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Influence of power line harmonic radiation on the VLF wave activity in the upper ionosphere: Is it capable to trigger new emissions?

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[1] We analyze the influence of Power Line Harmonic Radiation (PLHR) events on the overall VLF wave activity as observed by the low-altitude (about 700 km) DEMETER spacecraft. We take advantage of a unique set of 148 PLHR events identified in the Burst mode data, where a waveform of one electric and one magnetic field component is measured. It is shown that the occurrence rate of PLHR events over the industrialized areas is quite large (more than about 8%). However, among all the identified events, we have found only two cases of possibly PLHR-triggered emissions. There is no evidence that the total power spectral density of electromagnetic waves over industrialized regions and geomagnetically conjugate regions is larger than what would be expected without man-made influence. Finally, we have analyzed the presence of the weekend effect (i.e., a different behavior during the weekends as compared to the weekdays due to the lower power consumption), demonstrating that no such phenomenon seems to be present in the analyzed data set.

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1. Introduction

[2] Electromagnetic waves radiated by electric power systems on the ground can propagate up to the upper ionosphere (and sometimes even along the Earth's magnetic field lines to the geomagnetically conjugate regions), where they are detected by low-altitude satellites [*Bell et al.*, 1982; *Tomizawa and Yoshino*, 1985; *Rodger et al.*, 1995; *Parrot et al.*, 2005; *Němec et al.*, 2006, 2007b, 2008]. Such events are usually called Power Line Harmonic Radiation (PLHR), and in a traditional representation of frequency-time spectrograms with color-coded intensity, they have a form of several horizontal lines occurring at constant frequencies. These lines are separated in frequency by 50/100 Hz or 60/120 Hz, depending on the base frequency of the generating electric power system [*Němec et al.*, 2006, 2007b]. PLHR events are typically observed by the low-altitude DEMETER satellite during a few tens of seconds along its orbit, corresponding to the spatial dimensions of a few hundreds of kilometers [*Němec et al.*, 2008].

[3] As well as PLHR events, there are other emissions that exhibit a line structure, but their frequency spacing does not correspond to the base frequency of the electric power systems [*Rodger et al.*, 1995]. These are typically called Magnetospheric Line Radiation (MLR), and their properties are significantly different from PLHR [*Němec et al.*, 2007a]. Most important, they are more intense than usually quite weak PLHR events, and, moreover, the frequency bandwidth of individual lines forming the events is larger (i.e., the lines forming MLR events are thicker). Finally, while the lines forming PLHR events are strictly horizontal (i.e., appearing at constant frequencies) and clearly separated always by the same frequency interval, the lines forming MLR events are significantly less organized and they can slightly drift in frequency. A typical time duration of MLR events determined from ground-based observations is about 30 min [*Rodger et al.*, 2000a], with some of them lasting as long as 2 hr [*Parrot et al.*, 2007]. *Helliwell et al.* [1975] suggested the possibility that MLR originates as PLHR. This possibility was further discussed by *Bullough* [1995] and investigated by *Nunn et al.* [1999] using numerical simulations. *Němec et al.* [2009] presented an event consisting of PLHR and MLR located in conjugate regions. They suggested that this could be an observation of MLR triggered by PLHR. A variety of line radiation events and associated wave phenomena observed by a low-altitude satellite was described by *Parrot and Němec* [2009].

[4] *Park and Miller* [1979] reported an existence of "Sunday effect"; they claimed that the magnetospheric wave intensity in the 2 to 4 kHz frequency range monitored at Siple, Antarctica, shows a distinct minimum on Sunday. They attributed this effect to the lower power consumption on Sundays as compared to the other days of week. *Parrot et al.* [1991] analyzed data from the AUREOL-3 satellite and showed that the electric field component parallel to the Earth's magnetic field has a modulation depending on the

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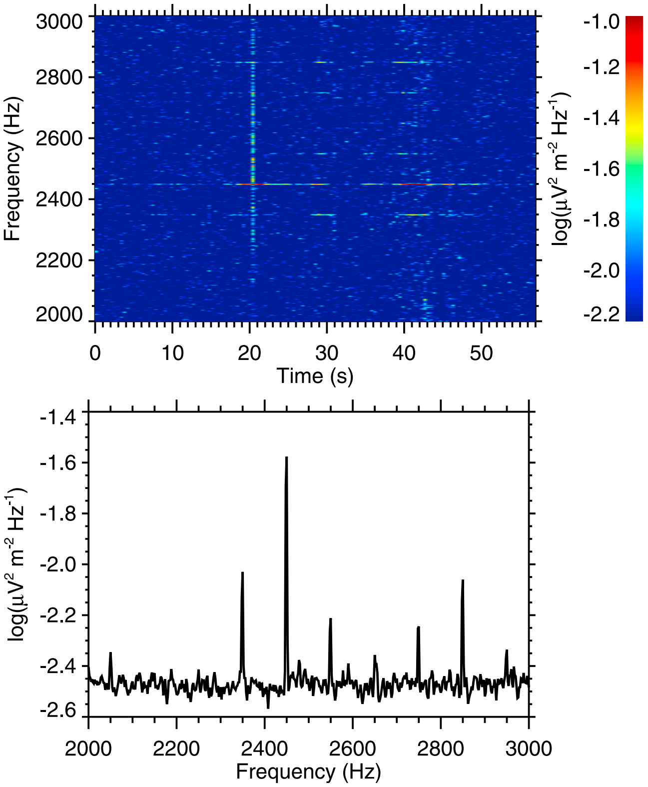

Figure 1. (Top) An example of a frequency-time spectrogram of power spectral density of electric field fluctuations corresponding to one of the identified PLHR events. The data were recorded on 3 November 2009 after 1001:33 UT when the satellite was passing over central Europe. (Bottom) Corresponding power spectrum. Several peaks, located at 2350 Hz, 2450 Hz, 2550 Hz, 2650 Hz, 2750 Hz, and 2850 Hz (and corresponding thus to the frequency spacing 100 Hz), can be clearly distinguished.

days of the week. *Molchanov et al.* [1991] attributed this effect not only to the lower power consumption during weekends but also to a different current distribution in the power systems as compared to weekdays. *Rodger et al.* [2000b] examined 4 months of ground-based measurements made at Halley, Antarctica. They showed that there is no evidence of a Sunday effect in the occurrence of MLR events or in the overall VLF wave intensity. *Karinen et al.* [2002] showed that there is no statistically significant "weekend effect" in global geomagnetic activity expressed by the A_p index, although *Fraser-Smith* [1979] reported the contrary when analyzing an older data set.

[5] In this paper, we report an analysis based on 148 PLHR events observed by the low-altitude DEMETER satellite. We discuss the occurrence rate of these events, their capability to trigger new (MLR-like) emissions, and their importance for the overall intensity of electromagnetic waves observed by a low-altitude satellite. Finally, we check for the presence of the weekend effect. The DEMETER satellite is described in section 2. A set of the identified PLHR events is presented in section 3. Section 4 reports on a search for emissions triggered by PLHR events, while a check for the presence of weekend effect is presented in section 5. Obtained results are discussed in sections 6 and 7, which summarize the most important results that we have obtained.

2. DEMETER Satellite

[6] In the present study, we have used data from the French microsatellite DEMETER. It was launched in June 2004 on a nearly circular polar orbit and it is still operational. Owing to the specific parameters of the orbit, the satellite is always located either in the local day (about 1030 LT) or in the local night (about 2230 LT). The original altitude of the satellite was about 710 km, but it was slightly decreased to about 660 km in December 2005. The wave instruments placed on board perform both electric [*Berthelier et al.*, 2006] and magnetic [*Parrot et al.*, 2006] field measurements all over the satellite orbit except for the regions with geomagnetic latitudes larger than 65 degrees.

[7] Owing to a limited capacity of the telemetry, it is not possible to transfer all measured data, and two scientific modes of operation have been thus introduced. During the Burst mode, which is active only above some specific areas of interest, more accurate (and consequently more voluminous) data are acquired. In contrast, the Survey mode of the satellite is active at all other times, but provides only lower-resolution data. In the VLF range (up to 20 kHz) that we are interested in, the waveform of one electric and one magnetic field component is available in the Burst mode (sampling frequency 40 kHz). During the Survey mode, the power spectrum of one electric and one magnetic field component is calculated on board with a predefined frequency resolution 19.53 Hz and with the time resolution either 0.512 s or 2.048 s, depending on the submode of the instrument.

[8] We have used the data measured both during the Burst and Survey mode, using the Burst mode whenever possible because the frequency resolution is of great importance for our purposes. Only the electric field data have been used, because in the frequency range of interest DEMETER magnetic field data usually contain a large amount of interference, being less suitable for the analysis [*Němec et al.*, 2006].

3. Data Set

[9] An automatic procedure for identification of the PLHR events in the electric field Burst mode data based on a search for a single nearly horizontal line lasting more than 5 s in the frequency time spectrogram and subsequent manual elimination of "false alarms" was developed by *Němec et al.* [2006] and further used by *Němec et al.* [2007a, 2007b, 2008]. The same procedure is used in the present paper as well. Its application to all the data measured up to the beginning of November 2009 results in 148 positively identified and visually confirmed PLHR events. All these events were included in the study.

[10] An example of one of the identified PLHR events is shown in Figure 1. The data were recorded on 3 November 2009 after 1001:33 UT when the satellite was passing over central Europe. The top of Figure 1 represents the frequency-time spectrogram of the power spectral density of electric field fluctuations. A few rather weak horizontal lines forming the event can be seen. The event is much clearer in the bottom of Figure 1, which shows the corresponding power

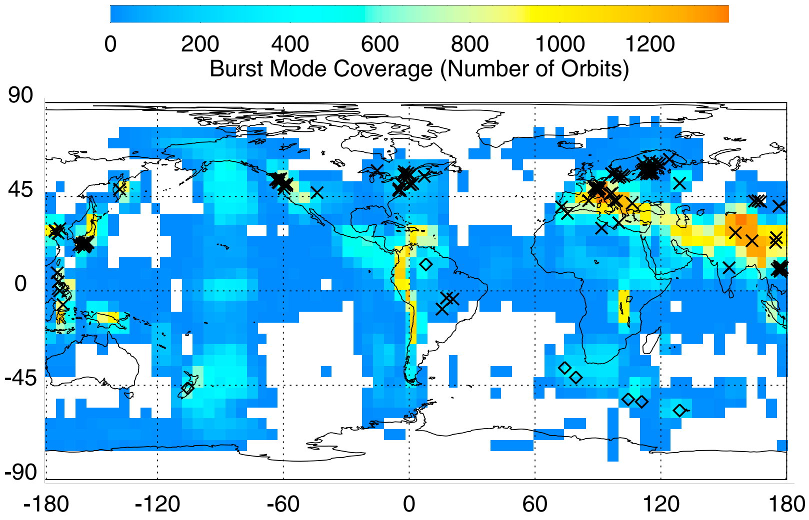

Figure 2. Map in geomagnetic coordinates showing the positions of the identified PLHR events. The events generated just below the point of observation are shown by crosses. The events probably generated in the conjugate region are shown by diamonds. Color-coded is the number of satellite orbits with the Burst mode active above the appropriate latitude-longitude bin.

spectrum. Several peaks located at frequencies 2350 Hz, 2450 Hz, 2550 Hz, 2650 Hz, 2750 Hz, and 2850 Hz are well observable. The frequency separation between the individual peaks (or between the lines in the top, respectively) is thus 100 Hz. This corresponds to the base frequency of the electric power system in the generation region (50 Hz), as already noted in the systematic studies by *Němec et al.* [2006, 2007b].

[11] The positions of the identified PLHR events are shown in Figure 2. Geomagnetic coordinates have been used instead of geographical ones, because they enable an easy check for geomagnetically conjugate regions; these are located at the same values of geomagnetic longitudes and at opposite values of geomagnetic latitudes. Since PLHR events can be identified only in the Burst mode data, knowledge of Burst mode distribution is crucial to make any conclusions concerning their occurrence. Color-coded in the same figure is thus a distribution of the Burst mode coverage expressed in the number of DEMETER orbits with the Burst mode active above a given latitude-longitude bin. Taking into account this distribution, it can be seen that the areas where PLHR are usually observed correspond to the industrialized regions (Europe, coastal parts of the USA, and Japan). Moreover (not shown), the frequency spacing of the individual lines forming the events corresponds to the base frequency of electric power systems in probable generation regions [*Němec et al.*, 2006, 2007b].

[12] This enables an easy check whether the observed PLHR event was generated just below the point of observation or in the conjugate region. It turns out that of the 148 identified PLHR events, only 7 were probably generated in the conjugate region and had thus to propagate to the opposite hemisphere before being detected. These events are distinguished in Figure 2 by using diamond symbols instead of cross symbols to mark their position. Five of these events have 50 Hz spacing and are located to the south of Africa, in the region geomagnetically conjugated to Europe. Although there are some minor electric power systems located at islands in this area (e.g., French Kerguelen Islands with a permanent presence of 50 to 100 scientists), the more suitable explanation seems to be that these events were generated in Europe and they propagated up to point of observation roughly along the magnetic field lines. The sixth PLHR event which is probably generated in the geomagnetically conjugated point is the event observed above New Zealand. The reason is that although the base frequency of the electric power system in New Zealand is 50 Hz, the frequency spacing of the event is 60 Hz, corresponding better to the geomagnetically conjugated Alaska region. The last event possibly generated in the region geomagnetically conjugated to the place of observation is the event with 60 Hz spacing observed in the northern part of South America. However, since the electric power systems both in the region of observation and in the geomagnetically conjugated region operate at 60 Hz, we cannot determine the generation region in this particular case.

[13] To estimate the occurrence rate of PLHR events over the regions where the total number of observed events is particularly large, we selected four geographical regions: Finland region (geomagnetic longitude 111°–120°, geomagnetic latitude 55°–62°), Japan region (geomagnetic longitude 202°–207°, geomagnetic latitude 20°–24°), Northwest USA region (geomagnetic longitude 296°–302°, geomagnetic latitude 48°–54°) and Northeast USA region (geomagnetic longitude 356°–2°, geomagnetic latitude 50°–57°). It is then possible to check out that the Finland region contains 24 PLHR events, while there were 305 DEMETER orbits passing over the region with active Burst mode. This means that a PLHR event was detected in about 8% of orbits passing over the region. Since PLHR events do not necessarily last over all the selected region, it is useful to define the occurrence rate of PLHR events as a ratio of the total time duration of PLHR events above the selected region and the total time duration of DEMETER Burst mode measurements above the selected region. It is found that the occurrence rate of PLHR events above the Finland region is about 6%. Similarly, we can calculate the percentage of

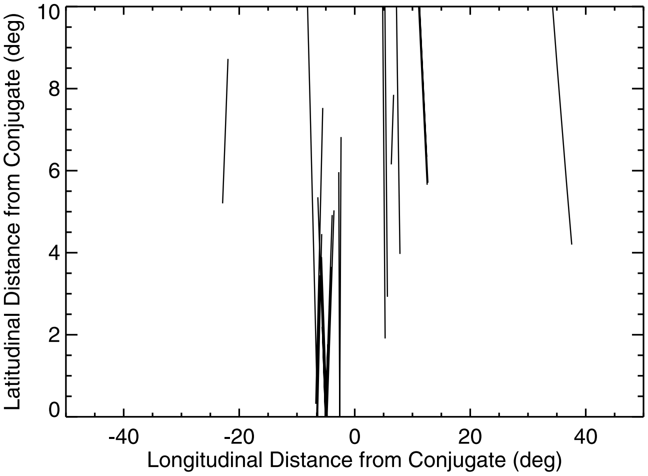

Figure 3. Parts of the DEMETER orbits with the Burst-mode active passing close to the points geomagnetically conjugate to the PLHR events.

orbits containing a PLHR event and the occurrence rate of PLHR events over the remaining regions: There were 19 PLHR events identified over the Japan region in 457 orbits with Burst mode (occurrence rate of PLHR events 3%), 15 PLHR events identified over the Northwest USA region in 584 orbits with Burst mode (occurrence rate of PLHR events 2%), and 12 PLHR events identified over the Northeast USA region in 376 orbits with Burst mode (occurrence rate of PLHR events 3%).

[14] It should be noted that the obtained values are most likely lower estimates of occurrence rate of PLHR events, because the efficiency of the applied automatic identification procedure is expected to be lower than 100%. Moreover, it is rather tricky to compare the occurrence rate of PLHR events above these regions, because they are located at different geomagnetic latitudes (which affects the penetration characteristics of the ionosphere; see, e.g., *Němec et al.* [2008]) and, more important, the background wave intensity in these regions is quite different owing to the effects of position-dependent lightning activity. Consequently, we roughly estimate the occurrence rate of PLHR events above industrialized regions to be about 5%. During the remaining time, PLHR events are too weak as compared to “natural” waves observed.

4. Emissions Triggered by PLHR

[15] Having shown that the occurrence rate of PLHR events is reasonably large, a natural question arises how significant these events can be for the overall wave intensity observed by a low-altitude spacecraft. Since PLHR emissions on their own are rather weak and occur only in narrow frequency bands centered at the appropriate harmonics [*Němec et al.*, 2008], their direct influence is probably negligible. However, they might be able to trigger new, more intense electromagnetic emissions, which would significantly increase their importance. An event which most probably represents an example of such a situation has been reported by *Němec et al.* [2009]. In the following, we systematically search for the presence of this phenomenon to determine the probability of its occurrence.

[16] Taking into account that PLHR events propagate along magnetic field lines to the opposite hemisphere and that the preferred region for wave-particle interactions is the geomagnetic equator [*Trakhtengerts and Rycroft*, 2008], a natural place to look for potentially triggered emissions is the regions geomagnetically conjugate to the points of observation of PLHR events. For each of the identified PLHR events, we have determined the position of the geomagnetically conjugate point. Afterward, we have verified the presence of PLHR, PLHR-triggered or other PLHR-related emissions close to these points. Because DEMETER does not orbit exactly along magnetic field lines, it usually encounters the geomagnetically conjugate latitudes at slightly shifted geomagnetic longitudes. Consequently, it is not possible to check for the triggered emissions directly at the points geomagnetically conjugate to PLHR events, but rather in their vicinity. As demonstrated by the event presented by *Němec et al.* [2009], triggered emissions can probably be separated quite significantly in geomagnetic longitude from the originating PLHR event (about 50 degrees), but they occur at nearly the same L-value. We have thus concentrated on the data intervals with geomagnetic latitudes corresponding exactly (as far as possible) to the desired regions, not taking into account the longitudinal distance, which is consequently determined purely by the satellite orbit. Finally, only the PLHR events located at geomagnetic latitudes larger than 10 degrees were considered; for the events located too close to the geomagnetic equator, it is not possible to distinguish between originating and conjugate regions and, moreover, the corresponding L-values are so low that no wave-particle interactions are expected. For each of these events, we have verified the interval ±10° of geomagnetic latitude from the point geomagnetically conjugate to the point of observation of the PLHR event. Altogether, this corresponds to 137 analyzed data intervals.

[17] Although all the identified PLHR events were observed during the active Burst mode, this does not ensure that the Burst mode is active also close to the geomagnetically conjugate point. In fact, such a situation is rather rare, taking place only in 17 of the 137 events. DEMETER orbits passing close to the points geomagnetically conjugated to PLHR events with the Burst mode active are plotted in Figure 3. Please note that the scale of the axes is quite different: while all the Burst mode data intervals get very close to the geomagnetically conjugate points as far as geomagnetic latitude is concerned (all of them within 7 degrees), their longitudinal separation can be rather large (up to nearly 40 degrees). We have carefully checked all the 17 data intervals for the presence of triggered emissions, but the result was negative in all the cases. Not only have we not observed any new, stronger, emission, but we have not observed even the originating PLHR events.

[18] For the events for which the Burst mode was not available close to the conjugate region, principally the same procedure has been done using the Survey mode. We take advantage of the fact that although the identification of PLHR events in the Survey mode data is usually quite difficult owing to their low intensity and frequency bandwidth of individual lines forming the events, expected triggered emissions should be more intense and thus visible even in

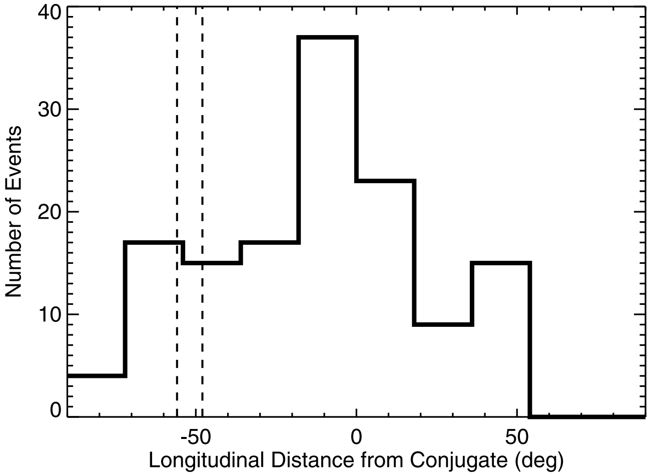

Figure 4. (Thick solid line) Histogram of the longitudinal distances of the satellite passes from the points geomagnetically conjugate to the PLHR events. (Thin dashed vertical lines) Geomagnetic distances of the satellite passes from the points geomagnetically conjugate to the PLHR events for the two events where possibly triggered emissions were observed.

the Survey mode data. A histogram of the longitudinal distances of the satellite passes from the points geomagnetically conjugate to the PLHR events is shown in Figure 4. We decided to use this kind of representation instead of the one used in Figure 3 because of the larger number of events included and because of the continuous coverage of Survey mode data, which results in the minimal latitudinal distance between the satellite pass and the point geomagnetically conjugate to the PLHR event being equal to zero.

[19] Among all the 137 data intervals close to the points geomagnetically conjugate to the PLHR events, unexpected and possibly PLHR-triggered emissions have been found only in two of them. Their longitudinal distances from the corresponding PLHR events are marked in Figure 4 by vertical dashed lines. The first event, measured on 13 April 2007 between 0759:30 UT and 0838:00 UT, was already reported by *Němec et al.* [2009]. It was observed above the South Atlantic Ocean at geographic coordinates about 53°S 14°E. The corresponding possibly triggering PLHR event was located above Russia at geographic coordinates about 57°N 45°E. The second event was observed on 23 December 2007 between 1016:00 UT and 1054:30 UT. It was located also above the South Atlantic Ocean, this time at geographic coordinates about 55°S 22°W. The corresponding possibly triggering PLHR event was located above western Europe at geographic coordinates about 47°N 6°E. The frequency range of both these events is similar to the frequency range of possibly triggering PLHR events. Moreover, they exhibit a line structure and their characteristics correspond to MLR events.

[20] To verify the possibility that PLHR-triggered emissions could play an important role in the overall intensity of electromagnetic waves, we checked the median value of power spectral density of electric field fluctuations calculated using about 3.5 yr of Survey-mode data (all the data measured at the new satellite altitude 660 km up to the end of August 2009) as a function of the position in geomagnetic coordinates. The results obtained for an example region of the geomagnetic longitudes of the USA are plotted in Figure 5. They were obtained for the frequency range between 2 and 3 kHz, which are the typical frequencies of PLHR events [*Němec et al.*, 2007a], separately for the daytime data (left) and nighttime (right). Finally, only the data measured during November–April (i.e., the "northern winter period") were

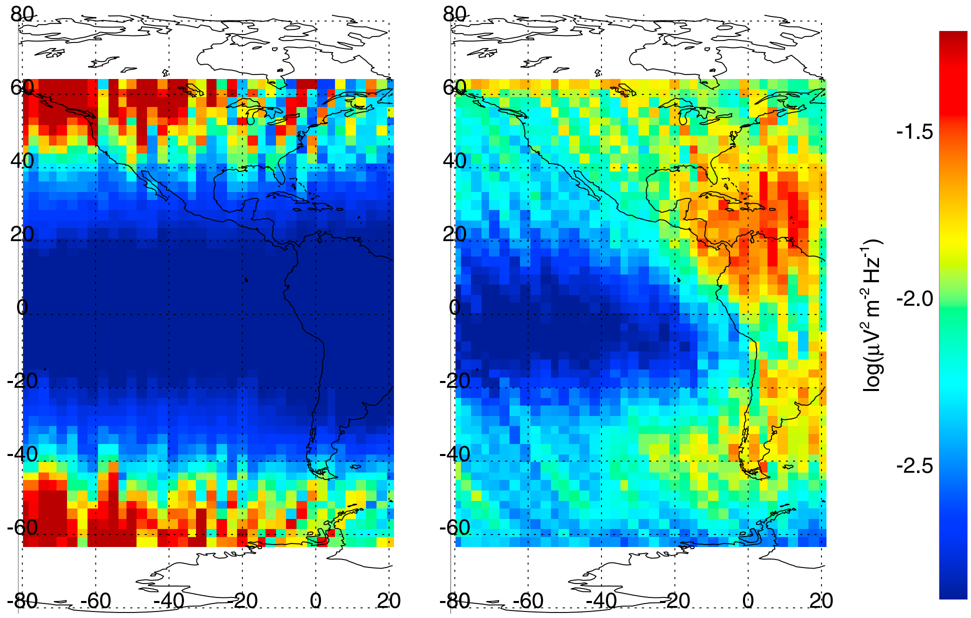

Figure 5. Map in geomagnetic coordinates of median power spectral density of electric field fluctuations at geomagnetic longitudes of the USA. Only the data measured during November–April ("northern winter period") were taken into account. (Left) Daytime data. (Right) Nighttime data.

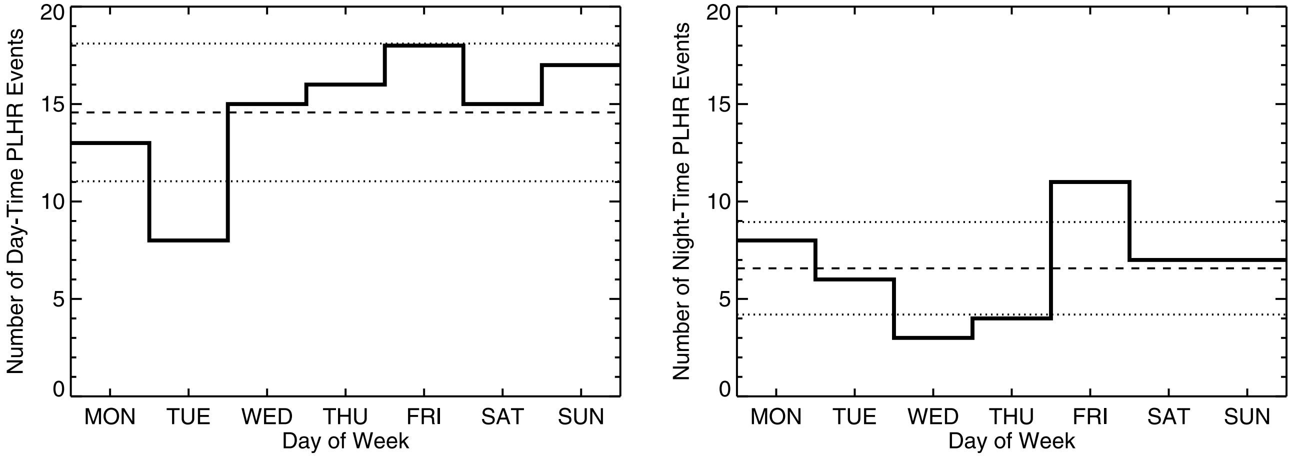

Figure 6. Number of the identified PLHR events as a function of the day of the week (thick). Mean value and standard deviation (horizontal lines). (Left) Daytime data. (Right) Nighttime data.

used, because the lightning activity that can significantly affect the observed wave intensity is weaker during this period [*Christian et al.*, 2003]. If PLHR events did play a significant role in the overall intensity of electromagnetic waves, it is likely that there should be areas of enhanced wave intensity located above heavily industrialized parts of the USA and the geomagnetically conjugate regions. This does not seem to be the case; the only area of increased wave intensity that can be identified is the area to the north of South America, centered at about 0° of geomagnetic longitude and 20° of geomagnetic latitude. However, this area is not related to the PLHR events, but rather to the increased lightning activity in the region observed even during the northern winter period [*Christian et al.*, 2003]. We have also tried to separate the data according to the level of geomagnetic activity expressed by the Kp index and perform the same visual check for other heavily industrialized areas all over the world, as well as for various frequency ranges. However, we have obtained always the same negative result.

5. Search for the Weekend Effect

[21] A week period, not normally present in nature, represents a unique check for the influence of manmade activity. We have checked the presence of the week period in the occurrence rate of the PLHR events from our data set. The obtained results are shown in Figure 6 separately for the daytime (left) and the nighttime (right). The thick line represents the number of identified PLHR events as a function of the day of the week. Horizontal dashed line shows the mean value. The appropriate standard deviations are marked by horizontal dotted lines. It can be seen that although the number of PLHR events slightly varies from day to day, these differences are not very significant as compared to the standard deviation. Finally, larger number of PLHR events observed during the day than during the night is most probably due to electric power systems being more loaded during the day, as already reported and discussed by *Němec et al.* [2008].

[22] We performed the same check of the week period also for the observed power spectral density of electric field fluctuations. The data were separated according to the level of geomagnetic activity expressed by the Kp index, and various frequency bands and different locations all over the world were examined. However, no conclusive 1 week period has been found.

6. Discussion

[23] A crucial starting point for all the performed analysis is the list of PLHR events found by an automatic procedure in the Burst mode electric field data. A detailed description of the procedure as well as a discussion of potential problems involved can be found in *Němec et al.* [2006]. For our purposes, the most important consequence is to understand that although we do not have any means of how to determine the efficiency of the procedure, it is most likely not 100%. Consequently, the obtained rate of occurrence of PLHR events above specifically selected regions in Figure 2, which is about 8%, represents only a lower estimate of the real occurrence rate. The occurrence rate of PLHR events therefore is, at least above heavily industrialized regions, rather large, much larger than expected before.

[24] Concerning the effects of PLHR events and their influence on the overall intensity of electromagnetic waves, a preliminary guess can be made already from the low number of PLHR events observed in the regions geomagnetically conjugate to the source locations. Among 148 identified PLHR events, only 7 were most probably generated in the conjugate region and were thus able to make their way between the hemispheres. The reason for this low number most probably stems from the very low intensity of PLHR events. If they undergo even a weak attenuation during their path, they become too weak to be observed. Consequently, PLHR events do not seem to be able to play any important role in the dynamics of the upper ionosphere unless they are able to trigger new, more intense emissions. An example of one such possibly triggered emission has been presented already [*Němec et al.*, 2009]. However, there was still a question of how often such a phenomenon occurs.

[25] *Helliwell et al.* [1980] used an experiment consisting of VLF transmitter located in Siple Station, Antarctica, and receiver located at the conjugate point, Roberval, Quebec, Canada. They reported that to observe growth and triggering

of VLF emissions, the radiated power must be larger than a threshold value. This threshold value was found to vary significantly, with minimum radiated power for growth and triggering being about 1 W. The radiated power peaks above the transmitter and is reduced by ≈14 dB at horizontal distances about 200 km [*Helliwell et al.*, 1980]. We can estimate the Poynting flux S_t required for the wave growth and triggering by assuming that the radiated power follows a two-dimensional symmetrical Gaussian distribution, resulting in $S_t \approx 2.6 \times 10^{-2}$ nW m^{-2}. The maximum estimated radiated Poynting fluxes of individual PLHR lines determined from DEMETER data are about 5×10^{-4} nW m^{-2}, with about three lines forming the PLHR event being typically observed [*Němec et al.*, 2008]. This indicates that the intensities of PLHR events are in most cases too low for wave growth and triggering. However, they might occasionally reach the required threshold, especially taking into account that the value of minimum radiated power reported by *Helliwell et al.* [1980] was obtained for one particular location and that at different locations it might be slightly different.

[26] The experimental answer to the triggering efficiency of PLHR events is, at least to some extent, given by Figures 3 and 4. The limited coverage of Burst mode data significantly complicates a check for potentially triggered emissions. We have used Burst mode data whenever possible. These provide us with high-resolution data that are ideal for checking of the presence of PLHR events and/or triggered emissions. However, Burst-mode coverage is rather poor. Consequently, there are only 17 events with Burst mode active really close to the region geomagnetically conjugate to the point of observation of a PLHR event (Figure 3). Triggered emissions and PLHR are not observed in these 17 conjugated regions. However, it should be noted that among the 17 checked events, only a few of them were located really close to the point geomagnetically conjugate to the point of observation of a PLHR event. The remaining events were separated by at least a few degrees in geomagnetic latitude and by up to nearly 40 degrees in geomagnetic longitude. Moreover, one must also consider that the studied phenomena might be significantly time-dependent. Since the DEMETER spacecraft needs about 30 minutes to get from a given location to the magnetically conjugated region (supposing a geomagnetic latitude of about 60°), it is possible that, by the time it gets there, the originating PLHR event as well as any connected triggered emissions (e.g., MLR events) in the conjugated region are already gone. Such a situation might occur relatively often, taking into account that the typical time duration of MLR events found using ground-based measurements is about 30 min [*Rodger et al.*, 2000a]. Nevertheless, some MLR events last significantly longer; e.g., *Parrot et al.* [2007] reported an MLR event lasting for about 2 hr. This indicates that at least in some cases, DEMETER should be able to travel between the hemispheres fast enough to observe first the original PLHR and then the induced MLR in the opposite hemisphere.

[27] Unlike the Burst mode data, Survey mode data are not restricted in coverage, but they have significantly lower resolution. Usually, it is very difficult (sometimes even impossible) to distinguish PLHR events in this kind of data. However, since we look for triggered emissions which should be more intense than originating PLHR events, it is very likely that we should be able to identify them in the Survey mode data. An investigation of all the 137 data intervals close to the regions geomagnetically conjugate to the points of observation of PLHR events reveals new possibly triggered emissions only in two of them. It may be of some importance that in both cases, the possibly triggered emissions were not observed directly in the conjugate region, but rather shifted about 50 degrees to the west, being located above the South Atlantic Ocean. It is also possible that they extend over a large interval of geomagnetic longitudes (e.g., *Němec et al.* [2009] have shown that the longitudinal dimensions of MLR events can be as large as 100 degrees) and that they thus occur also directly in the conjugate region. Finally, we would like to underline that the only indication of these events being linked to PLHR events is that they are observed at the same L-values as PLHR events, with PLHR events being observed about 30 min earlier.

[28] Having investigated the individual emissions triggered by PLHR events, it is of great importance to determine whether such emissions play a significant role in overall intensity of electromagnetic emissions observed by a low-altitude spacecraft. If their influence should play any important role, one would expect to observe increased wave intensity above industrialized regions in maps similar to those from Figure 5. However, this is not the case. This negative result strongly suggests that PLHR-triggered emissions are too rare/too weak to significantly affect the total wave intensity, which is mainly dominated by the lightning activity. This seems to be in contradiction with low-altitude surveys of VLF emissions by the Ariel 3 and 4 satellites [*Bullough et al.*, 1976; *Tatnall et al.*, 1983]. These reported the existence of a permanent zone of emissions at 3.2 kHz occurring over the industrialized regions of northern America and its geomagnetically conjugate zone in the Southern Hemisphere, attributing it to PLHR. Similarly, world maps of ELF/VLF emissions observed by the AUREOL-3 satellite revealed intense emissions over North America at all frequencies [*Parrot*, 1990]. An increase of radiation in the VLF range, both in the electric and magnetic component, at nighttime over Europe has been reported by *Rothkaehl and Parrot* [2005]. However, as demonstrated by *Němec et al.* [2010], the existence of these areas of increased wave intensity can be explained by the lightning activity, being consistent with the recent results. Finally, geomagnetic latitudes in northern America are larger than the geomagnetic latitudes of other areas with the same geographic latitudes, and increases of wave intensity observed over northern America can be explained by intense waves propagating in the auroral and subauroral regions.

[29] Different power consumption during the weekends as compared to the weekdays was reported to significantly affect the overall wave intensity observed by low-altitude satellites [*Parrot et al.*, 1991; *Molchanov et al.*, 1991]. The occurrence rate of PLHR events should be affected in the same manner, being the largest during weekdays when the power consumption is larger and the lowest during weekends when the power consumption is lower. However, the results obtained for our list of PLHR events represented in Figure 6 do not exhibit such a dependence. Most likely this is caused by an insufficient number of events included in the study. However, such a result is definitely useful to demonstrate that the weekend effect, if it exists, is probably

rather weak. The same negative result obtained for overall power spectral density of electric field fluctuations above various geographic regions and in various frequency bands suggests that the weekend effect does not play a significant role in the wave activity in the upper ionosphere.

[30] This seems to be in contradiction with the study of *Parrot et al.* [1991]. However, they observed the weekend effect for the electric field component parallel to the Earth's magnetic field, while the electric field component analyzed in the present study is perpendicular to the orbit plane. Moreover, big industrial companies nowadays often operate all the time, including weekends, eliminating thus the primary reason for the weekend effect to be observed. *Rodger et al.* [2000b] reported that in 1998, the average maximum peak electrical consumption on Sundays in the state of Texas was about 9% smaller than the weekday maximum. Although this is significantly less than about 15% difference reported for the period of 1973–1975 [*Park and Miller*, 1979], they argued that the comparison with the results by *Park and Miller* [1979] suggests that it should still be enough to bring about an observable change in MLR occurrence in their data. However, this was not observed. *Rodger et al.* [2000b] also noted that North American holidays can lead to very large decreases in power consumption (20–25%), but that this does not lead to an observed "holiday effect" in the total wave intensity. Our results seem to be largely consistent with their conclusions. Finally, it may be relevant to mention that a study by *Karinen et al.* [2002] (although using rather different data) indicates that previous observations of the weekend effect may result from statistical fluctuations.

7. Conclusions

[31] Results based on the analysis of 148 PLHR events identified by an automatic identification procedure are presented. The occurrence rate of PLHR events and their influence on the overall wave intensity observed by a low-altitude satellite are determined. Our results show that the occurrence rate of PLHR events above industrialized regions is reasonably large (lower estimate of the occurrence rate is about 5%). Nevertheless, the overall influence of PLHR events seems to be quite sporadic. They are too weak and the individual lines forming them are too narrow to significantly increase the total wave intensity above industrialized regions. Although there are some indications that they could be capable of triggering new emissions with characteristics corresponding to MLR events, this does not seem to happen very often. Finally, no weekend effect was observed either in the occurrence rate of PLHR events or in the overall wave intensity.

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