Power line harmonic radiation (PLHR) observed by the DEMETER spacecraft

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[1] Results of a systematic survey of Power Line Harmonic Radiation (PLHR) observed by a recently (June 2004) launched French spacecraft DEMETER are presented. In order to obtain a statistically significant number of events, an automatic identification procedure has been developed and all the available high-resolution data have been processed. Altogether, 58 events have been found in 865 hours of data recorded during the first year of operation. These events form three different classes: with frequency spacing of spectral lines of 50/100 Hz (10 events), with frequency spacing of 60/120 Hz (13 events), with other spacings/not clear cases (35 events). The first two classes of events are discussed in detail, showing that their origin is most probably connected with the radiation from the electric power systems which are magnetically conjugated with the place of observation. Additionally, in more than one half of the cases, the frequencies of PLHR lines well corresponded to the multiples of the power system frequency. The frequency drift of all the observed events was very slow, if observable. The events occurred without any significant preference for low or high geomagnetic activity, although more intense events were observed during disturbed times. Simultaneous observations of electric and magnetic components of PLHR suggest that the waves propagate in the electromagnetic right-hand polarized whistler mode.

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1. Introduction

[2] Power Line Harmonic Radiation (PLHR) are electromagnetic waves radiated by electric power systems at harmonic frequencies of 50 or 60 Hz. In frequency-time spectrograms they usually look like a set of intense parallel lines with mutual distances of 50/100 or 60/120 Hz because odd/even harmonics can be strongly suppressed in some cases. There are many observations of PLHR on the ground [*Helliwell et al.*, 1975; *Park and Helliwell*, 1978; *Matthews and Yearby*, 1978; *Park and Helliwell*, 1981, 1983; *Yearby et al.*, 1983], giving evidence for its propagation through the magnetosphere. However, direct observations by satellites are still rather rare and described only in a few papers [*Bell et al.*, 1982; *Koons et al.*, 1978; *Tomizawa and Yoshino*, 1985; *Rodger et al.*, 1995; *Parrot et al.*, 2005]. Moreover, one must admit that there is quite a controversy about the origin of these events because many of the observed lines are not separated by 50/100 or by 60/120 Hz. These are usually called Magnetospheric Line Radiation (MLR) and their generation mechanism is a matter of discussion. *Rodger et al.* [1995] analyzed observations of MLR by ISIS 1 and ISIS 2 satellites and found no correlation with 50 or 60 Hz multiples. The same conclusion was obtained for ground-based observations made at the Halley station [*Rodger et al.*, 1999, 2000a, 2000b]. On the other hand, some researchers [*Park and Miller*, 1979] have reported a "Sunday effect"; they claim that the occurrence rate was significantly lower on Sundays in comparison to other days of week. *Parrot* [1991] and *Molchanov et al.* [1991] attributed this reduced occurrence not only to lower power consumption during weekends but also to different current distribution in the power systems as compared to weekdays. Finally, in a review paper concerning observations of PLHR and MLR both on the ground and satellites, *Bullough* [1995] discussed the possibility that MLR originates as PLHR.

[3] Results of a systematic survey of PLHR observed by the DEMETER spacecraft are reported in this paper. In section 2 the wave experiment on board DEMETER is briefly introduced. In section 3 an automatic identification of PLHR is described. An analysis of events is performed in section 4, whereas section 5 presents the discussion of results. Finally, section 6 contains conclusions.

2. Experiment

[4] We have used data from the French microsatellite DEMETER, which was launched in June 2004 on a low-

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altitude (≈710 km) nearly Sun-synchronous polar orbit. The primary purpose of the DEMETER mission is to study ionospheric effects connected with the seismic activity. The mission also aims at the analysis of anthropogenic effects in the ionosphere. The IMSC and ICE instruments on board DEMETER measure electromagnetic waves at geomagnetic latitudes less than 65 degrees. There are two principal modes of operation: the survey mode, in which spectra of one electric and one magnetic field component are calculated onboard in the VLF range (up to 20 kHz) and the burst mode, in which the waveforms of one electric and one magnetic field component are recorded in the VLF range and a full set of three electric and three magnetic components are measured in the ELF range (up to 1250 Hz). The survey mode has a limited frequency resolution (worse than 19.5 Hz), which is insufficient for a study of PLHR. Therefore we have used the burst-mode data, which are only recorded for several minutes during each half-orbit, mostly above seismic areas (the zones are marked by shading in Figures 2 and 3). Besides these zones there are about 20% of volume of the burst-mode data which are recorded above different regions of interest which can be added or modified during the operational phase of the mission. Detailed descriptions of the DEMETER wave experiments and analysis methods can be found in papers by *Berthelier et al.* [2006], *Parrot et al.* [2006], and *Santolík et al.* [2006].

3. Automatic Identification of PLHR Events

[5] The PLHR events are known to be very rarely observed on spacecraft. In order to detect a reasonably high number of such events, it is necessary to process a large amount of data. Since a visual survey of all the data would be very time-consuming (if not almost impossible), we have developed a procedure for an automatic identification of possible PLHR events. All these candidate PLHR events, found by a computer, have been visually verified and we have decided, if they correspond to real PLHR events.

[6] The automatic identification procedure, instead of searching for a group of parallel equally spaced lines on a frequency-time spectrogram (possibly drifting in frequency), has been designed to search for a single line. This simplification fails in the case of the spacecraft interferences. However, the artificial interferences always occur at the same, known, frequencies, not showing the frequency drift, and can be therefore easily distinguished.

[7] We have used electric field data obtained during the Burst mode in the VLF range. The main reason for using the electric field data was that these measurements contain significantly less interferences than the magnetic field data. In order to easily access the entire set of the DEMETER data files, the program for automatic identification of PLHR events has run in the DEMETER control center in Orléans, France as the level-3 data processing [*Lagoutte et al.*, 2006].

[8] The waveforms are recorded with a sampling frequency of 40,960 Hz. The automatic recognition procedure starts by analysis of these data sets using the fast Fourier transform (FFT) with 8192 data samples. Seven consecutive spectra are then averaged with 50 percent overlapping. This results in a frequency-time spectrogram with a frequency resolution of 5 Hz and time resolution of 0.8 s. This seems to be a good compromise between the required frequency resolution (identification of narrow lines with frequency separation of about 50 Hz), time resolution (lines are expected to drift even several Hz per second), and statistical errors of spectral estimates.

[9] The next step is to find frequencies with an intense signal at a given time. We focus on a frequency interval from 500 to 4000 Hz, because there are not many PLHR events reported outside of this interval. For a given time, we scan the power spectra, taking into account sets of N consecutive frequency points. N is one of the parameters of the method which will be discussed later. In order to suppress systematic trends across each set of N points, a least-squares polynomial fit of the nth degree is subtracted. In each corrected set, we define frequencies at which the intensity exceeds the average intensity by more than k standard deviations (k and n are additional parameters of the procedure). In the given frequency interval, all the possible sets of N consecutive frequency points are processed by the same procedure, shifting the set always by one frequency point.

[10] The final step is to search for continuation of the lines in the next time interval. Each of the frequency points found by the above procedure is initially supposed to be the beginning of a new spectral line. For each of the detected lines we store the time of its beginning, the frequency at which it was observed for the first time, and information on its estimated minimum and maximum frequency drift. In the new time interval we determine whether this line continues by comparing the presently found frequency points to the points that would correspond to the lines stored in the memory. This comparison takes into account the beginning frequency and frequency drift of each line. If the frequencies match, the line continues to the next time interval. In this case, its minimum and maximum frequency drift are recalculated.

[11] If the next time interval does not contain any frequency point corresponding to a given line, the line is terminated and its duration is compared to the predefined threshold t. If the line lasts longer than t, it is classified as a possible PLHR event: the time and frequency of its beginning are saved and a frequency-time power spectrogram containing the line is plotted. If the line does not last long enough, it is not taken into account.

[12] The above described algorithm contains several crucial parameters. Their values have been defined using test data, by requiring that 100% of the PLHR events in the test data are identified. On the other hand, we have tried to find parameters which minimize the number of "false alarms." The parameters used in the present study have been defined as follows. Number of frequency points in a set, $N = 40$; degree of the fitted polynomial function, $n = 3$; minimum multiple of the standard deviation, $k = 2.5$; minimum duration of a line, $t = 5.0$ s.

4. Analysis of Events

[13] We have run the described identification procedure on the entire data set recorded by the DEMETER spacecraft during the first year of its operation, from the beginning of the mission in July 2004 till July 2005. Altogether, this represents 865 hours of the burst-mode data organized into

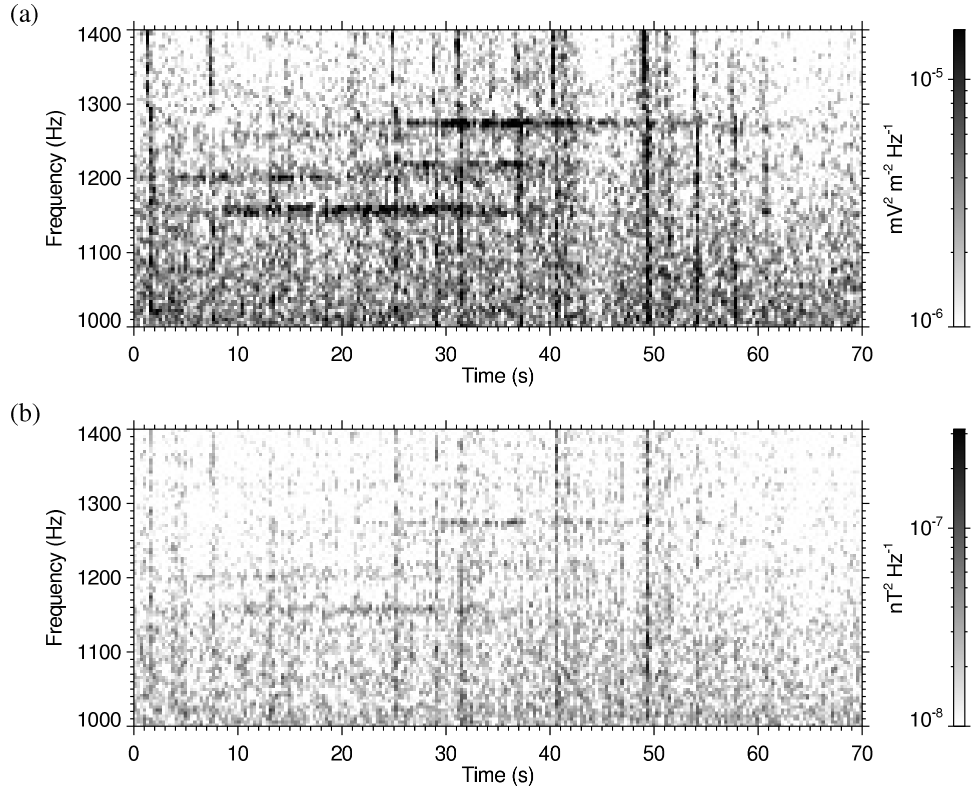

Figure 1. An example of (a) frequency-time spectrogram of the electric and (b) magnetic field fluctuations corresponding to one of the analyzed events. The data were recorded on 11 November 2004, after 1400:05 UT, when the spacecraft overflew Philippines; the frequency separation of the spectral lines is 60 Hz.

5920 half-orbits. In this data set, possible PLHR events have been identified in 317 half-orbits (about 5 percent).

[14] We have manually checked all these events for the presence of PLHR. The results revealed a large number of "false alarms." They were mostly caused by the presence of a sharp cutoff below the local proton cyclotron frequency [*Santolík and Parrot*, 1999], looking in some cases as intense spectral line on the frequency-time spectrograms. In the entire data set, we have found only 58 cases of PLHR-like events which can be divided into three classes: (1) 10 events where the frequency separation of spectral lines is equal to 50 or 100 Hz; (2) 13 events where the frequency separation of spectral lines is equal to 60 or 120 Hz; (3) 35 events which cannot be clearly classified as PLHR, where only one single spectral line was detected or, more often, where several lines were found with spacing which is neither 50/100 nor 60/120 Hz (MLR).

[15] The origin of this last class of events is not very clear. We believe that at least some of them can originate from plasma instabilities in the magnetosphere because they are mostly observed during large magnetic activities. However, a thorough discussion of these events will be the subject of another paper. In the following, we will focus on the analysis of PLHR events with 50/100 Hz and 60/120 Hz spacings.

[16] Recall that these 23 recorded events have been found by analyzing the power spectrograms of the electric field fluctuations. We have also checked the magnetic field data for these cases and found only six events (26%) where similar lines in the magnetic field spectrograms were simultaneously detectable at the same frequencies. These six events also have the largest amplitudes of the the electric field fluctuations among the 23 cases. The observed ratios of magnetic to electric power spectral densities correspond to the electron densities between 2×10^4 cm^{-3} and 3×10^5 cm^{-3}, supposing that the waves propagate in the right-hand polarized whistler mode along the magnetic field lines. This, in turn, roughly corresponds to usual values of the local electron density measured on board DEMETER. The magnetic field in the remaining 17 cases is too weak to be observable under the same hypothesis on the wave mode, given the measured intensities of the wave electric field. Consequently, all the recorded events are consistent with propagation of PLHR in the right-hand polarized electromagnetic whistler mode.

[17] Figure 1 shows an example of an event from the group of the six most intense cases. It is represented in the form of the frequency-time power spectrograms of the electric and magnetic field fluctuations. The data were recorded on 11 November 2004 between 1400:06 UT and 1401:16 UT above Philippines where a 60-Hz electrical network is used. A magnetically conjugated region is located in Taiwan where a 60-Hz network is also used. Since the magnetic field data contain spacecraft interference signals which could be confused with PLHR, we have used a tool for DEMETER data analysis allowing us to suppress a part of these interferences [*Santolík et al.*, 2006]. Three lines at frequencies of 1160, 1220, and 1280 Hz can be

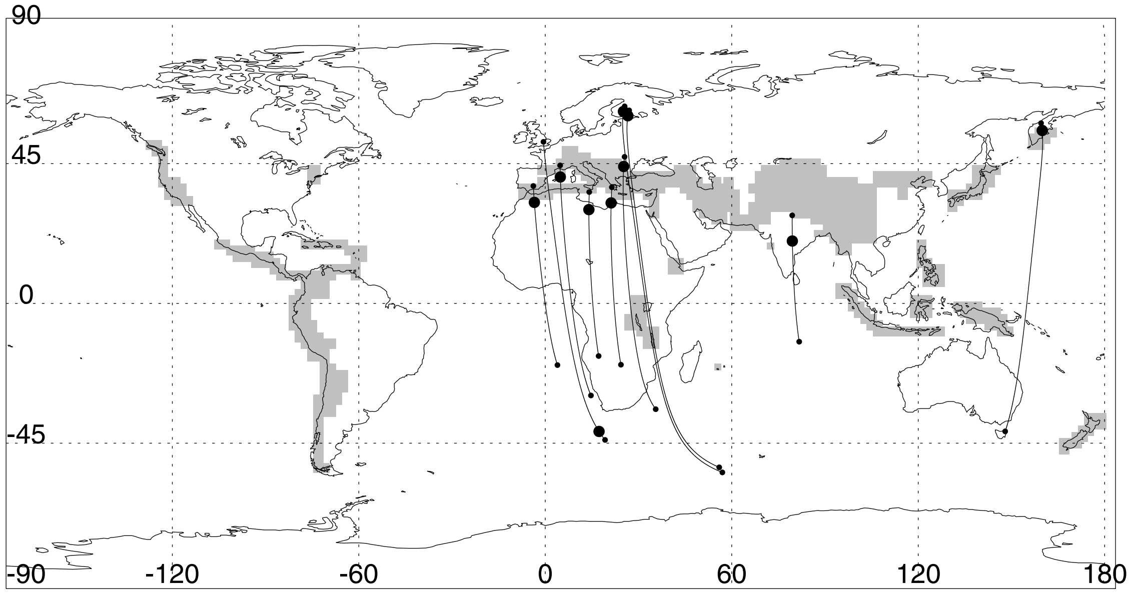

Figure 2. Geographic locations of observed PLHR with mutual distance of lines 50/100 Hz (large points). Magnetic field lines and footprints of the points of observations (thin lines and small points). Seismic zones with permanently active burst-mode coverage are shown by gray shading; the operational-phase burst-mode regions (approximately 20% of the burst-mode data volume) are not shown since their positions vary during the time interval analyzed in this study.

identified in both spectrograms, the magnetic signature being much weaker. During the first half of the time interval in which the event is detected, we can also recognize lines at 1200 and 1260 Hz which are, unlike the previous three frequencies, exact multiples of the fundamental frequency of 60 Hz.

[18] Figures 2 and 3 show locations of PLHR events in geographic coordinates (large points on the world maps) for the frequency separations of 50/100 and 60/120 Hz, respectively. For each of these events, the following properties have been determined: spacecraft position in the time of observation, duration of the event, magnetic local time, Kp index, and the list of identified lines, which means their frequency and maximum intensity of the electric field fluctuations. We have also used the IGRF-10 model of the Earth's magnetic field implemented in the GEOPACK-2005 program (N. A. Tsyganenko, http://nssdcftp.gsfc.nasa.gov/models/magnetospheric/tsyganenko/) to calculate the magnetic footprints of the point of observation by tracing the magnetic field lines. The footprints are shown by small points on the world maps and the projections of the corresponding magnetic field lines on the Earth's surface

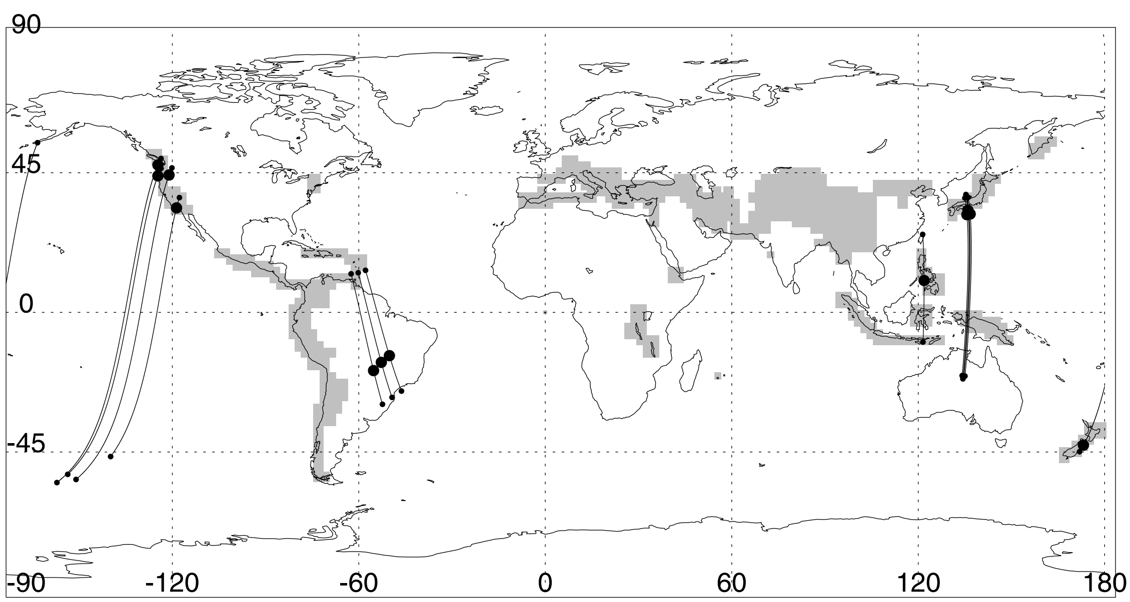

Figure 3. The same as in Figure 2 but for PLHR with mutual distance of lines 60/120 Hz.

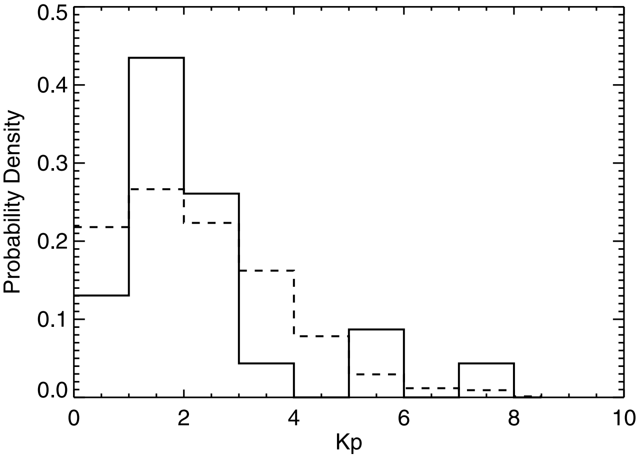

Figure 4. Histogram of Kp indices at the time of the PLHR events (solid line). Overplotted is a histogram of all Kp indices that occurred during the analyzed year (dashed line).

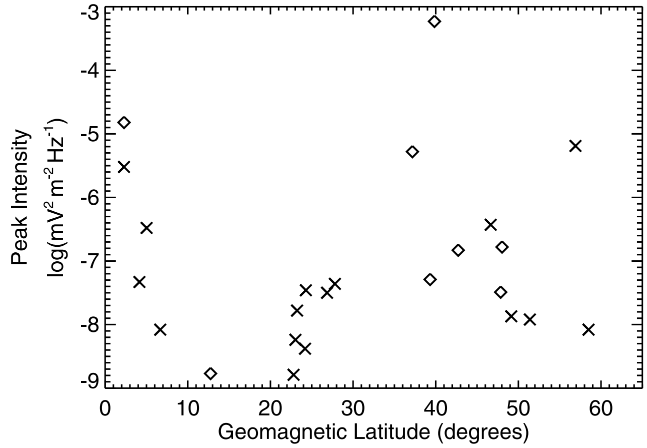

Figure 6. Peak intensity of observed PLHR events as a function of geomagnetic latitude. The symbols are the same as in Figure 5.

are shown by thin lines. This indicates possible source regions, supposing the propagation in the ducted mode.

[19] Note that the observed frequency separations of lines correspond very well to the frequencies of electric power systems in the possible geographic regions of generation. Separations of 50/100 Hz are mostly observed above Europe and Northern Africa (with a probable source region, a footprint of magnetic field line, lying in Europe for all these cases). One event is observed above India and one above northeastern Asia with a magnetic conjugate point in Australia. Separations of 60/120 Hz are observed mostly above the USA, Brazil, and Japan. One such event has been detected above Philippines and one above New Zealand. This is rather surprising because New Zealand has a power system with a frequency of 50 Hz, but we have to notice that the magnetic conjugate point is in Alaska where the power-system frequency is 60 Hz.

[20] Histogram of Kp indices at the time of PLHR events is shown in Figure 4 by a solid line. A histogram of all the Kp indices that occurred during the analyzed year (July 2004 to July 2005) is overplotted by a dashed line for comparison. It can be seen that the PLHR events occur during both low and high geomagnetic activity, with no significant preference for quiet or disturbed periods.

[21] All the PLHR events have occurred at frequencies higher than 1 kHz, not allowing us to analyze the wave propagation using six components of the electromagnetic field. These methods [*Santolík et al.*, 2006] can be only used in the ELF range below 1 kHz. Most of the cases have been observed at frequencies around 2 kHz, with the number of observations slowly decreasing towards higher frequencies. In 15 out of 23 cases (65%), the frequencies of observed PLHR lines have corresponded well (within the experimental error) to the exact multiples of power system frequency. The absolute position of spectral lines in the frequency spectrum of the remaining eight cases appeared to be random, with no connection to the observed line spacings. The frequency drift of all the cases was very slow, not observable within the experimental errors.

[22] Figures 5, 6, and 7 show the peak intensities of observed PLHR events as a function of the Kp index, geomagnetic latitude, and magnetic local time, respectively. For each event, the peak intensity is defined as the intensity of the most intense line. The events with frequencies corresponding to the multiples of the power system frequency are plotted as crosses, the events with frequencies not corresponding to these multiples are plotted as diamonds. Figure 5 shows that the peak intensity of PLHR increases with the Kp index. The peak intensity of PLHR seems to be independent of magnetic latitude (Figure 6). Finally, the peak intensity is higher during the night than during the day (Figure 7). Note that the bunching of observed events in two MLT intervals is connected to the nearly Sun-synchronous orbit of the DEMETER spacecraft. The MLT is thus either just before noon or just before midnight. However, approximately 1 year of data has been analyzed and therefore the distribution of sampled geo-

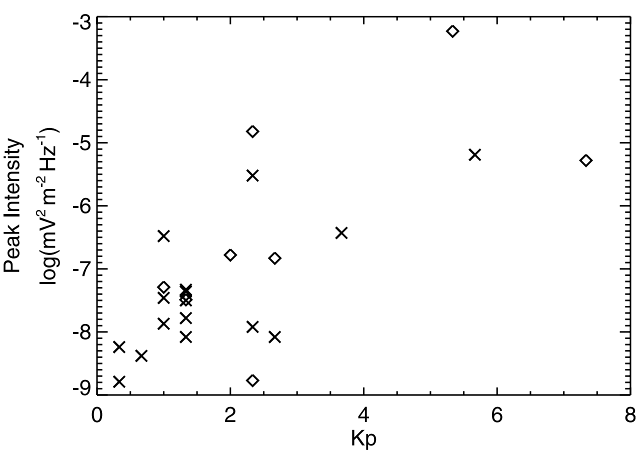

Figure 5. Peak intensity of observed PLHR events as a function of the Kp index. The events, whose frequencies correspond to the multiples of the power system frequency, are plotted as crosses. The events with frequencies not corresponding to the multiples of the power system frequency are plotted as diamonds. The time interval from Figure 1 corresponds to two events, since it successively contains both types of PLHR.

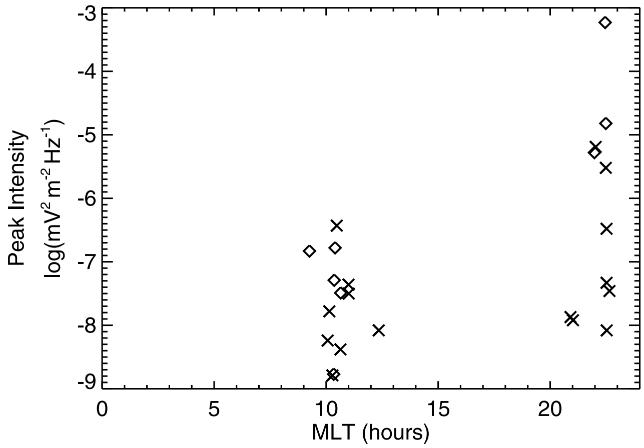

Figure 7. Peak intensity of observed PLHR events as a function of magnetic local time. The symbols are the same as in Figure 5.

graphical longitudes should be almost uniform all over the Earth for both MLT intervals. No clear dependence on whether the frequencies correspond to the multiples of power system frequency or not (crosses versus diamonds) has been observed.

5. Discussion

[23] The most problematic element in the presented study is the procedure for automatic identification of PLHR events (section 3). This procedure was needed in order to analyze a large amount of available data. However, it is very difficult to estimate the consequences of this step. There is no exact way to determine the total number of PLHR events contained in the data set. Although the parameters of the detection procedure have been set to ensure a 100% detection of the small set of the test PLHR data, there is no guarantee that we have not missed an unknown fraction of PLHR events in 865 hours of analyzed data. Another consequence could be a possible presence of a "selection effect." That is, the detected events do not necessarily represent a "randomly chosen" subset from the total set of PLHR events contained in the data, but events with some specific signatures could be detected with a higher probability. Although we cannot exclude the presence of this effect, we have no indication that it significantly biases our results.

[24] In spite of these technical difficulties, the striking result of our study is that the occurrence frequency of PLHR events in the topside ionosphere is probably very low. Supposing the 100% detection probability of our procedure, a low orbiting spacecraft would on average detect one PLHR event per 38 hours of observations. If we miss a fraction of events the occurrence frequency would be correspondingly higher but, most probably, the results would not be significantly different.

[25] Concerning the geographical coverage of our study, recall that we have used the data obtained during the burst mode of the DEMETER spacecraft. This mode is activated regularly above the seismic zones but from time to time burst mode zones have been added in different parts of the Earth. This selection can potentially bias the analysis. The consequences for the maps of geographic locations of observed PLHR (Figures 2 and 3) are evident. Moreover, results obtained at different latitudes in Figure 6 are in fact also obtained at different longitudes. However, this probably does not strongly affect our results.

[26] Previous investigations of PLHR events have shown contradictions concerning the level of magnetic activity which is the most favorable for observations. Figure 4 shows that the PLHR events occur without any significant preference for a level of geomagnetic activity, although the number of events is not high enough to allow us to make a clear conclusion.

[27] The observed frequency spacing of all the PLHR events corresponds well to power system frequencies in possible geographical regions of generation (Figures 2 and 3). This represents a good evidence for a hypothesis that PLHR events are really caused by an electromagnetic radiation from the ground power systems. Moreover, in 15 out of the 23 cases the frequencies of the observed PLHR lines corresponded (within the experimental error) to the exact multiples of the power system frequency. This is in contradiction with previous reports [e.g., *Rodger et al.*, 1995]. However, these results were derived for MLR, while our results have been obtained for PLHR (with frequency spacing strictly 50/100 or 60/120 Hz) without any significant frequency drift. This probably shows the crucial difference between PLHR and MLR: while there is a strong evidence that PLHR events are caused by radiation from electric networks, there is no such an evidence for MLR. The question whether MLR can be created in a completely natural way or whether some PLHR-like emissions are necessary as triggers, is a matter of debate and is beyond the scope of this paper. However, it becomes clear that PLHR and MLR have to be considered separately as two different phenomena.

[28] The peak intensity of observed PLHR events does not seem to vary with the geomagnetic latitude (Figure 6), although the intensity of natural emissions is higher in subauroral areas than close to the magnetic equator [*Parrot*, 1990]. However, it increases with Kp index and it is also higher during the night (Figures 5 and 7). In this case, the peak intensity behaves in the same way as the intensity of natural emissions. There are two possible explanations of these observations. (1) The PLHR events with a low intensity compared to the natural background could be simply too weak to be observed. The average peak intensity of observed events would than necessarily be higher in places with higher intensity of natural background. (2) The electromagnetic emissions radiated by a power system could be modulated by the plasma environment in such a way that their intensity would become higher at places with more intense natural background. This second possibility seems to be more likely true. The first mechanism would, for example, just eliminate the less intense events for high geomagnetic activity when the natural background becomes stronger. In that case, however, we would observe both less intense and more intense cases at geomagnetically quiet times. This does not seem to be the case: Figure 5 indicates that only the less intense cases are observed at quiet times.

[29] The intensity of PLHR events is thus partially connected to the intensity of natural background. This

shows that although the origin of PLHR is tied to the radiation from electric power systems, some processes changing its intensity according to the level of the natural background are taking place. Moreover, these processes must have such a behavior that in many cases the frequencies of observed PLHR lines correspond to the multiples of the fundamental power system frequency.

[30] Finally, one should keep in mind that the efficiency of coupling through the ionosphere for ground transmitters depends on many parameters and could possibly explain some of the observed variations. For example, the coupling is easier on the nightside than on the dayside ([*Green et al.*, 2005]).

6. Conclusions

[31] We have presented results of an initial survey of observations of PLHR by the DEMETER spacecraft. The data were collected during the first year of its operation and an automatic procedure has been used to detect the PLHR events. Altogether, 23 PLHR events (10 with 50/100 Hz spacing and 13 with 60/120 Hz spacing) have been found in the entire set of 865 hours of available high-resolution data. Our results show the following.

[32] 1. PLHR events occur during both low and high magnetic activity. No level of activity seems to be significantly preferred.

[33] 2. The observed frequency spacings of all the PLHR events correspond well to power system frequencies in possible geographical regions of generation.

[34] 3. The frequencies of observed PLHR lines correspond to the multiples of power system frequency in 65% of cases.

[35] 4. The peak intensity of observed PLHR events increases with Kp index and it is higher during the night. The peak intensity thus seems to be partially connected to the intensity of the natural background emissions. It suggests that electromagnetic emissions radiated by a power system are modulated by the plasma environment. However, the day/night asymmetry of coupling of electromagnetic waves from the ground to the ionosphere might also play a role.

[36] 5. In 26% of most intense cases we also observe the magnetic field component of PLHR. These observations are consistent with propagation in the electromagnetic right-hand polarized whistler mode.

[37] **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. Němec thanks the French embassy in Prague for his support during his stay in Orléans. O. Santolík and F. Němec acknowledge additional support from the ESA PECS contract 98025 and from the GACR grant 205/06/1267.

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