1.25 kHz in the top panel of Fig. 28 because the six



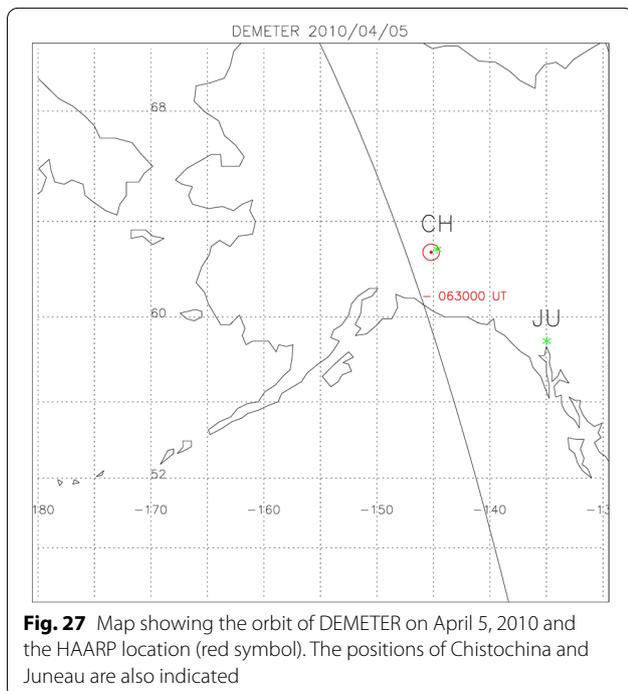
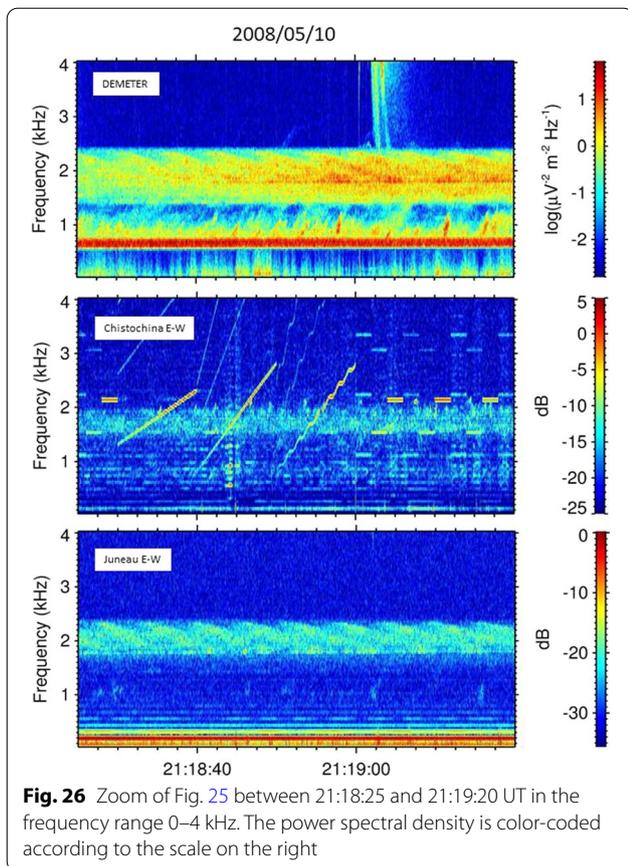
components of the electromagnetic field are available in burst mode (see above the section about DEMETER). Figure 29 shows the wave propagation analysis of these two set of pulses. Frequency–time spectrograms of the magnetic and electric field fluctuations are shown in the



first two panels. The third panel represents the ellipticity E_B (ratio of the axes of the polarization ellipse) obtained using a Singular Value Decomposition (SVD) method (Santolík et al. 2003). The sign of E_B represents the information about the sense of polarization with respect to the stationary magnetic field: negative values are used for left-handed polarization sense and positive values for the right-handed polarization sense. The SVD method is also used to calculate the direction of the wave vector. The fourth panel shows the wave-normal angle θ defined as the angle between the Earth’s magnetic field B and the wave vector. The bottom panel gives the Poynting vector component along the terrestrial magnetic field normalized by its standard deviation resulting from the statistical errors of the spectral analysis (Santolík et al. 2001).

The empty areas in the panels correspond to frequency–time intervals with magnetic power spectral densities less than $10^{-7} \text{ nT}^2 \text{ Hz}^{-1}$. These areas are empty because the analysis is not meaningful for low-power waves.

The results of this multidimensional analysis of plasma wave measurements as a function of the universal time (UT) and frequency indicate that the pulses are



right-handed circularly polarized (E_B is close to +1). One can see that the θ values vary as function of time. Outside the trough the propagation is not field-aligned (high θ values), but inside, the θ values are much lower.

Concerning the propagation, the analysis indicates in the bottom panel that the pulses are propagating in the opposite direction of the Earth’s magnetic field (blue part). As the case 6 takes place in the northern hemisphere, it means that the pulses are propagating upward as expected. The ELF/VLF pulses are generated in the D region of the ionosphere by HAARP, i.e., below the satellite (see for example, Fig. 1 of Piddychiy et al. 2008).

Discussion

The main results from the different cases are summarized in Table 1. It is shown that the HAARP pulses are a good substitute for PLHR. In cases 1 and 2, one can see that the emitted pulses can trigger emissions which are very similar to emissions triggered by PLHR (e.g., Figure 5 of Parrot and Němec 2009).

The first example of formation of a set of magnetospheric lines is given in the case 3 where emissions with faller tones are observed in the Southern hemisphere. These emissions return in the Northern hemisphere where they are observed at Juneau. The case 4 is a case where DEMETER is in burst mode in the Northern hemisphere and in the Southern hemisphere close to the conjugate of HAARP. In the two time intervals one can see on the DEMETER spectrograms bursts of rising tones around a couple of pulses with close frequencies. These bursts do not specially follow the time occurrence of the pulses. In the South it leads to the appearance of MLR in the low-resolution spectrogram.

The case 5 is a perfect example of MLR event observed in the Northern hemisphere at Juneau and in both hemispheres by DEMETER. This is a long-duration event lasting more than 43 min which combines the main features of the previous cases. The detailed spectral analysis of this complex event shows the influence of the HAARP pulses and their propagation to generate MLR which are the result of sidebands, spectral broadening, increase of intensity, and QP emissions. Similar spectral broadening has been observed in the past with pulses emitted by VLF ground-based transmitters (Bell et al. 1983; Inan and Bell 1985, and references therein). Gołkowski et al. (2008) have also observed spectral broadening of the HAARP pulses and shift of their central frequency. It is attributed, together with the increase of intensity, to the equatorial wave–particle interaction. These wave–particle interactions are enhanced when the magnetic activity is sustained in order to have enough particles in the equatorial region. Effectively a study with all MLR events recorded by DEMETER indicates that they statistically occur 17 h

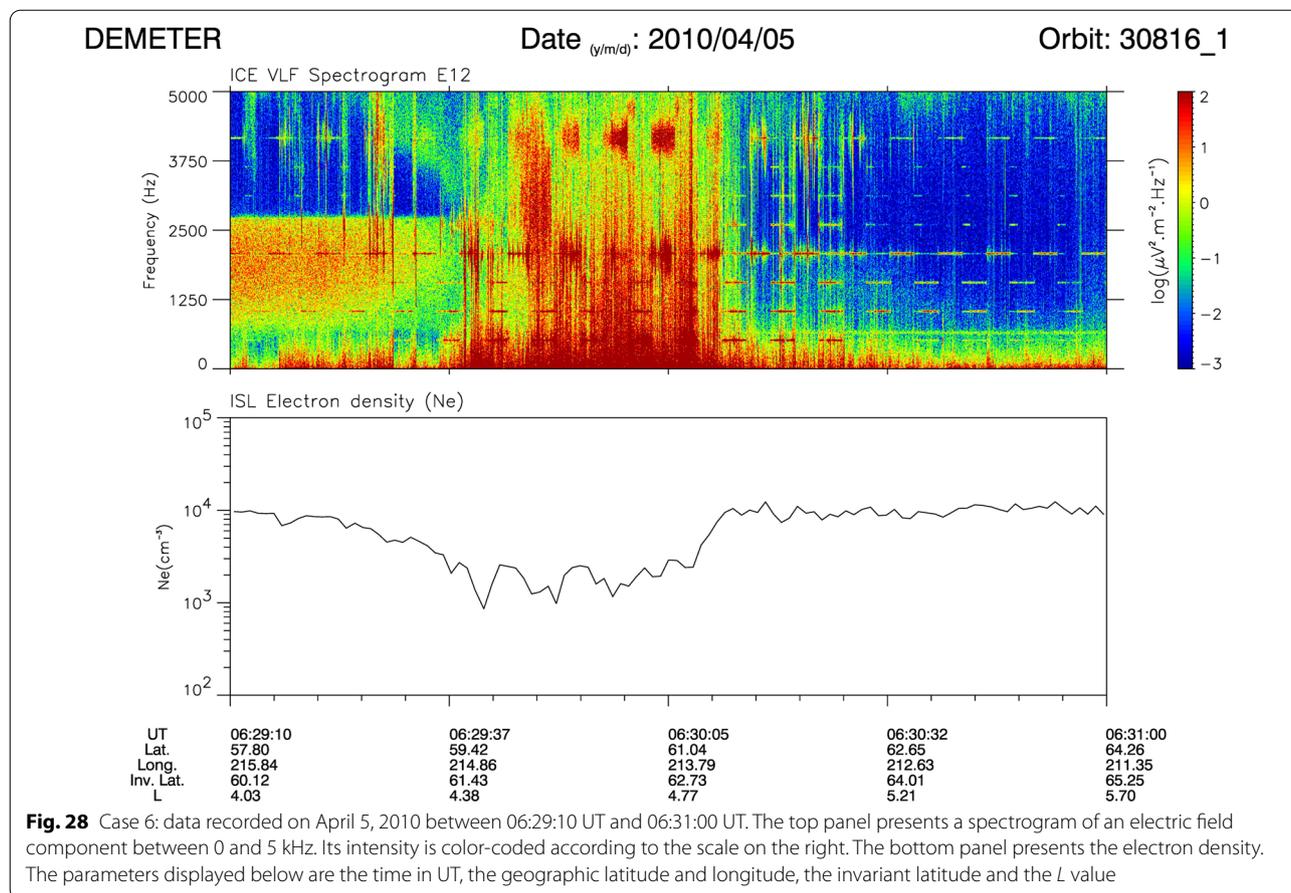


Fig. 28 Case 6: data recorded on April 5, 2010 between 06:29:10 UT and 06:31:00 UT. The top panel presents a spectrogram of an electric field component between 0 and 5 kHz. Its intensity is color-coded according to the scale on the right. The bottom panel presents the electron density. The parameters displayed below are the time in UT, the geographic latitude and longitude, the invariant latitude and the L value

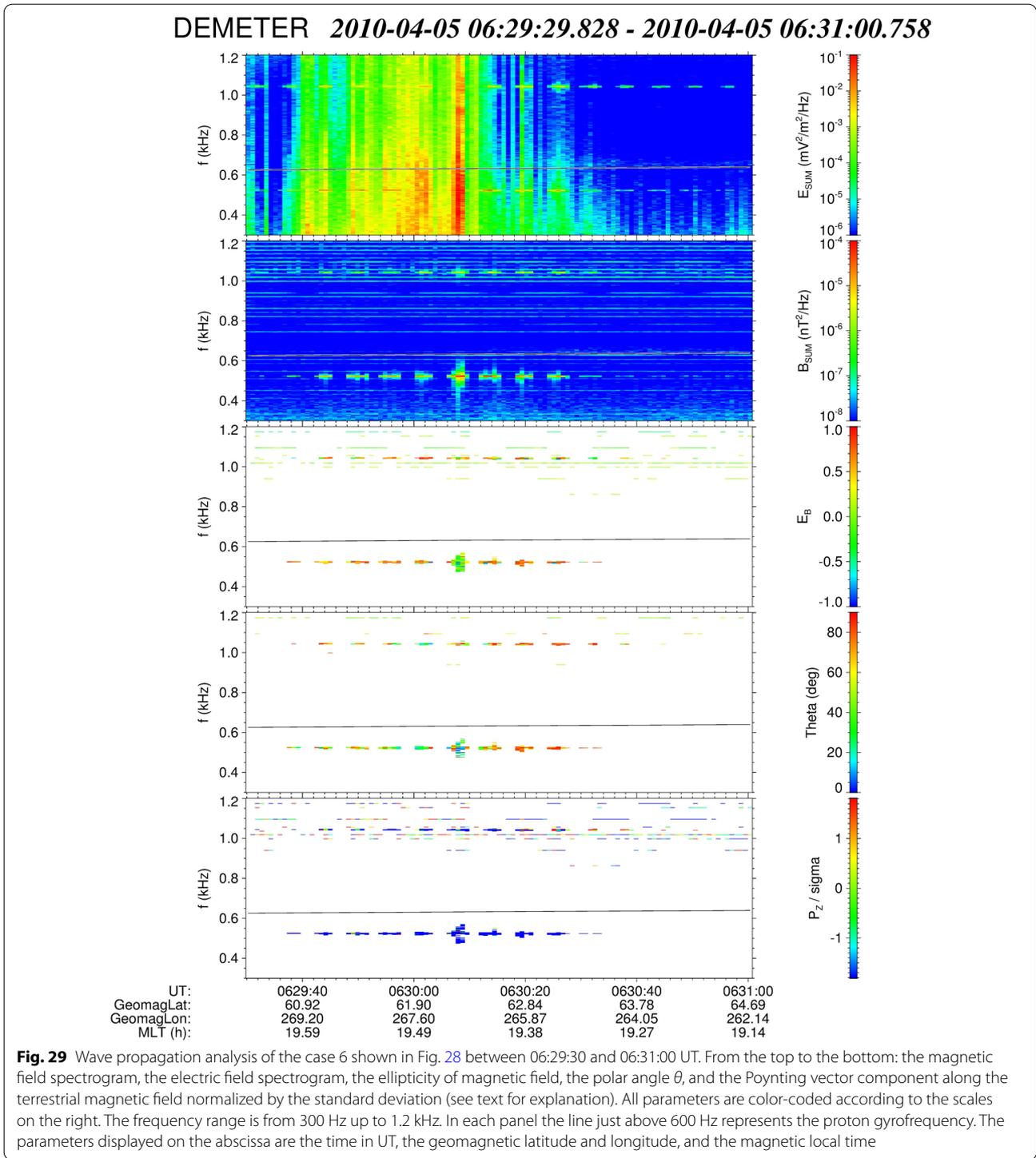
after a decrease of the Dst index, the lowest mean value being equal to -23.7 nT (Němec et al. 2009a). Our MLR events in case 3, 4, and 5 have been also registered after a weak magnetic activity (for example $Dst = -24$ nT on May 5, 2008).

It has been previously shown that sidebands can be triggered by coupling between a VLF transmitter pulse and a natural ELF emission (Bell 1985; Sotnikov et al. 1991, and references therein). Costabile et al. (2017) posit that the sidebands are generated as a result of oscillation of the electron phase-space hole at the trapping frequency, creating a hybrid amplitude/frequency modulation of the injected pulse. Sidebands can also be produced by two beating waves. Several sidebands have been observed by Helliwell et al. (1986) when two monochromatic signals closely spaced in frequency have been emitted from Siple in Antarctica and received at Roberval (Quebec) the conjugate station. They even said that the triggering of several frequency emissions with close frequencies will lead to a noise-like spectrum similar to the mid-latitude hiss. In fact it is the effect we can notice at the end of the case 5 in Fig. 24. Rastani et al. (1985) also report observation by a satellite of sidebands around

Siple pulses. It was additionally found by Gołkowski et al. (2019) that sideband amplitude of HAARP pulses may be symmetrical or asymmetrical about the frequency carrier, and in the asymmetrical case it is usually the upper sideband that is stronger.

The 1-hop time duration, which is experimentally determined, is between 3.1 and 4.5 s because it depends on the conditions of propagation and density along the path. This 1-hop time is similar to previous observations of HAARP echoes (Inan et al. 2004; Gołkowski et al. 2008). The calculation shows that the largest observed value (~ 5.5 s in the case 5 for the snake ramp) can be obtain if, under quiet conditions and parallel propagation at $L = 5.1$, we assume an equatorial electron density of 400 cm^{-3} (inside the plasmopause).

Nunn et al. (1999) said that the strongest power line frequencies are only observed at high harmonics due to the power system used by industrial plants. But pulses emitted by HAARP to simulate PLHR have been also observed at specific frequencies although they have been really emitted in a large frequency range if we consider the harmonics. It means that there is a problem of propagation and/or attenuation for pulses at particular



frequencies. In all cases this is shown (see Table 1). It seems that there are a lower and an upper frequency cut-off depending on the plasma parameters, and that the parent pulses or the echoes can be only observed in a frequency window. For example, DEMETER in the North

can observe 2-hop echoes but not Chistochina in the cases 2, 4 (North) and 5, although in the case 4 (South) the 2-hop echoes can reach the ground. The cases, where 2-hop echoes are observed on board DEMETER but not at the ground stations below, also show the observation

Table 1 Summary of the observations for the different cases defined by the DEMETER half-orbit number and the date

Case	Orbit/date	HAARP	DEMETER	Chistochina	Juneau	1-hop time
1	16781.0	571 Hz	South 1-hop	No data	2-Hop	4.0 s
	Day	1973 Hz	2 kHz + TR		2 kHz + TR	
	2007/08/23	2011 Hz R: 0–2 kHz				
2	16883.0	571 Hz	North 2-hop	Pulses at 2 kHz + harmonics of 571 Hz	No data	4.5 s
	Day	1973 Hz	2 kHz + TR			
	2007/08/30	2011 Hz R: 0–2 kHz				
		1710 Hz	South 1-hop	Pulses at all freq. + harmonics	No data	
		1890 Hz 2370 Hz R: 0.5–3.5 kHz	1710 Hz + TR 1890 Hz + TR			
3	20534.1	571 Hz	South 1-hop	Pulses at 1713 Hz + 2 kHz	2-hop	3 s
	Night	1973 Hz	1713 Hz + QP		1713 Hz + QP	
	2008/05/05	2011 Hz R: 0–2 kHz				
4	20585.0	500 Hz	North 2-hop	Pulses at all freq. + harmonics	No data	4 s
	Day	2575 Hz	2.5–2.7 kHz + TR			
	2008/05/08	2755 Hz 3235 Hz				
		2375 Hz	South 1-hop	2-hop	No data	
		2555 Hz	2.3–2.6 kHz + TR	All freq. + 2375 Hz + TR		
		3035 Hz R: 0.5–3.5 kHz				
5	20614.0	1110 Hz	North 2-hop		2-hop	3.15 s
	Day	1525 Hz	2125 Hz + TR/QP		2125 Hz + TR/QP	
	2008/05/10	2125 Hz R: 1.3–2.3 kHz		Pulses		
		R: 0.8–2.8 kHz	South 1-hop	1525 Hz		
		SR: 0.8–2.8 kHz	~ 2 kHz + TR/QP	2125 Hz	2-hop	
6	30816.1	520.8 Hz	North pulses	No data	No data	
	Night	2083 Hz	520.8 Hz			
	2010/04/05		2083 Hz + harmonics			

The frequencies of the pulses and the ramps (SR is for snake ramp) emitted by HAARP are indicated together with the frequencies of the pulses observed by DEMETER in the northern or in the southern hemisphere, and by the ground stations Chistochina and Juneau. TR is for triggered emissions and QP for quasi-periodic emissions

of 2-hop echoes at geomagnetic footprints hundreds of km away from HAARP. For a 2-hop echo to return to the northern hemisphere, the path must be ducted or plasmapause guided in the equatorial region since unguided whistler mode waves in a smooth plasmasphere quickly propagate across L-shells. The waves thus observed must exit their ducted paths above the DEMETER spacecraft. A diversity of guiding structures and irregularities can thus be concluded. Sometimes ducts extend well into the ionosphere (100 km) allowing 2-hop echoes to be observed on the ground, other times the ducts likely terminate at 1000 km altitude.

The wave propagation analysis of the pulses in the case 6 indicates that they propagate in the whistler mode. Then propagation of HAARP pulses must suffer the same constraints as the propagation of usual whistlers. This whistler propagation has been already widely discussed in the past. The ionospheric and magnetospheric propagation of whistlers is mainly controlled by the lower hybrid resonance (LHR) frequency, the equatorial electron gyrofrequency, and the presence of high- or low-density ducts (see for example Bošková et al. 1988; Streltsov et al. 2006; Gołkowski et al. 2019; Xu et al. 2020). Normally whistlers emitted in a hemisphere cannot reach the ground

in the opposite hemisphere but the ground-based receivers show that it does. Whistlers at any frequency can be guided by low-density ducts, whereas whistlers in high-density ducts can only propagate for frequencies below half the equatorial gyrofrequency (~ 3.7 kHz for $L=4.9$). Then in some events, 3.7 kHz must be an upper cutoff frequency of the HAARP pulses. It is all the more true since it has been reported that artificial ducts of density enhancement can be created under certain conditions by the high-power HF radio waves emitted by the Sura facility (Frolov et al. 2008) or HAARP (Milikh et al. 2008; Vartanyan et al. 2012).

Concerning the LHR frequency, when the whistlers are going to higher latitudes unguided waves that propagate at oblique wave-normal angles suffer an LHR reflection at low altitudes. The reflection occurs when the frequency of the whistlers approaches the local LHR frequency. The lowest frequency of the spectra represents the highest LHR frequency along the propagation path. In order to have an evaluation of the LHR frequency f_{LHR} above HAARP, we use the classic expression:

$$f_{LHR}^2 = \frac{1}{M_{eff}} \frac{f_c^2 f_p^2}{f_c^2 + f_p^2},$$

where f_c is the electron gyrofrequency (f_c in Hz = $28 * B$, where B is in nT), f_p is the plasma frequency (f_p in Hz = $9 * n_e^{1/2}$, where n_e is in m^{-3}), and M_{eff} is the dimensionless effective ion mass determined by the relation

$$\frac{1}{M_{eff}} = \frac{m_e}{n_e} \sum_{ions} \frac{n_\alpha}{m_\alpha}.$$

Here n_e , m_e are the electron density and mass, respectively, n_α , m_α are the same for ions of species α , and summation is assumed over all ion species. The altitude profile of the Earth's magnetic field B is given by the IGRF model (Thébault et al. 2015), whereas the altitude profiles of electron and ion densities are given by the IRI2016 model (Bilitza et al. 2017). Note that, for simplicity, the f_{LHR} profiles are calculated right above HAARP and its magnetically conjugate point and not along the expected propagation path of the pulses but this will not invalidate the following explanations.

The LHR frequency profiles shown in Fig. 30 have been evaluated for the two local times of DEMETER (10.5 and 22.5). It can be seen that there is a slight dissymmetry between the two conjugate points because the B profiles and the densities profiles are not identical. First, if we consider the normal f_{LHR} profiles in the Northern hemisphere (black lines), the important fact is that, whether in day or in nighttime, it is impossible for a whistler emitted in the Northern hemisphere at a frequency less than ~ 8 kHz to normally propagate in the South and

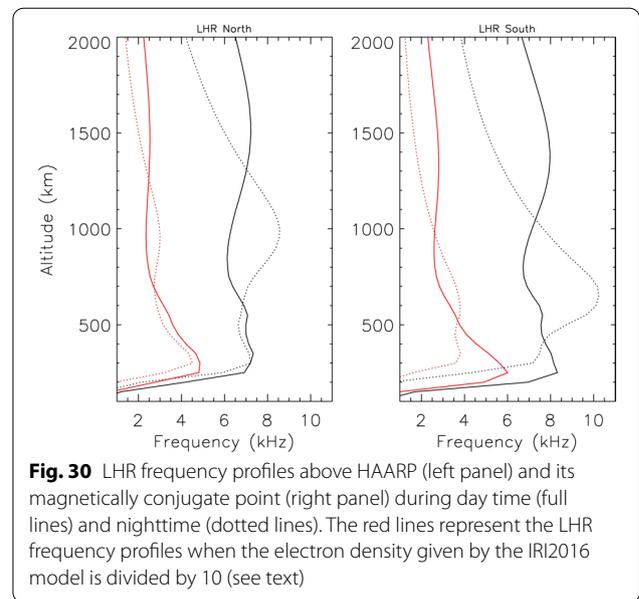


Fig. 30 LHR frequency profiles above HAARP (left panel) and its magnetically conjugate point (right panel) during day time (full lines) and nighttime (dotted lines). The red lines represent the LHR frequency profiles when the electron density given by the IRI2016 model is divided by 10 (see text)

to reach the satellite which is at 660-km altitude above HAARP. Whistlers will be detected only by a satellite moving above the upper maximum of the f_{LHR} altitude profile. Second, we consider the density profiles in disturbed conditions (red curves) in Fig. 30 which have been obtained with a normal electron density divided by 10 in order to take into account density decrease in depletion ducts as it is for the trough of case 6 (see the bottom panel of Fig. 28). One can see that we have now a rough estimate of the frequencies we can observe on DEMETER, i.e., a whistler with frequencies larger than ~ 2 kHz coming from the South is able to reach the satellite in the North and oppositely. Normally this whistler cannot reach the ground without attenuation. This problem was theoretically analyzed by Besselov et al. (2018). It is generally admitted that the whistlers coming from the opposite hemisphere can only reach the ground if the waves propagate in a duct. But recently, Shklyar and Prokhorenko (2020) using numerical simulations have shown that attenuated waves can be observed in any cases. To resume, whistler waves at frequencies higher than about 2 kHz are less attenuated by the propagation. This is well confirmed by Němec et al. (2009a) who have shown with a statistical analysis of about 650 MLR events recorded by DEMETER that they have a peak of occurrence at a frequency equal to 3 kHz (see their Fig. 10).

Conclusions

ELF waves emitted by HAARP in the lower ionosphere have been used to replicate the PLHR and to study its effects. Pulses of different lengths and different frequencies have been triggered in order to investigate their

propagation. Data were simultaneously recorded by two ground-based experiments located in Alaska close to HAARP (Chistochina and Juneau), and by the low-altitude satellite DEMETER when it was above HAARP or its magnetically conjugate point. Six cases have been analyzed which reveal the following points:

- Pulses triggered by HAARP are appropriate to simulate PLHR. They propagate in the whistler mode.
- 2-hop echoes are often observed.
- The propagation of pulses around 2 kHz is less attenuated and this is partially attributed to the LHR frequency and the equatorial electron gyrofrequency.
- We often observe a periodicity of the triggered or QP emissions at times different that the periodicity of the pulses seen on the ground. It means that the pulses are important for the initial generation of the emissions, but once the emissions are generated, the periodicity might be (at least partly) determined by the bounce period rather than solely by the radiated pattern.
- Looking to the end of the case 5 in Fig. 20, one can see that the MLR tends to disappear and to be more like a diffuse noise similar to hiss. Then this kind of event can be considered as one of the hiss generation mechanisms which is under debate since a long time (see Thorne et al. 1979, and more recently Tsurutani et al. 2018, 2019, and references therein).

In conclusion, it is shown that any monochromatic waves emitted at a frequency around 2 kHz (1.5–2.5 kHz) even during a rather short time can lead to the formation of MLR because during their propagation back and forth in the magnetosphere, they are submitted to the physical processes described above (sidebands, spectral broadening, equatorial increase of the intensity, triggered emissions, frequency dispersion). Are there such natural monochromatic waves in the ionosphere? In the past, two kinds of electromagnetic emissions with frequency line structures have been observed by DEMETER, but it was during very high magnetic activity and at lower frequencies because they were related to ion gyrofrequencies. The first were located in the trough (Parrot et al. 2006), and the second were located in the equatorial region (Němec et al. 2016; Parrot et al. 2016). Since all DEMETER MLR events (including cases 3, 4, and 5) were recorded after a weak magnetic activity at high latitudes and at higher frequencies, we can conclude that only man-made waves emitted by power lines can be the cause of MLR.

Abbreviations

PLHR: Power Line Harmonic Radiation; MLR: Magnetospheric Line Radiation; HAARP: High-frequency Active Auroral Research Program; DEMETER:

Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions;; FFT: Fast Fourier transform; TEM: Transverse electro-magnetic; MLT: Magnetic local time; UT: Universal time; LT: Local time; QP: Quasi-periodic; HF: High frequency; ELF: Extremely high frequency; VLF: Very low frequency; wrt: With regard to; IGRF: International Geomagnetic Reference Field; DMT: DEMETER; SVD: Singular value decomposition; LHR: Lower hybrid resonance; CNES: Centre National d'Etudes Spatiales; ICE: Instrument Champ Electrique; ISL: Instrument Sonde de Langmuir; PI: Principal investigator; GACR: Grantová Agentura České Republiky; CDPP: Centre des Données de la Physique des Plasmas; WALDO: Worldwide Archive of Low-frequency Data and Observations; LPC2E: Laboratoire de Physique et Chimie de l'Environnement et de l'Espace; CNRS: Centre National de la Recherche Scientifique.

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Authors' contributions

MP, FN, MC and MG designed this study. FN and MP took care of the DEMETER data, whereas MC and MG provided their HAARP expertise. FN and MP prepared the figures. MP prepared the draft. FN, MC and MG revised the draft. All authors discussed the results. All authors read and approved the final manuscript.

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Availability of data and materials

The DEMETER data shown in this paper can be obtained at <https://cdpp-archi-ve.cnes.fr/>. The Alaska ground-based data can be downloaded from <https://waldo.world/>. The values of the Earth's magnetic field and the electron and ion density altitude profiles have been extracted on line from https://ccmc.gsfc.nasa.gov/modelweb/models/igrf_vitmo.php and https://ccmc.gsfc.nasa.gov/modelweb/models/iri2016_vitmo.php, respectively. The magnetic activity has been checked with the Dst index using http://wdc.kugi.kyoto-u.ac.jp/dst_final/index.html.

Declarations

Competing interests

The authors declare that they have no competing interests regarding the publication of this paper.

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