Simultaneous observation on board a satellite and on the ground of large-scale magnetospheric line radiation

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[1] Very Low Frequency (VLF) spectrograms show sometimes sets of lines called MLR (Magnetospheric Line Radiation) with frequency spacing close to 50 or 60 Hz. It is very tempting to attribute these MLR to Power Line Harmonic Radiation (PLHR). PLHR are the ELF and VLF waves radiated by electric power systems at the harmonic frequencies of 50 or 60 Hz. Here we show for the first time large scale MLR observed simultaneously on ground and on board a low altitude satellite which is flying over the same zone. This two hours event is observed over a large area in the Northern hemisphere ($\sim$7,400,000 km^2) and in the conjugate region. It is hypothesized that these MLR are due to PLHR propagating in the ionosphere and the magnetosphere. When they cross the equator, the PLHR undergo a nonlinear interaction with particles and may play a role in the dynamics of the radiation belts. **Citation:** Parrot, M., J. Manninen, O. Santolík, F. Němec, T. Turunen, T. Raita, and E. Macúšová (2007), Simultaneous observation on board a satellite and on the ground of large-scale magnetospheric line radiation, *Geophys. Res. Lett.*, *34*, L19102, doi:10.1029/2007GL030630.

1. Introduction

[2] Evidence of PLHR propagation in the magnetosphere was first observed on ground by *Helliwell et al.* [1975], who published simultaneous observations at conjugate points. Other ground observations have been done by *Matthews and Yearby* [1978], *Helliwell* [1979], *Park and Helliwell* [1981], *Yearby et al.* [1983], and *Manninen* [2005]. Direct observations by satellites are shown in a few papers [*Koons et al.*, 1978; *Bell et al.*, 1982; *Tomizawa and Yoshino*, 1985; *Parrot*, 1994; *Rodger et al.*, 1995]. More recently other observations have been done with the ionospheric satellite DEMETER [*Parrot et al.*, 2005; *Němec et al.*, 2006, 2007]. They have performed a systematic analysis of MLR events observed by the spacecraft during its first two years of operation. They found that there are principally two different classes of events: events with frequency spacing of 50/100 or 60/120 Hz (PLHR) and events with different frequency spacing. For the first class, the frequencies of all the observed events well correspond to power system frequencies in possible regions of generation. While the PLHR events occur during both low and high geomagnetic activity, with no significant preference for quiet or disturbed periods, MLR events seem to occur mostly under disturbed conditions. They also found that the MLR events are more intense than PLHR.

[3] Many observations show that the MLR lines drift in frequencies. One must say that there is a controversy about the origin of these lines which are observed in space or on ground because many of them are not separated by 50 or 60 Hz. For example there is a group of MLR events observed by DEMETER close to the geomagnetic equator with characteristics corresponding to emissions at harmonics of ion gyrofrequencies, known from previous spacecraft observations, but at higher radial distances. The generation mechanism of the MLR observed outside the equatorial plan is not well determined although it is most probably due to a nonlinear interaction between electrons and the coherent PLHR. In their study of ISIS2 data, *Rodger et al.* [1995] observed MLR and did not find a frequency correlation with 50 or 60 Hz or multiples. It was the same for observations of MLR at Halley bay [*Rodger et al.*, 1999, 2000a, 2000b]. In a review paper concerning observations of PLHR and MLR emissions by ground based experiments and satellites, *Bullough* [1995] discussed about the possibility that MLR are due to PLHR. Simulations have also been performed by *Nunn et al.* [1999] to explain ground observations of PLHR and associated triggered emissions in Finland. Recently, *Ando et al.* [2002] analyzed the penetration of PLHR through the ionosphere and underlined the importance of the ion gyrofrequency relatively to the wave frequency of this man-made emission. This paper is related to a MLR event simultaneously observed by the satellite DEMETER and a ground-based experiment during a special campaign. The satellite experiments and the ground-based experiments will be briefly described in section 2. Section 3 will present the MLR observation whereas discussion and conclusions are given in section 4.

2. Satellite and Ground-Based Experiments

[4] DEMETER is a low-altitude satellite (660 km) with a quasi sun-synchronous polar orbit which measures electromagnetic waves and plasma parameters all around the Earth except in the auroral zones. The frequency range for the electric field is from DC up to 3.5 MHz, and for the magnetic field from a few Hz up to 20 kHz. There are two scientific modes: a survey mode where spectra of one

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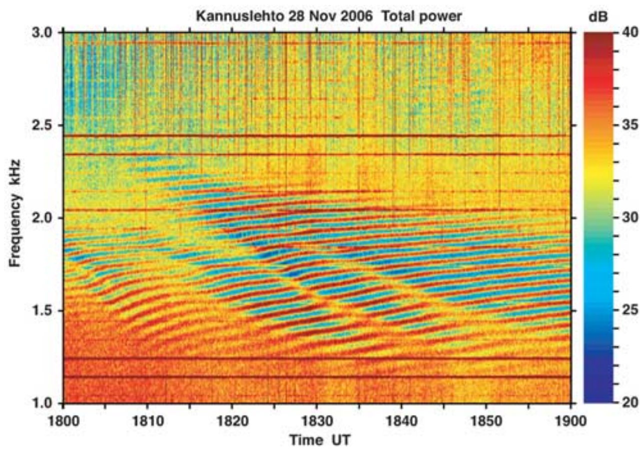

Figure 1. Spectrogram of the signal received at Kannuslehto between 18.00 and 19.00 UT. The frequency range is between 1 and 3 kHz. The signal intensity is color coded according to the scale on the right. The horizontal lines observed just above 1 kHz and between 2 and 3 kHz are the PLHR which are at exact harmonics of 50 Hz. MLR with drifting frequencies are observed between 1.2 and 2.4 kHz.

electric and one magnetic component are onboard computed up to 20 kHz and a burst mode where waveforms of two components of the electromagnetic field (one electric and one magnetic) are recorded up to 20 kHz. The burst mode allows us to perform spectral analysis with better time and frequency resolutions. Details of the wave experiment are given by *Parrot et al.* [2006b] and *Berthelier et al.* [2006].

[5] The ground-based experiment was located at Kannuslehto (67.74°N, 26.27°E, L = 5.41) in Finland. The receiver consisted of two orthogonal magnetic loop antennae with the effective area of 1000 m^2 each. The receiver has been designed for 24-bit digital recordings. The signal from both loops were sampled with frequency of 78.125 kHz and saved in the same file as 32-bit words. The lowest 8 bits were used for control information and GPS time code. Data from two orthogonal loops are handled as complex numbers in the analysis. The basic computation is the complex Fourier transform and Fourier coefficients are used for getting the estimates for signal power as a function of frequency at different polarizations. Details of the receiver and analysis method are given by *Manninen* [2005].

3. MLR Observation

[6] Figure 1 shows the data recorded at Kannuslehto during one hour on November 28, 2006. They are represented as a spectrogram between 1 and 3 kHz. We can see two different sets of lines which are rarely observed simultaneously. There is a set of horizontal lines at fixed frequencies (PLHR) with many harmonics of 100 Hz. Most intense lines are at 1150, 1250, 2050, 2350, 2450 Hz. It is typical of the PLHR observed in Finland which are radiated at frequencies f = 50 (cp ± 1) Hz with p = 12 and c = 1, 2, 3, 4, . . . because the industrial plants use 12 pulse bridges to convert 220V/3 phases to DC power [*Nunn et al.*, 1999; *Manninen*, 2005]. The other set of lines is representative of MLR. Their frequency intervals are not equal to 50 or 100 Hz and the lines are drifting in frequency but the frequency drift is not equal for all lines. Its average value is ∼0.11 Hz/s. The experimental device allows measuring the wave polarization and it appears that the MLR are whistler mode waves propagating along the direction of the Earth's magnetic field. It means that the MLR are coming from above towards the Earth.

[7] Ground observations are done during two hours in the local night between 17.40 and 19.40 UT. During this event DEMETER was close to Finland and it performed similar observations along its orbit from 18.15.00 UT until the end of the registration at 18.26.30 UT (see Figure 2). Figure 3 shows a spectrogram of an electric component when DEMETER is in the burst mode. There is one minute of data between 18.23.30 and 18.24.30 UT in the frequency range 1–3 kHz. MLR with lines at frequency intervals not equal to 50 or 100 Hz are observed but without PLHR as it was the case on ground. At the beginning of the burst mode a detailed spectral analysis indicates that the line frequency interval varies between 52.3 and 71.6 Hz with an average value of 59.2 Hz. The MLR are also slightly drifting in

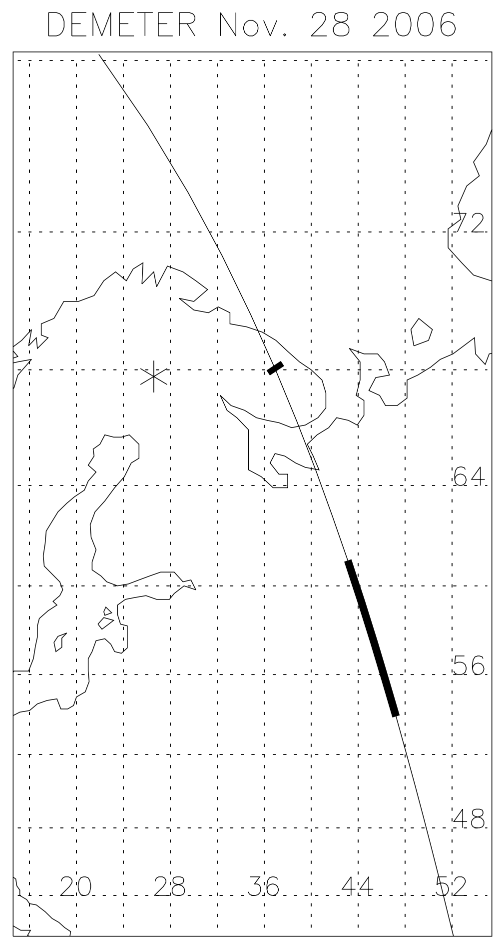

Figure 2. Map showing the area where the event has been recorded. The star indicates the position of Kannuslehto (67.74°N, 26.27°E) in Finland. The line represents the projection of the orbit of the satellite DEMETER (12842.1) on November 28, 2006. The thick part shows the location where DEMETER is in burst mode and the tick shows where DEMETER stops to record data.

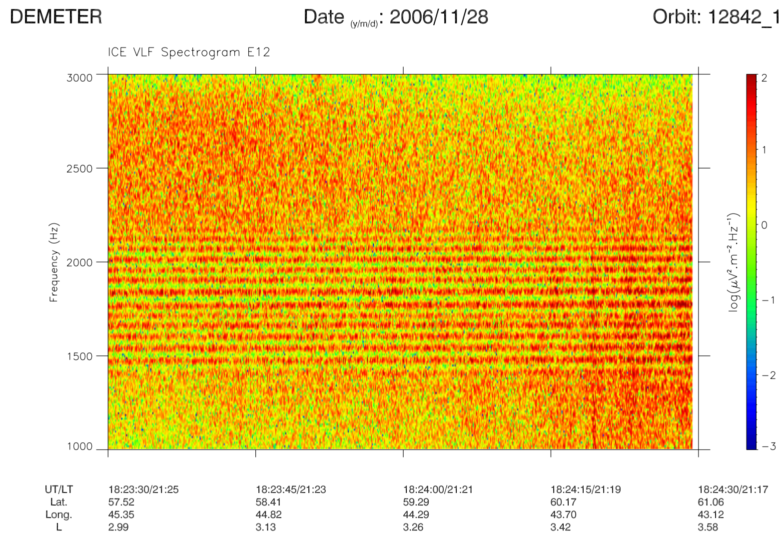

Figure 3. Spectrogram of the signal received by the satellite DEMETER between 18.23.30 and 18.24.30 UT at the end of the burst zone shown in Figure 2. The signal intensity is color coded according to the scale on the right. MLR are observed between 1.4 and 2.2 kHz. Orbital parameters are indicated at the bottom: Latitude, longitude and L value. The local time indicates that it is a night time observation.

frequency. Moreover, DEMETER also observed MLR in the conjugate hemisphere from 17.53 until 17.59 UT in the beginning of the same orbit and from 19.30 until 19.34 UT in the beginning of the next orbit which is shifted westward by 22° in longitude (not shown). But at these times DEMETER was in survey mode and no detailed analysis was possible. To estimate the space extension of this MLR emission in the north hemisphere we consider that along the orbit shown in Figure 2 DEMETER starts to record the emission at a geographic latitude of 27° and stops at 68°. Considering that the MLR are observed on two consecutive orbits it roughly gives a surface of 7,400,000 km^2.

[8] It is the first time where two independent measurements of MLR are simultaneously done on the ground and on board a spacecraft, and Figure 4 shows a comparison of the lines between the two observations. It is clear that it concerns observation of the same phenomena. Taking into account the frequency resolution of the spectral analysis, the lines are at the same frequency on ground and on the satellite. They are drifting at the same rate. On the ground and on board DEMETER the frequency drift is of the order of 0.11 Hz/second. This is in agreement with previous observations [see, e.g., *Nunn et al.*, 1999].

4. Discussion and Conclusions

[9] The fact that the drifts and the frequency spacing are identical on ground and on board the satellite indicates that this is not due to a propagation effect. It also shows that there is no Doppler shift induced by the satellite. It means that this frequency shift and the frequency interval between the lines are not induced during the propagation in a disturbed ionosphere between the satellite and the ground. The simultaneous observations of MLR on the ground, on board the satellite close to Finland at an altitude of 660 km, and in the conjugate hemisphere indicate that these waves are propagating back and forth in the magnetosphere.

[10] Our hypothesis is that the origin of these waves is due to the propagation of the PLHR observed on ground because the only other possibilities concerns:

[11] 1. The electromagnetic harmonic ELF emissions emitted in the equatorial region at the harmonics of the proton gyrofrequency. With the frequency spacing we observe (59.2 Hz) it would mean that these harmonic waves would have been generated in the magnetic equatorial plane at L = 1.95, would be propagated up to L = 5.37 (the

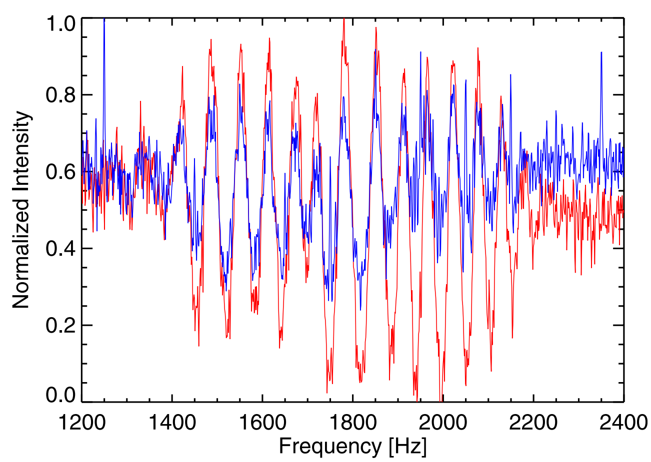

Figure 4. Comparison between the line frequencies observed at Kannuslehto (in blue) and on board the satellite (in red). The spectra are from 1200 up to 2400 Hz and their amplitudes are normalized relative to the maximum intensity of each spectrum. It corresponds to the time interval 18.24.20–18.24.30 UT. It is shown that both MLR observed at Kannuslehto and on board the satellite have similar frequencies and that even their amplitudes at the different frequencies follow the same variation. In addition to the MLR, the Kannuslehto spectrum shows clear PLHR at 1250, 1450, 1650, 1950, 2050, 2150, and 2350 Hz.

average L value of our observations) and then down to lower altitudes. These harmonic waves are effectively observed by DEMETER [*Parrot et al.*, 2006a], and even above Finland (see the quick-look of the orbit 2957.1 on the DEMETER web server http://demeter.cnrs-orleans.fr), but only during very high magnetic activity (it is not the case on Nov. 28, 2006, K_p maximum = 2^+), with a completely different duration and separation of the lines, and close to the ionospheric trough which is not the case here.

[12] 2. ELF emissions at harmonics of ion local gyrofrequencies which are also observed at low altitudes by DEMETER in the equatorial region but these waves are only enhanced at the equator and during high magnetic activity [*Němec et al.*, 2006, 2007].

[13] Then the only explanation is that on the way from the ground the PLHR undergo an interaction with particles in the magnetic equatorial region which is the most favourable region for this kind of interaction. The PLHR intensities are enhanced and their frequencies are changed. This interaction is through a cyclotron resonance mechanism. Then the frequency change of the lines can be the result of a nonlinear wave-particle interaction [*Nunn et al.*, 1999; *Shklyar et al.*, 1992]. They are observed when the waves are coming back in the ionosphere and the atmosphere.

[14] This event is a further evidence that some MLR observed in space are due to PLHR. It is important to survey these waves because the world electric power consumption is constantly increasing and there are indications that PLHR influences the atmosphere-ionosphere-magnetosphere coupling. Nonlinear interactions between electrons and PLHR can participate in the precipitation of electrons from the slot region in the radiation belts [*Bullough et al.*, 1976; *Tatnall et al.*, 1983].

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