Comparison of magnetospheric line radiation and power line harmonic radiation: A systematic survey using the DEMETER spacecraft

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Received 22 October 2006; revised 2 December 2006; accepted 26 December 2006; published 7 April 2007.

[1] Results of a systematic search for magnetospheric line radiation (MLR) observed by the DEMETER spacecraft since the beginning of the mission are presented. DEMETER is a French microsatellite (altitude of orbit about 700 km, inclination 98°) designed to study electromagnetic phenomena connected with seismic or man-made activity that has been launched in June 2004. An automatic identification procedure of possible MLR events has been used in order to analyze a large amount of measured data. It is shown that there are two principally different classes of events: (1) events with frequency spacing of 50/100 or 60/120 Hz (power line harmonic radiation, PLHR) and (2) events with a different frequency spacing. The first class of events is generated by power systems on the Earth's surface, with frequency spacing well corresponding to the fundamental frequency of the radiating power system. On the other hand, the second class is most probably generated in a completely natural way. All the detected events are thoroughly analyzed, and different properties of the two classes are statistically demonstrated. We have found that PLHR events occur both during low and high geomagnetic activity, with none of them significantly preferred. However, MLR events occur more frequently under disturbed conditions. Most of the PLHR events are observed at frequencies of 2 to 3 kHz. On the other hand, MLR events most frequently occur at frequencies below 2 kHz and seem to be more intense than PLHR. Additionally, PLHR events are more intense during the night than during the day, and there is about the same number of PLHR events observed during the day and during the night. On the contrary, no dependence of MLR peak intensities on magnetic local time was found, and more MLR events were observed during the day than during the night, although this difference is not statistically very significant. Finally, there is a group of MLR events with characteristics corresponding to the previous spacecraft observations of equatorial noise.

Citation: Němec, F., O. Santolík, M. Parrot, and J. J. Berthelier (2007), Comparison of magnetospheric line radiation and power line harmonic radiation: A systematic survey using the DEMETER spacecraft, *J. Geophys. Res.*, *112*, A04301, doi:10.1029/2006JA012134.

1. Introduction

[2] This paper deals with electromagnetic emissions propagating through the magnetosphere that exhibit a line structure. These emissions are usually called magnetospheric line radiation (MLR), and in frequency-time spectrograms, they typically look like a set of intense parallel lines whose mutual frequency separation is often the same for all consecutive lines from the set. Moreover, in some cases, the lines have a mutual distance of 50/100 or 60/120 Hz. These are believed to be caused by electromagnetic radiation from ground-based electric power systems and are called power line harmonic radiation (PLHR). Both ground [*Helliwell et al.*, 1975; *Park and Helliwell*, 1978, 1981, 1983; *Matthews and Yearby*, 1978; *Yearby*, 1982; *Yearby et al.*, 1983; *Rodger et al.*, 1999, 2000a, 2000b; *Manninen*, 2005] and satellite [*Koons et al.*, 1978; *Bell et al.*, 1982; *Tomizawa and Yoshino*, 1985; *Rodger et al.*, 1995; *Parrot et al.*, 2005, 2006a; *Němec et al.*, 2006b] observations of MLR-like phenomena were reported in the past. However, direct satellite observations of the events are rather rare, usually reporting only a few cases. Moreover, a lot of controversy still remains about the origin of these events. *Rodger et al.* [1995] analyzed observations of MLR events by satellites International Satellite for Ionosphere Studies (ISIS) 1 and ISIS 2, finding no correlation between 50/60 Hz multiples and the frequency of the observed lines. Concerning the ground-based observations, they concluded the same after

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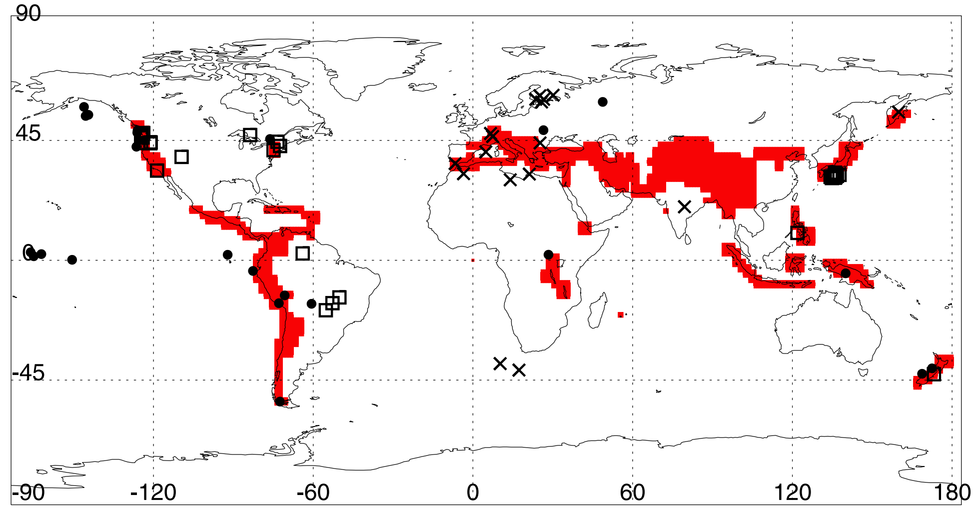

Figure 1. Map showing geographic locations of the observed events. PLHR events with 50/100 Hz spacing are plotted by crosses, PLHR events with 60/120 Hz spacing are plotted by squares, and MLR events are plotted by solid circles. Zones with the permanently active burst-mode coverage are shaded.

analyzing the data measured at Halley station [*Rodger et al.*, 1999, 2000a, 2000b]. *Němec et al.* [2006b] performed a systematic analysis of events with frequency spacing of 50/100 or 60/120 Hz (PLHR) and found that the frequency spacings of all the observed events correspond well to power system frequencies in possible regions of generation. Finally, *Parrot et al.* [2006a] described six storm-time observations of MLR-like events, performing their detail analysis and discussing a possible link to electromagnetic ion cyclotron waves at proton cyclotron harmonics emitted from the equatorial region. The role of PLHR in the ionosphere could be important because they can trigger new emissions [*Nunn et al.*, 1999].

[3] Results of a systematic survey of MLR-like events observed by the DEMETER spacecraft are reported in this paper. In section 2, the wave experiment onboard DEMETER and procedure for an automatic identification of MLR events are briefly introduced. An analysis of the detected events is described in section 3, whereas section 4 presents the discussion of results. Finally, section 5 contains conclusions.

2. Experiment and Automatic Identification of Events

[4] Wave data from the French microsatellite DEMETER (launched in June 2004, altitude of ≈710 km, nearly Sun-synchronous orbit) have been used. The primary purpose of this spacecraft is to study ionospheric effects connected with the seismic activity; the secondary goal of the mission is to study man-made effects in the ionosphere. The electromagnetic waves at geomagnetic latitudes less than 65° are measured by the Instrument Magnetometre Search Coil (magnetic field component) and the Instrument Champ Electrique (electric field component) instruments onboard DEMETER. There exist two principal modes of operation: (1) the burst mode, active mostly above the seismic areas, in which the waveforms of one electric and one magnetic component in very low frequency (VLF) range (up to 20 kHz) and a full set of three electric and three magnetic components in extremely low frequency (ELF) range (up to 1250 Hz) are recorded; and (2) the survey mode, in which power spectra of one electric and one magnetic field component are calculated onboard for VLF range. This mode has a limited frequency resolution (19.5 Hz), which is insufficient for the intended study. We are consequently forced to use the burst mode, which is active for only a few minutes during each half orbit, limiting our study only to specific areas (mostly seismic ones, but about 20% of the volume of the burst-mode data are recorded above different regions of interest and can be added/modified during the operational phase of the mission). More information concerning the DEMETER mission and onboard instruments can be found in the works of *Berthelier et al.* [2006], *Parrot et al.* [2006b], and *Santolík et al.* [2006].

[5] The spacecraft observations of MLR are rather rare. In order to detect a reasonably high number of such events, it is therefore necessary to check a large amount of data. Since a visual survey of all the measured data would be practically impossible, we have developed a procedure for an automatic identification of possible MLR. Candidate computer-found MLR events have then been visually checked, and we have decided if they correspond to the real MLR events or not. The automatic identification procedure is running in the DEMETER control center in Orléans and is described in detail by *Němec et al.* [2006b]. Altogether, 1650 hours of burst-mode data measured during the first 2 years of the DEMETER mission has been analyzed. In this data set, 764 possible MLR events have been detected. Manual verification of the events revealed that most of them are "false alarms," finally yielding only 72 MLR-like events: 17 PLHR events with frequency spacing of 50/100 Hz, 32 PLHR events with frequency spacing of 60/120 Hz, and 23 MLR events with different frequency spacing. The geographic locations of these events as well as the areas with the permanently active burst-mode coverage are shown in Figure 1. The operational phase burst-mode regions are not shown since their positions vary during the time interval analyzed in this study.

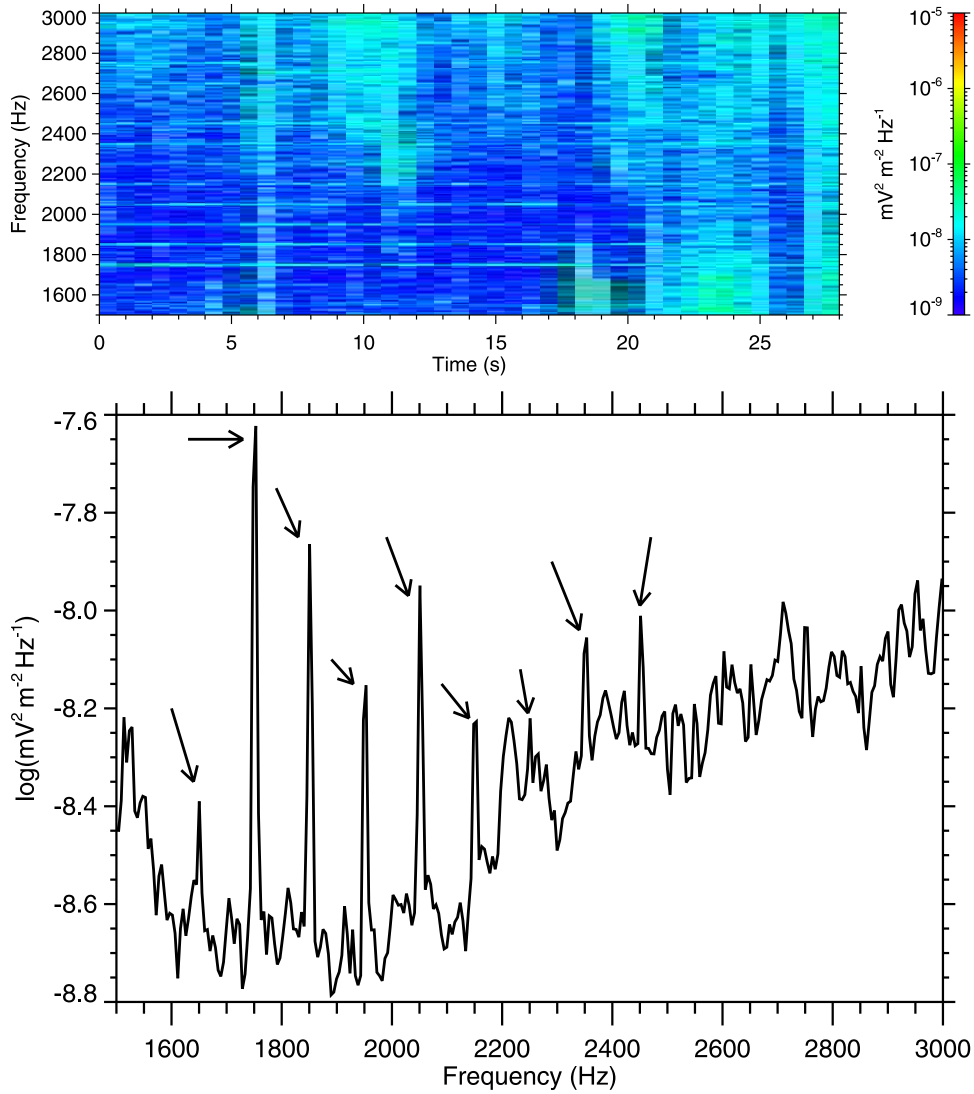

Figure 2. Top: An example of frequency-time spectrogram of electric field fluctuations corresponding to one of the analyzed PLHR events with 50/100 Hz spacing. The data were recorded on 25 March 2006 from 1913:32 UT when the spacecraft was flying over Finland. Bottom: Power spectrum of the first 18 s of data, with the most important peaks marked by arrows.

[6] The first two groups of events are most probably caused by electromagnetic radiation from power systems (PLHR) and have been quite thoroughly analyzed by *Němec et al.* [2006b]. In this paper, we compare them with the third group of events (“real MLR” events), showing that their properties are substantially different.

3. Analysis of Events

[7] An example of one of the events from the first group (frequency spacing 50/100 or 60/120 Hz) recorded on 25 March 2006 from 1913:32 UT, when the spacecraft was flying over Finland, is shown in Figure 2. It is represented in the form of a frequency-time spectrogram of electric field fluctuations (top panel) together with the power spectrum corresponding to the first 14 s of data (bottom panel). The arrows are used to mark the most important peaks of the spectrum located at frequencies 1650, 1750, 1850, 1950, 2050, 2150, 2250, and 2350 Hz. These peaks are separated by 100 Hz and located exactly at 50 Hz (odd) harmonics. Moreover, much weaker peaks can be observed at even harmonics. The observed frequencies are in a good agreement with independent ground-based measurements performed by *Manninen* [2005]. A slowly growing intensity as a function of frequency above 2000 Hz (bottom panel) is caused by naturally occurring whistlers with low dispersion, coming most probably from the lightning sources below the spacecraft.

[8] Figure 3 represents another example of one of the observed events, this time from the third group (frequency spacing other than 50/100 or 60/120 Hz), recorded on 16 May 2005 between 0816:02 and 0818:42 UT when the spacecraft was flying over the Pacific Ocean. The first two panels represent frequency-time spectrograms of electric and magnetic field fluctuations. Since this time the emissions occurred during the burst mode in the DEMETER

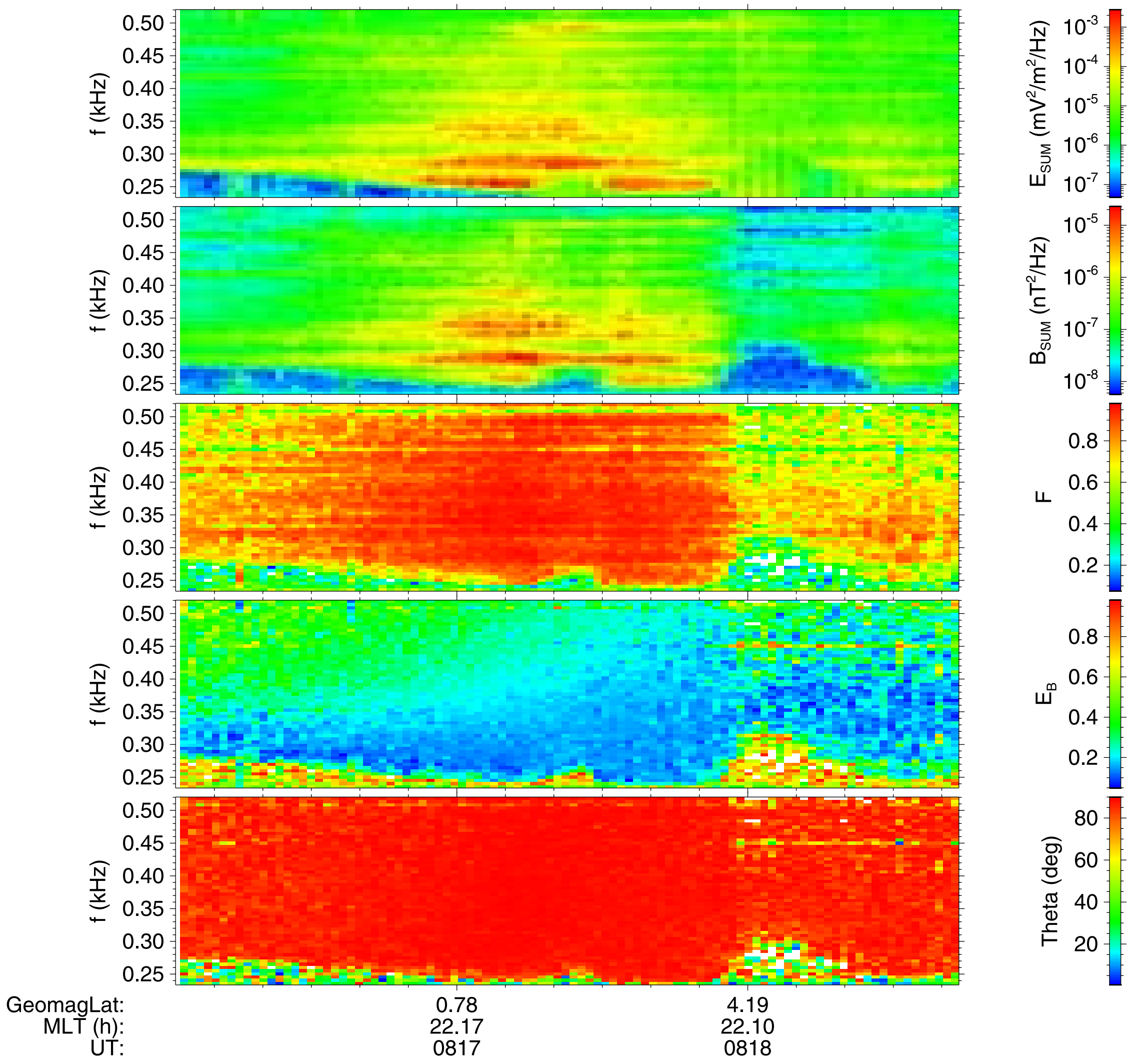

Figure 3. An example of a real MLR event (from the third group: frequency spacing other than 50/100 or 60/120 Hz). The data were obtained on 16 May 2005 between 0816:02 and 0818:42 UT, and the occurrence in ELF band allowed us to perform a detail analysis. From the top: frequency-time power spectrograms of electric and magnetic field fluctuations, of the planarity, ellipticity, and polar angle of wave vector direction with respect to the ambient magnetic field.

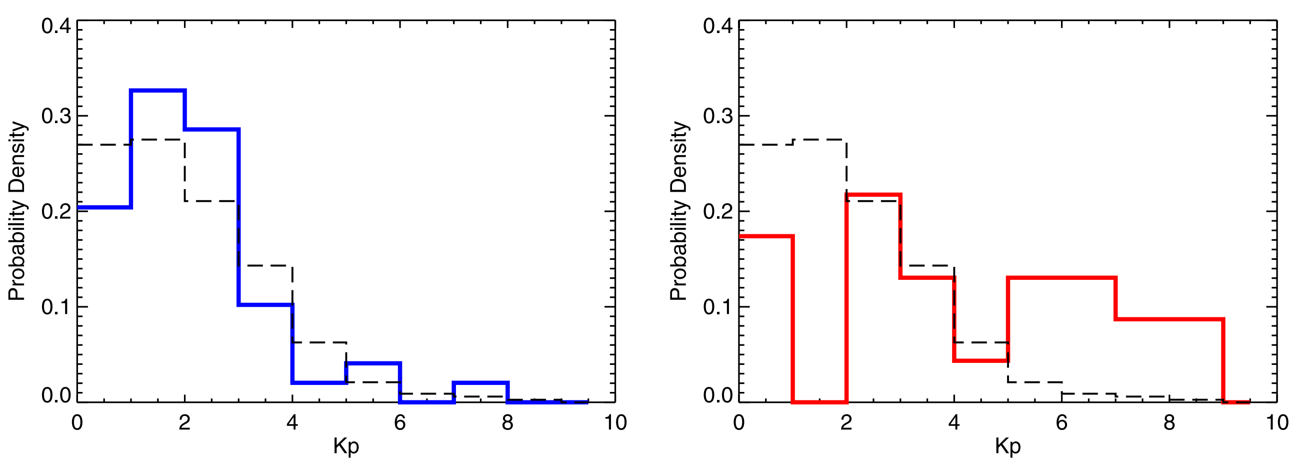

Figure 4. Histograms of Kp indices (left panel) at the time of PLHR events (solid line) and (right panel) at the time of MLR events (solid line). Histogram of all Kp indices that occurred during the analyzed year is overplotted in both panels by dashed line.

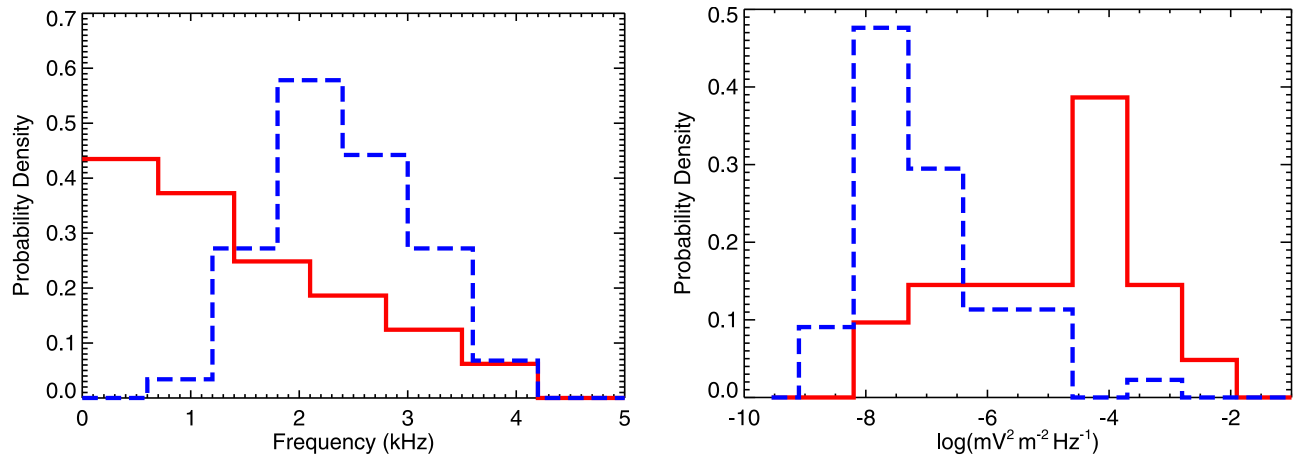

Figure 5. Left: Histograms of central frequencies of PLHR events (dashed line) and MLR events (solid line). Right: Histograms of peak intensities of PLHR events (dashed line) and MLR events (solid line).

ELF band, it was possible to perform a complex analysis. An example is presented in the last three panels of Figure 3 (see description at the end of this section for more details).

[9] Figure 4 shows histograms of Kp indices that occurred during the detected events. The left panel represents results obtained for PLHR events (frequency spacing 50/100 or 60/120 Hz), and the right panel represents results obtained for MLR events (different frequency spacing). It can be seen that 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 more frequently under disturbed conditions.

[10] For each of the observed events, we evaluate a central frequency and a peak intensity. The central frequency is defined as an arithmetic average of the minimum and maximum frequencies detected in the observed set of lines. The peak intensity is defined by the most intense line. Histograms of central frequencies of the observed events are shown in the left panel of Figure 5, by a dashed line for the PLHR events, and by a solid line for the MLR events. Histograms of peak intensities of the observed events are shown in the right panel of Figure 5. It can be seen that most of the PLHR events have been observed at frequencies of 2 to 3 kHz. On the other hand, MLR events most frequently occur at frequencies below 2 kHz, with the number of observations slowly decreasing toward higher frequencies. Moreover, the MLR events are more intense than PLHR.

[11] Figure 6 represents the peak intensity of the PLHR and MLR events as a function of magnetic local time. It shows that the peak intensity of the PLHR events is higher during the night than during the day, although the peak intensity of MLR does not seem to depend on the magnetic local time. Moreover, about the same number of the PLHR events was observed during the night (24) and during the day (25). However, more MLR events were observed during the day (15) than during the night (8). The bunching of the observed events into two distinct groups is caused by the specific Sun-synchronous orbit of DEMETER. This orbit is reflected by two peaks in the MLT coverage, around 11 and 23 MLT, both of them containing the same number of orbits.

[12] Figure 7 shows how the central frequency of the observed MLR events depends on the geomagnetic latitude. It can be seen that two distinct groups of events are formed. The first of them is observed at higher frequencies and

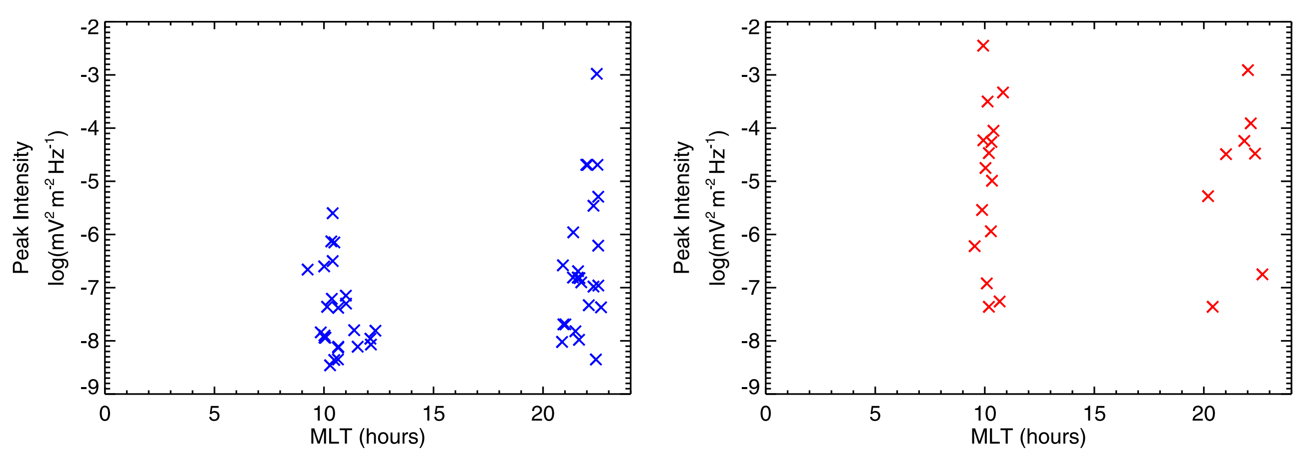

Figure 6. Left: Peak intensity of PLHR events as a function of magnetic local time. Right: Peak intensity of MLR events as a function of magnetic local time.

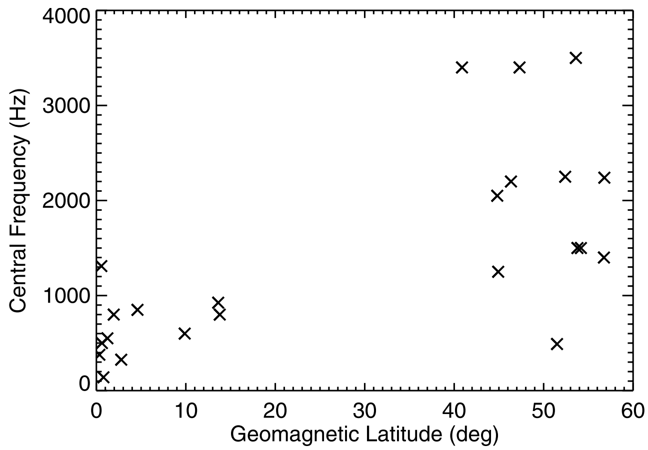

Figure 7. Central frequency of the observed MLR events as a function of geomagnetic latitude.

located at higher geomagnetic latitudes, while the second group is observed close to the geomagnetic equator at significantly lower frequencies.

[13] At frequencies below 1 kHz, we can analyze the ELF band where all the six electromagnetic components are measured. The analysis reveals that there is a group of MLR events (5 out of 23) located close to the geomagnetic equator with characteristics corresponding to recent observations of equatorial noise [*Santolik et al.*, 2002, 2004; *Němec et al.*, 2005, 2006a, and references therein].

[14] A detailed analysis of one of the events that belong to the "equatorial noise" group is shown in Figure 3. The top two panels contain spectrograms representing power-spectral densities of electric and magnetic field fluctuations, respectively. The third panel contains a spectrogram representing the planarity of magnetic field fluctuations, which is determined by the singular value decomposition (SVD) method [*Santolík et al.*, 2003]. It varies between 0 and 1 and describes a confinement of the fluctuations to a single plane: a value of 1 would represent an ideal plane wave. A value of ≈0.8 for the observed emissions suggests fluctuations very close to a single plane, with a small fraction of random three-dimensional fluctuations. The fourth panel contains a spectrogram representing the ellipticity of polarization of magnetic field fluctuations, which is again determined by the SVD method and varies between 0 (linear polarization) and 1 (circular polarization). It can be seen that the emissions of the equatorial noise type have polarization close to linear [*Russel et al.*, 1970]. The last panel represents a frequency-time spectrogram of polar angle of wave vector direction with respect to the ambient magnetic field (also determined by the SVD method). It shows that the wave vector is perpendicular to the ambient magnetic field.

4. Discussion

[15] A surely problematic element in the presented study is the procedure for automatic identification of MLR events. Although this procedure was necessary in order to analyze a large amount of data, it is practically impossible to determine all consequences of this step. Another basic limitation of the presented study is caused by the use of burst-mode data, which are collected only above some specific areas. Both these complications are discussed in detail by *Němec et al.* [2006b].

[16] The main purpose of this study is to demonstrate a striking difference between the two groups of events: PLHR (events with frequency spacing of 50/100 or 60/120 Hz) and "real MLR" events (with different frequency spacing). Fundamental difference in conditions needed for their generation is demonstrated in Figure 4. While PLHR events occur during both low and high geomagnetic activity, with no significant preference for any of them, MLR events occur more likely under highly disturbed conditions. This most probably suggests a completely different generation mechanism for the two classes. PLHR events seem to be electromagnetic emissions radiated by electric power systems on the ground that propagate in right-hand polarized whistler mode and are only modified by the plasma environment [*Němec et al.*, 2006b]. On the other hand, we believe that emissions that are classified as real MLR (or at least some of them) are generated in a completely natural way by instabilities of particle distribution functions. Different properties of PLHR and real MLR events are shown in Figures 5 and 6. PLHR events are less intense than real MLR and occur mostly at frequencies between 2 and 3 kHz, with a clearly distinguishable peak in probability of occurrence. On the contrary, MLR events occur mostly at frequencies below 2 kHz, with the probability of observation slowly decreasing toward the higher frequencies. This is rather different from the frequencies of MLR reported by other researchers [e.g., *Rodger et al.*, 1995, 1999]. This can be most probably explained by the fact that the events observed at low frequencies are located at low geomagnetic latitudes (see Figure 7). These low geomagnetic latitudes have not been covered by *Rodger et al.* [1995, 1999]. Furthermore, the peak intensity of PLHR events is higher during the night than during the day, but the peak intensity of MLR events does not show this effect. This could be explained by the fact that the Earth-ionosphere coupling is more efficient during the night than during the day [*Green et al.*, 2005]. This represents further support for the idea that PLHR and real MLR have to be considered as two completely different phenomena. However, this does not completely exclude the possibility that these two classes of events may be connected in some way; for example, some authors suggest that PLHR can serve as a trigger for MLR [*Bullough*, 1995; *Manninen*, 2005].

[17] More MLR events were observed during the day than during the night. This is in quite a good agreement with ground-based observations by *Rodger et al.* [2000b]. We can estimate a statistical significance of this difference. Supposing that the probability of observing MLR events is the same during the night and during the day ($p = p_1 = p_2 = 0.5$), one can calculate the mean value and standard deviation of the number of night/day observations. Having 23 MLR events altogether (n = 23), the two mean values are equal, $\overline{n_{\text{night}}} = \overline{n_{\text{day}}} = np = 11.5$. The standard deviations can be then obtained using binomial distribution of probability, $\sigma = \sqrt{np(1-p)} \approx 2.4$. Consequently, it can be seen that the difference between the mean value and the measured number of observations is only about 1.5 standard deviations and is therefore statistically not very significant.

[18] This simple analysis arises the question, how significant are the observed differences between PLHR and MLR? Basically, we need to determine whether two distributions (obtained experimentally and represented in the form of histograms in Figures 4 and 5) are significantly different from a statistical point of view. This can be done by the Kolmogorov–Smirnov test [*Press et al.*, 1992], which gives the probability of rejection of the null hypothesis of no difference between the two data sets. Applying this calculation to the measured data, we can conclude that the probability of the obtained distributions being the same for PLHR and MLR is less than 0.1% for all the presented histograms.

[19] There are two distinct classes regarding the geomagnetic latitude of observed MLR events: (1) events that occur close to the geomagnetic equator and (2) events located at relatively high geomagnetic latitudes (≈50°). Moreover, the events that belong to the first class usually occur at lower frequencies (up to 1 kHz). This suggests that there probably exist (at least two) different generation mechanisms of MLR events, and a lot of attention needs to be paid when classifying them and making general conclusions concerning their properties. For instance, there are 5 events (out of 23) with characteristics corresponding to the recent observations of equatorial noise. These observations are rather unique, though the altitude of the DEMETER satellite is only about 700 km and up to now the equatorial noise was believed to occur at radial distances between 2 and 7R_E [*Laakso et al.*, 1990; *Kasahara et al.*, 1994; *Němec et al.*, 2006b].

5. Conclusions

[20] We have presented results of a systematic survey of observations of MLR by the DEMETER spacecraft. The data were collected during the first 2 years of its operation. An automatic identification procedure has been used to detect the MLR events. Altogether, 72 events have been found in the entire set of 1650 hours of high-resolution data.

[21] There are two principally different classes of events: (1) events with frequency spacing of 50/100 or 60/120 Hz (so-called power line harmonic radiation, PLHR) and (2) events with different frequency spacing. While the first class of events originates from power systems on the Earth's surface and their frequency spacing well corresponds to the fundamental frequency of the radiating power system, the second class is most probably generated in a completely natural way.

[22] 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. Most of the PLHR events have been observed at frequencies of 2 to 3 kHz. On the other hand, MLR events most frequently occur at frequencies below 2 kHz, with the number of observations slowly decreasing toward higher frequencies. Moreover, MLR events are more intense than PLHR. PLHR events are more intense during night than during the day. There is about the same number of PLHR events observed during day and night. In contrary, no dependence of MLR peak intensity on magnetic local time was found. Finally, more MLR events were observed during day than night, although this difference is not statistically very significant. There is a group of MLR events occurring close to the geomagnetic equator with characteristics corresponding to emissions of equatorial noise, known from previous spacecraft observations, but at higher radial distances.

[23] **Acknowledgments.** We thank J.-Y. Brochot of LPCE/CNRS Orléans for his help with running the PLHR recognition algorithm as the DEMETER level-3 processing procedure. F. Nemec and O. Santolik acknowledge support from the GACR grant 205/06/1267.

[24] Amitava Bhattacharjee thanks Jyrki Manninen and Vittorio Sgrigna for their assistance in evaluating manuscript 2006JA012134.

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