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VLF Electromagnetic Waves Observed by DEMETER

Abstract of Doctoral Thesis

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Preface

Results based on wave measurements performed by the DEMETER spacecraft (altitude 700 km) are presented. We focus on two different phenomena: 1) effects possibly connected with seismic activity 2) emissions with a line structure.

1) We present a statistical study of intensity of electromagnetic waves observed in the vicinity of earthquakes. It is shown that during the night there is a statistically significant decrease of wave intensity shortly before the time of the main shock.

2) We present a survey of the events with a line structure. A statistically significant set of events has been obtained both by using an automatic identification procedure and visual inspection of the data. All the events are thoroughly analyzed and classified. Moreover, in the ELF range (where all the six electromagnetic field components are measured during the Burst mode), a detailed wave analysis has been performed.

Introduction

Electromagnetic effects connected with seismic activity

Possible existence of additional seismic-related effects was proposed quite a long time ago [Milne, 1890]. These effects may be various, ranging from changes of resistance of ground close to the epicenter of an imminent earthquake, through the emission of radioactive gasses, generation of anomalous electric fields and changes of temperature up to generation/attenuation of electromagnetic waves [Parrot, 1995; Pulinets and Boyarchuk, 2004; Sorokin et al., 2005; Molchanov, 1998]. These unusual phenomena have been reported both using ground-based and satellite experiments. However, most of the performed experimental studies were only case studies (or studies including only small number of events), which could not be consequently considered as entirely persuading. In addition, theoretical works were often quite problematic because of the lack of experimental data and problems with determining the appropriate values of the used parameters. A considerable part of the scientific community thus remains rather sceptical about these phenomena, and even their own existence is still a matter of debate [Rodger et al., 1996]. Anyway, these effects might be very important, because they are claimed to occur not only after the main shock, but also a short time before. They could therefore possibly serve as short-time precursors.

In the presented thesis we study the electromagnetic effects related to the seismic activity using the data from the French micro-satellite DEMETER. This project – and also the used data – are rather unique, because DEMETER is the first satellite whose primary objective is to study the ionospheric effects connected with seismic activity. The basic question that we try to answer in the presented study therefore is: "Is there a statistically significant correlation between seismic activity and the intensity of the observed electromagnetic waves?". In order to answer this question, we have performed a statistical study using more than 3.5 years of DEMETER data.

Emissions with a line structure

Emissions with a line structure represent a special type of electromagnetic waves observed in the upper ionosphere. These emissions – when represented in a traditional form of frequency-time spectrogram with color-coding of power spectral density – have a form of several almost parallel and often nearly horizontal intense lines. The frequency spacing between individual lines is thus quasi constant. In some cases, the frequency separation is 50/100 Hz or 60/120 Hz, corresponding to the base frequency of electric power systems on the ground. These emissions are believed to be caused by an electromagnetic radiation from electric power systems on the Earth's surface. The radiated electromagnetic waves are then detected by the satellite and usually called "Power Line Harmonic Radiation" (PLHR). However, such a scheme has still lacked a direct experimental evidence. The origin of the rest of the events is still not clear. Since there is a strong evidence for their propagation through the magnetosphere, they are usually called "Magnetospheric Line Radiation" (MLR). Such events have been reported both using the ground-based instruments [Rodger et al., 1999, 2000a,b; Manninen, 2005] and low-altitude satellites [Rodger et al., 1995; Parrot et al., 2005, 2006; Němec et al., 2007a]. There is a hypothesis that their origin might be connected to PLHR, which would serve as a "trigger" – an embryonic generator of further, more intense, emissions [Bullough, 1995; Rodger et al., 2000a; Manninen, 2005]. Another possibility would be that they are generated in a completely natural way.

We focus on the analysis of the satellite observations of electromagnetic emissions with a line structure. The large number of detected events allowed us to perform their systematic analysis. We were able to classify the events into three distinct groups. We analyze each of them more in detail and we discuss the possible generation mechanisms of the events.

DEMETER satellite

DEMETER is a French micro-satellite (weight 130 kg) launched in June, 2004 on a nearly circular orbit. The original altitude of the satellite (710 km) was decreased to 660 km in December, 2005. The satellite orbit is quasi Sun-synchronous – the satellite is always located either in the local day (10:30 LT) or in the local night (22:30 LT). There are five different instruments placed on board, namely:

1. Langmuire sonde for measurements of the basic characteristics of plasma (number density and electron temperature).

2. Plasma analyzer for measurements of the total number density and concentration of individual ion species.

3. Detector of energetic particles.

4. Four electric antennaes for electric field measurements.

5. Three search-coil magnetometers for measurements of magnetic field fluctuations.

We have used only the data from the last two instruments, i. e. the measurements of electric [Berthelier et al., 2006] and magnetic [Parrot et al., 2006] field fluctuations.

Due to the technical reasons the satellite records data only at geomagnetic latitudes lower than 65 degrees. Because of the limited capacity of the telemetry, there are two different modes of operation of the satellite, called "Burst" and "Survey". During the mode "Burst", which is active only above some specifically selected (mostly seismic) areas, more detailed – and consequently larger – data are recorded. In the extra low frequency (ELF) range, i. e. at frequencies up to 1250 Hz, the waveforms of all the three electric and three magnetic field components are recorded. In the very low frequency range (VLF), i. e. at frequencies up to 20 kHz, the waveforms of one electric and one magnetic field component are recorded. Mode "Survey", during which less accurate data are recorded, is active all the time. In the VLF range this provides us with an on-board calculated spectra of one electric and one magnetic field component. Frequency resolution of these spectra is 19.53 Hz and time resolution is 0.512 s or 2.048 s, depending on the sub-mode of the instrument.

Electromagnetic effects connected with seismic activity

The principal problem when studying electromagnetic effects connected with seismic activity is that – even if they exist – they are very weak as compared to the common natural fluctuations of intensity of electromagnetic waves. We must therefore apply such a method of the statistical analysis which is able to sufficiently eliminate these natural influences. We have developed two different data processing methods [Němec et al., 2008a, 2009b]; both are based on the analysis in several steps and distribution of usually observed wave intensities.

The first study that we have performed [Němec et al., 2008a] was based on more than 2.5 years of DEMETER data, which represents about 11500 hours of measurements. According to the USGS catalog (http://neic.usgs.gov/neis/epic/epic_global.html), about 9000 earthquakes with magnitude larger than or equal to 4.8 occurred all over the Earth during this period. All of them were included in our study.

In the first step of the data processing we construct so-called "map of electromagnetic emissions", which provides a statistical description of intensity of electromagnetic waves observed during the analyzed period. This map can be represented by a six-dimensional array with following indices:

- Geomagnetic latitude and geomagnetic longitude of the satellite. Geomagnetic coordinates are coordinates derived from the axis of the Earth's magnetic dipole, not from the axis of rotation. Their main advantage as compared to the geographic coordinates is that nearly all the analyzed phenomena are connected with the Earth's magnetic field and not with the Earth's rotation; they thus represent a natural coordinate system for studying these effects.

- Frequency of electromagnetic wave. We have analyzed only electromagnetic waves at frequencies lower than 10 kHz, in order to eliminate the frequencies of very low frequency transmitters on the Earth's surface.

- Kp index. Kp index is an index expressing the level of geomagnetic activity. During the increased geomagnetic activity the intensity of electromagnetic waves is generally larger – this index must be thus included in the analysis.

- Period of the year.

The last index of the array corresponds to the histogram of the observed wave intensities. For a given frequency of the wave, location of the satellite (geomagnetic latitude and geomagnetic longitude) and magnetospheric conditions (Kp index, period of the year) we thus obtain an experimental estimate of the probability density $f(E)$ of observing a power spectral density E. We can also easily obtain the estimate of a corresponding cumulative distribution function $F(E)$ by integration.

The basic idea of the second step of the data processing is that we are not interested in the measured intensity of electromagnetic emissions itself, but rather in the intensity of emissions related to the intensities usually observed at the same place during the similar magnetospheric conditions. We attribute therefore to the measured value of power spectral density E_i the appropriate value of cumulative distribution function F_i. In this way we obtain a probability (a number between 0 and 1) of occurring of a signal with an intensity lower than or equal to the measured level. The larger this number is, the more intense the emission is in comparison with the usual values.

We calculate the values of cumulative distribution function F_i for all the measurements of wave intensity close to earthquakes. During this process, we are interested only in the measurements for which the distance between satellite projection on the Earth's surface and the epicenter of an earthquake is less than 1100 km and which were done no more than 5 days before and 3 days after the earthquake. If there is more than one earthquake close to the measured data the data are not taken into account in the further analysis. This condition is equivalent to taking into account only "individually occurring" earthquakes, sufficiently isolated both in time and space.

The calculated values of cumulative distribution function are organized in an array as a function of the following three parameters:

- Frequency of electromagnetic wave. We use the same frequencies as for the "map of electromagnetic emissions".

- Time from/to an earthquake. Taking into account the time relative to the time of an earthquake allows us to combine all the measurements together, even if they are performed in different absolute times ("superposed epoch analysis").

- Distance between the satellite projection on the Earth's surface and the epicenter of an earthquake.

If we now define – separately for each bin of the created array – a "probabilistic intensity" as an arithmetic average of values of cumulative distribution function in the given bin, we obtain a number between 0 and 1 expressing how intense the emissions are in comparison with usually measured intensities of electromagnetic waves. If this number is significantly larger/lower than 0.5, the intensity of electromagnetic waves is significantly larger/lower than normally.

The only remaining point is to define quantitatively the meaning of the word "significantly". This will become clear when taking into account the statistical consequences of the applied procedure. The values of cumulative distribution function calculated from all the data set are uniformly distributed between 0 and 1, which is a direct consequence of their definition [Press et al., 1992]. Averaging them into the individual bins of the resulting array we thus obtain – according to the central limit theorem – a Gaussian distribution with mean value 0.5 and some standard deviation. If all the averaged values were independent, we could determine the standard deviation directly from the central limit theorem. Unfortunately, this is not the case and a bit more complicated approach has to be used for its determination [Němec et al., 2008a]. Knowing the standard deviation, we can introduce a "normalized probabilistic intensity" as a difference between the obtained probabilistic intensity and expected probabilistic intensity (i.e. one half) normalized by the standard deviation. Normalized probabilistic intensity defined in this way expresses if the observed emissions are less or more intense than usually (negative values mean less intense emissions than is usual, positive values mean more intense emissions than is usual), but it also expresses the statistical significance of the observed effect directly in the number of standard deviations. Effects with an absolute value of the normalized probabilistic intensity larger than about 3 can be thus considered as being statistically significant.

Because according to some studies a depth of an earthquake can be an important factor in processes connected with seismic activity [Rodger et al., 1999], we have divided the earthquakes into two groups according to their depth: 1) deep earthquakes (depth larger than 40 km) and 2) shallow earthquakes (depth less than or equal to 40 km). In addition, data measured during the day and during the night were treated separately, because the ionospheric conditions significantly vary as a function of the local time. Finally, the values of normalized probabilistic intensity have been evaluated for all the four combinations of deep/shallow earthquakes and day/night data in order to check for a possible presence of seismic-related effects.

Frequency-time spectrogram of the normalized probabilistic intensity obtained for the night-time electric field data in the vicinity of shallow earthquakes is plotted in Figure 1. It can be seen that there is a statistically significant decrease of wave intensity shortly before the time of the main shock (0-4 hours) at frequencies between approximately 1 and 2 kHz. The statistical significance of this effect is about 3 standard deviations for earthquakes with magnitudes larger than or equal to 4.8 and about 4 standard deviations for earthquakes with magnitudes larger than or equal to 5.0. Similar decrease of wave intensity was observed also in the magnetic field data, but it was significantly weaker, probably due to the lower sensibility of magnetic field instrument. No similar effect was observed for deep earthquakes nor during the day.

Figure 2 represents color-coded normalized probabilistic intensity in the frequency range where the effect was observed as a function of the distance between the satellite projection on the Earth's surface and the epicenter of an earthquake and of a time between the satellite pass and the time of the main shock. It can be seen that the spatial dimensions of the affected area are approximately 350 km. This corresponds rather well to the dimensions of the preparation zone of an earthquake

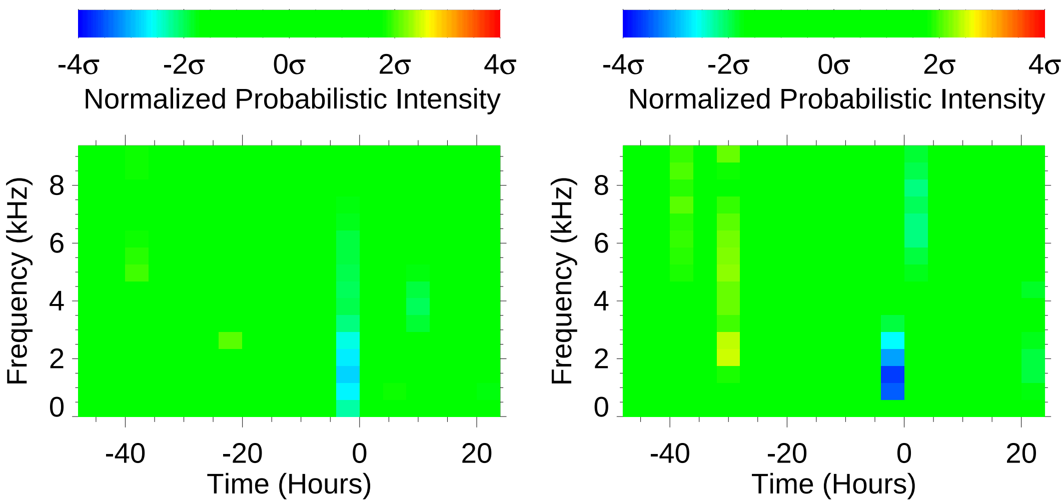

Figure 1: (left) Frequency-time spectrogram of the normalized probabilistic intensity (see text) obtained for the night-time electric field data measured within 330 km of the earthquakes with magnitudes larger than or equal to 4.8 and depth less than or equal to 40 km. (right) The same but for earthquakes with magnitudes larger than or equal to 5.0. (adopted from Němec et al. [2008a])

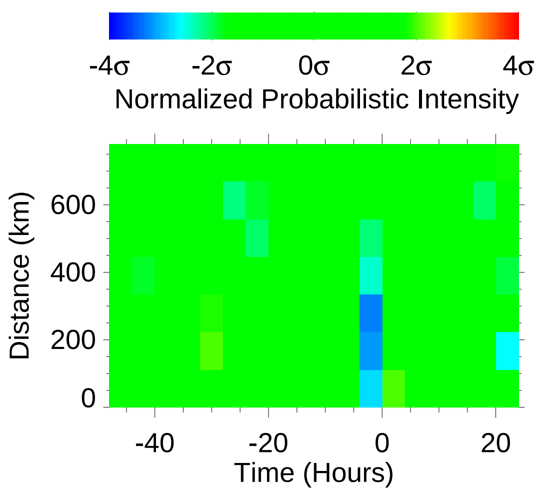

Figure 2: Normalized probabilistic intensity (see text) obtained for the night-time electric field data measured for earthquakes with magnitude larger than or equal to 5.0 and depth less than or equal to 40 km plotted as a function of the distance from the epicenters and of the time from the main shocks for a frequency band 10552383 Hz. (adopted from Němec et al. [2008a])

[Dobrovolsky et al., 1979].

In our next study [Němec et al., 2009b] we have analyzed the dependence of the observed effect on the properties of the earthquake. We have shown that the effect is stronger for shallow and larger earthquakes and that there seems to be no difference between earthquakes located below the ocean and below the continents. Moreover, the effect seems to be shifted by about two degrees to the West from the epicenter of an imminent earthquake, which might be related to the Earth's rotation.

The observed decrease of intensity of electromagnetic waves shortly before the main shock of shallow earthquakes observed during the night is very significant and interesting. However, one must keep in mind the two principal limiting factors of the performed studies. The first of them is that the effect was found only by using a large amount of the analyzed data; although on average the intensity of electromagnetic waves behaves as described, the behavior in individual cases may be rather different. The second limiting factor is that the number of earthquakes occurring within some distance from the satellite is proportional to the square of this distance. Consequently, even if the total number of earthquakes included in our study is huge, only a small part of them occurs close enough to an earthquake and forms the observed effect. Finally, it necessary to underline that up to now we do not have any explanation of the observed effect.

Emissions with a line structure

Classification

Satellite observations of emissions with a line structure are quite rare, the appropriate studies usually reported just a few cases. In order to find enough events for the analysis, it is necessary to analyze a large amount of data. We have analyzed DEMETER data in the VLF range (measured during both Burst and Survey mode) by an automatic procedure [Němec et al., 2006] as well as manually, obtaining – according to our knowledge – the largest satellite database of emissions with a line structure. A systematic analysis of the found events reveals that there are three different types of emissions with a line structure: PLHR, MLR and electromagnetic harmonic emissions in the ELF range. In this section we present a classification of the events into three groups. Next three sections present some more detailed results obtained separately for each of the groups.

Power Line Harmonic Radiation (PLHR) are electromagnetic emissions with a line structure, whose frequency separation between individual lines is 50/100 Hz or 60/120 Hz. An example of such an event is presented in Figure 3. The data were measured on March 25, 2006 after 19:13:32 UT when the satellite was passing over the Finland. The top panel represents the frequency-time spectrogram of the event, the bottom panel represents the power spectrum of the first 18 seconds of the data. The most important peaks in the power spectrum are marked by arrows. They are located at frequencies 1650 Hz, 1750 Hz, 1850 Hz, 1950 Hz, 2050 Hz, 2150 Hz, 2250 Hz, 2350 Hz and 2450 Hz, separated therefore by exactly (within an experimental error) 100 Hz. This corresponds well to the base frequency of electric

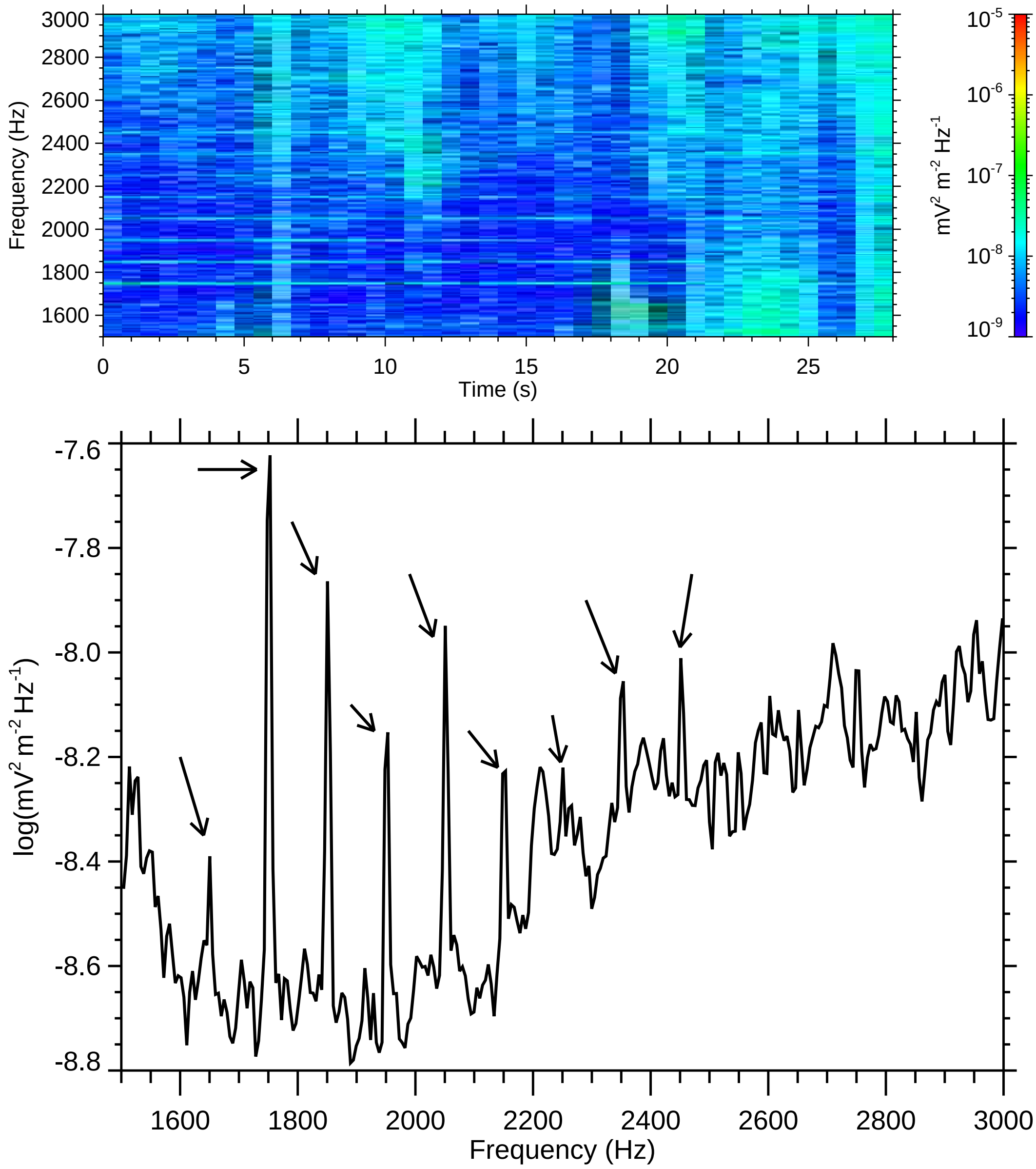

Figure 3: (top) Frequency-time spectrogram of power spectral density of electric field fluctuations corresponding to a PLHR event with a frequency separation of individual lines 50/100 Hz. The data were recorded on March 25, 2006 after 19:13:32 UT when the satellite was passing over the Finland. (bottom) Power spectrum of the first 18 seconds of the data. The most important peaks are marked by arrows. (adopted from Němec et al. [2007a])

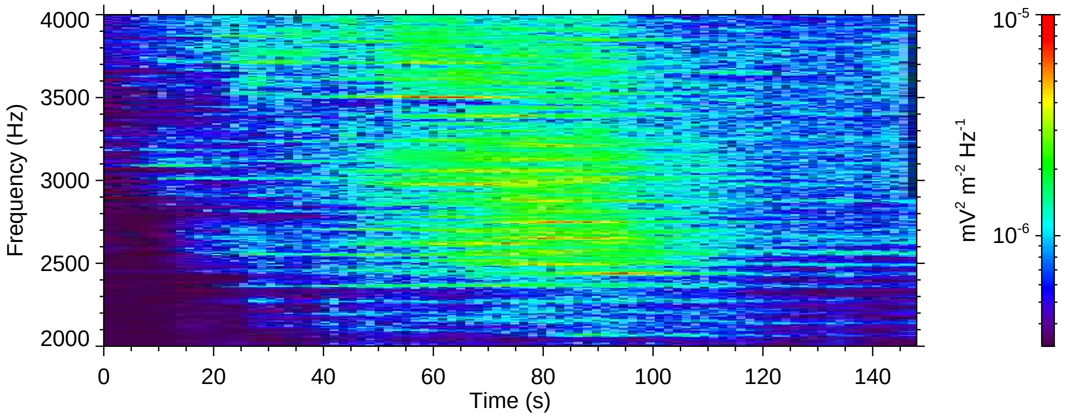

Figure 4: Frequency-time spectrogram of power spectral density of electric field fluctuations corresponding to an MLR event. The data were measured on January 19, 2007 after 06:26:02 UT.

power systems in Finland (50 Hz).

The emissions with a line structure whose frequency separation between individual lines is not 50/100 Hz nor 60/120 Hz can be either Magnetospheric Line Radiation (MLR) events or electromagnetic harmonic emissions in the ELF range. The distinction of these two classes is not always clear. However, the main difference between the two is that MLR events are observed at larger frequencies and at larger geomagnetic latitudes, while electromagnetic harmonic emissions in the ELF range are observed at frequencies usually lower than about 1 kHz and within about 15 degrees from the geomagnetic equator.

Figure 4 represents a frequency-time spectrogram of power spectral density of electric field fluctuations of an example of an MLR event. The data were measured on January 19, 2007 after 06:26:02 UT. A set of nearly horizontal lines at frequencies between 2 and 4 kHz can be clearly seen.

Figure 5 represents a frequency-time spectrogram of power spectral density of electric field fluctuations of an example of an electromagnetic harmonic emission in the ELF range. The data were measured on November 10, 2004 after 00:50:30 UT. The decrease of wave intensity at frequencies below about 450 Hz is caused by a cut-off close to the local proton cyclotron frequency [Santolík et al., 2006].

Power Line Harmonic Radiation (PLHR)

All the analyzed PLHR events were measured during the Burst mode and found by an automatic identification procedure [Němec et al., 2006]. Geographic locations of the observed PLHR events with frequency separation of individual lines 50/100 Hz are shown in Figure 6 (17 events). Geographic locations of the observed PLHR events with frequency separation of individual lines 60/120 Hz are shown in Figure 7 (32 events). Magnetic field lines and footprints of the points of observations are plotted by thin lines and small points, respectivel. In addition, zones with permanently active burst-mode coverage are shown by gray shading. However, the operational-

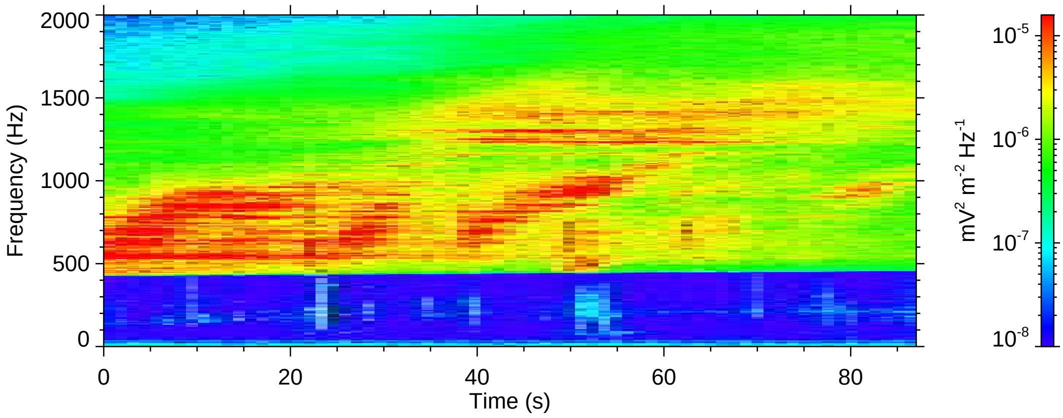

Figure 5: Frequency-time spectrogram of power spectral density of electric field fluctuations corresponding to electromagnetic harmonic radiation in the ELF range. The data were measured on November 10, 2004 after 00:50:30 UT.

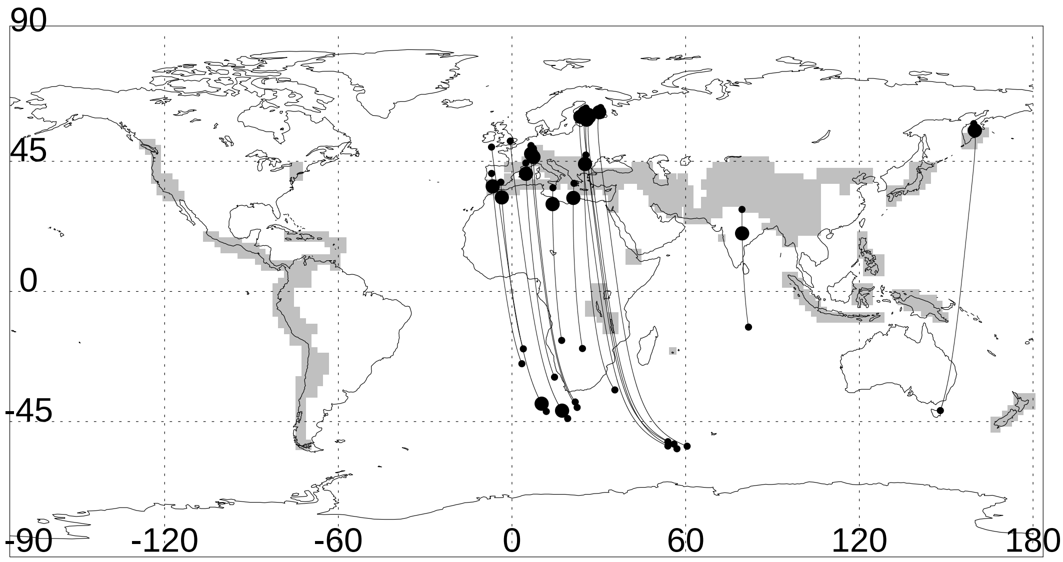

Figure 6: Map showing geographic locations of the observed PLHR events with frequency separation of 50/100 Hz (large points). Magnetic field lines and footprints of the points of observations are plotted by thin lines and small points, respectively. Zones with permanently active burst-mode coverage are shown by gray shading; however, the operational-phase burst-mode regions, which form approximately 20% of the burst-mode data volume, are not shown since their positions vary during the time interval analyzed in this study. (adopted from Němec et al. [2007b])

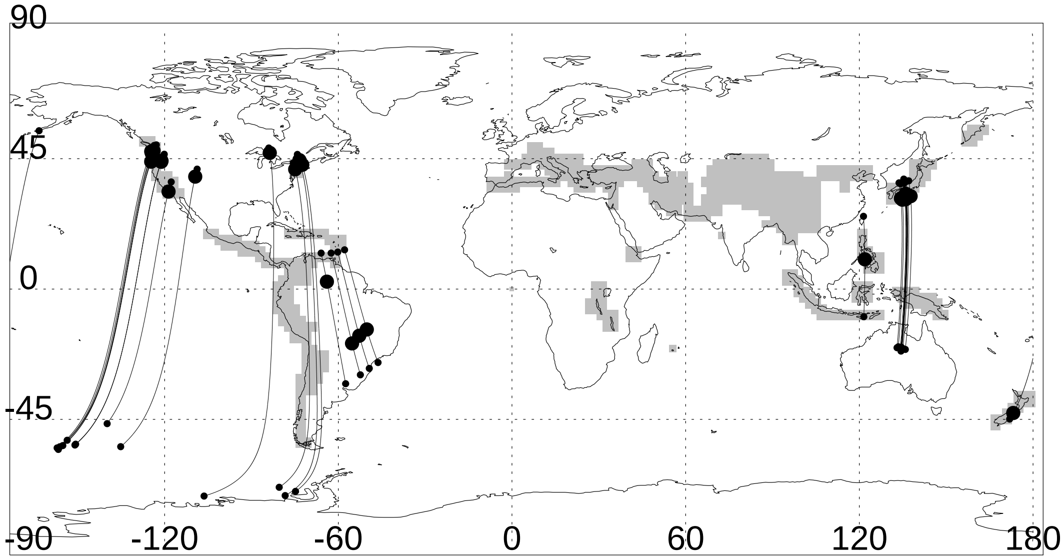

Figure 7: Same as Figure 6, but for PLHR events with frequency separation of lines 60/120 Hz. (adopted from Němec et al. [2007b])

phase burst-mode regions, which form approximately 20% of the burst-mode data volume, are not shown since their positions vary during the time interval analyzed in this study. It can be seen that the frequency separation of individual lines forming the events corresponds well to the base frequency of electric power systems below the point of observation or in the conjugate region: the events with frequency spacing 50/100 Hz are observed almost exclusively above Europe and events with frequency spacing 60/120 Hz are observed above United States, Brazil and Japan.

It has been shown that the intensities of PLHR events observed during the day are significantly lower than the intensities of PLHR events observed during the night [Němec et al., 2008b]. In order to explain this difference, we have performed a numerical "full-wave" calculation of the efficiency of coupling of electromagnetic wave from the Earth's surface up to the altitude of the DEMETER satellite. The results obtained for a frequency of electromagnetic wave 2.5 kHz (which is a typical frequency of PLHR events – see, e.g., Němec et al. [2007a]) are plotted in Figure 8 for two different geographic regions (Finland and Japan). One can see the enormous difference between the efficiency of coupling during the day and during the night (the coupling is about 5 times easier during the night). Moreover, the coupling is a bit easier in the region of Finland than in the region of Japan; this is due to the different geomagnetic latitudes (57.5° for Finland and 23° for Japan). The efficiency of coupling is larger at larger geomagnetic latitudes both because of magnetic inclination being closer to 90° and stronger ambient magnetic field. Finally, we have shown that this different efficiency of coupling can naturally explain the observed differences in the intensity of PLHR events [Němec et al., 2008b].

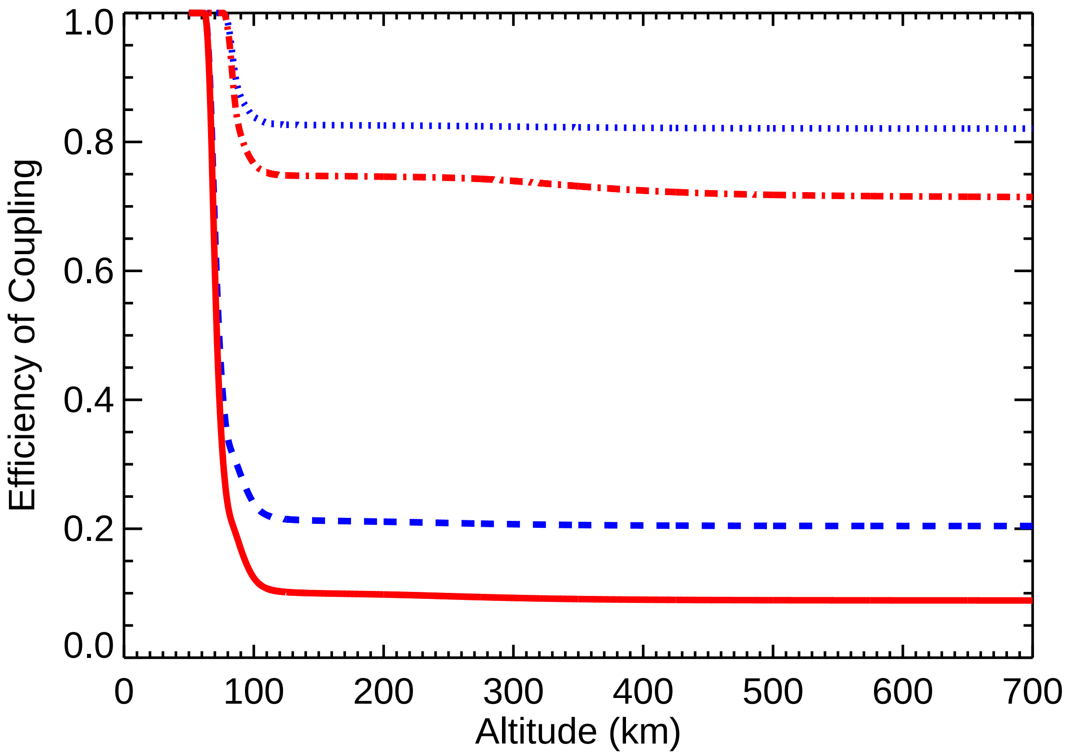

Figure 8: Efficiency of coupling for the frequency of wave 2.5 kHz as a function of the altitude for nighttime Finland region (dotted line), nighttime Japan region (dashdotted line), daytime Finland region (dashed line), and daytime Japan region (solid line). (adopted from Němec et al. [2008b])

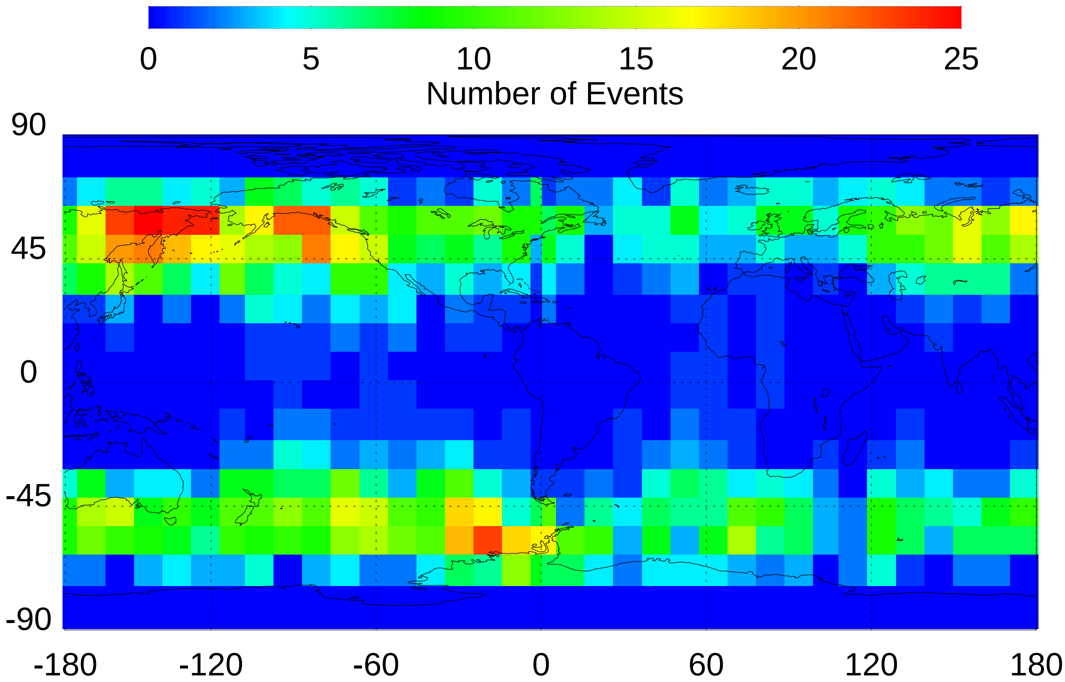

Figure 9: Map of occurrence of MLR events in geomagnetic coordinates. Shown color coded is the number of events observed in a given latitudinal-longitudinal bin. (adopted from Němec et al. [2009a])

Magnetospheric Line Radiation (MLR)

Altogether, we have analyzed 657 MLR events found manually in 3 years of VLF data measured during the Survey mode [Němec et al., 2009a]. These events were observed in 549 satellite half-orbits out of the 26036 verified (there can be two MLR events observed during the same half-orbit, localized in the conjugate regions). A verification of the local times when the events were observed reveals that 390 events were observed during the day-time and 267 during the night-time. This difference is statistically significant [Němec et al., 2009a].

A map of occurrence of the observed MLR events in geomagnetic coordinates is plotted in Figure 9. It can be seen that most of the events are localized at larger geomagnetic latitudes (note that the lack of events at geomagnetic latitudes larger than 65° is caused by the limitation of the DEMETER satellite). There is an interesting effect of lower occurrence rate of MLR events over the Atlantic Ocean, most probably caused by the South-Atlantic anomaly (see a more detailed discussion in Němec et al. [2009a]).

Figure 10 represents results of the superposed epoch analysis that we have used in order to check if the occurrence of MLR events is connected to the geomagnetic activity or not. The left panel represents the mean value of Kp index as a function of the time relative to the time of the MLR events and the appropriate standard deviation. The right panel represents the same dependence, but this time obtained for the median value of Kp index. It can be seen that there is an increase of geomagnetic activity a few days before the observation of MLR events. This effect

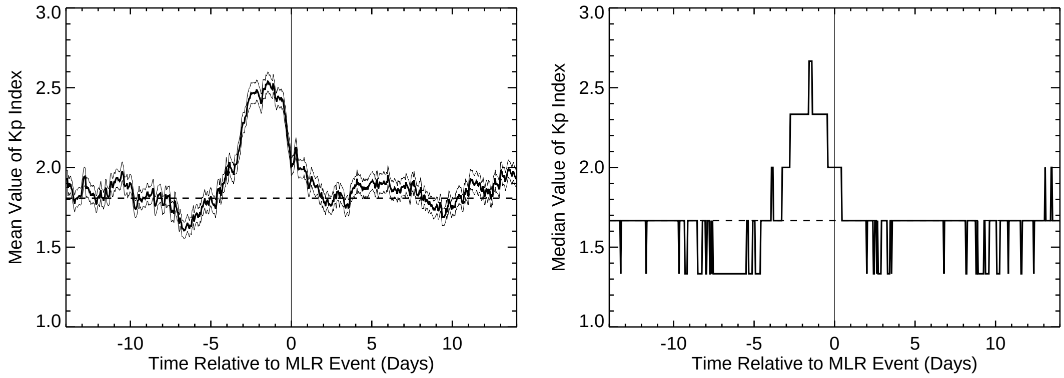

Figure 10: (left) Mean value of Kp index (bold) as a function of the time relative to the time of MLR events and standard deviation of the mean value (thin). (right) Median value of Kp index as a function of the time relative to the time of the MLR events. (adopted from Němec et al. [2009a])

is statistically significant, but its absolute value is rather small as compared to the normal fluctuations of Kp index. Similar results were obtained for Dst index as well [Němec et al., 2009a].

Electromagnetic harmonic emissions in the ELF range

Altogether, we have analyzed 24 events of electromagnetic harmonic emissions in the ELF range. All of them were measured during the Burst mode at frequencies up to 1250 Hz – we have the information about waveforms of all the three electric and all the three magnetic field components, which allows us to perform a detailed wave analysis.

An example of such an analysis is shown in Figure 11. The analyzed event was observed on May 16, 2005 between 08:16:40 UT and 08:17:55 UT. The individual panels represent frequency-time spectrograms of (from the top): power spectral density of electric field fluctuations, power spectral density of magnetic field fluctuations, ellipticity of magnetic field fluctuations E_B, ellipticity of electric field fluctuations E_E, polar angle of the wave vector θ_k, azimuthal angle of the wave vector ϕ_k, polar angle of the Poynting vector θ_P, azimuthal angle of the Poynting vector ϕ_P and the component of the Poynting vector parallel to the ambient magnetic field normalized by its standard deviation. A minimum intensity threshold has been used in order to plot only the results corresponding to the event.

Ellipticity of the magnetic field fluctuations E_B and ellipticity of the electric field fluctuations E_E vary between -1 and 1. The negative values correspond to the left-handed polarization, the positive values correspond to the right-handed polarization. The absolute value of ellipticity expresses the ratio between minor and major polarization axes: the value equal to 0 corresponds to the linear polarization, the value equal to 1 corresponds to the circular polarization. From the third panel of Figure 11 it can be seen that the polarization of magnetic field fluctuations is nearly linear. Electric field fluctuations are elliptical and right-handed polarized. The next

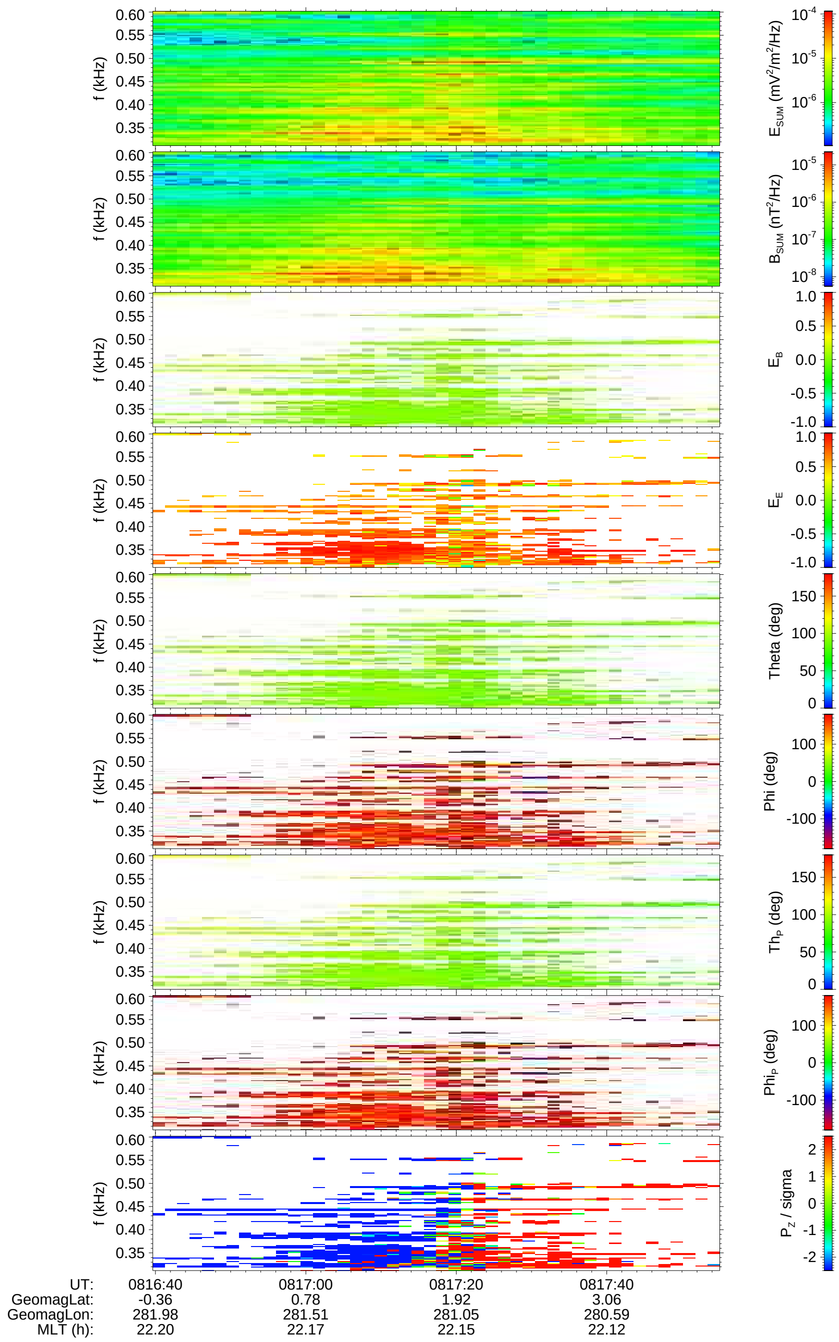

Figure 11: A detailed wave analysis of electromagnetic waves measured on May 16, 2005 between 08:16:40 UT and 08:17:55 UT. The individual panels represent frequency time spectrograms of (from the top): power spectral density of electric field fluctuations, power spectral density of magnetic field fluctuations, ellipticity of magnetic field fluctuations, ellipticity of electric field fluctuations, polar angle of the wave vector, azimuthal angle of the wave vector, polar angle of the Poynting vector, azimuthal angle of the Poynting vector and the component of the Poynting vector parallel to the ambient magnetic field normalized by its standard deviation.

four panels represent the directions of the wave vector and the Poynting vector. It can be seen that the two polar angles θ_k and θ_P are close to 90 degrees, corresponding to the orientation perpendicular to the ambient magnetic field. The azimuthal angles ϕ_k and ϕ_P are close to ± 180 degrees, corresponding to the orientation towards the Earth. All these characteristics are in a good agreement with the whistler mode propagation perpendicularly to the ambient magnetic field, with the magnetic field fluctuations oriented along the ambient magnetic field and the electric field fluctuations polarized elliptically in the plane perpendicular to the ambient magnetic field.

A very important result is represented in the last panel of Figure 11: the component of the Poynting vector parallel to the ambient magnetic field is oriented opposite the ambient magnetic field to the South from the geomagnetic equator and it is oriented along the ambient magnetic field to the North from the geomagnetic equator. There is thus a change of this component in the equatorial plane. A more detailed analysis of all the 24 events has revealed that this change is well systematic; we can conclude that the electromagnetic harmonic emissions in the ELF range propagate "away from the geomagnetic equator", indicating that their generation region is located just there.

Conclusions

We have presented the results obtained using electromagnetic data from the DEMETER satellite. Most of the presented results have been already published in the international scientific journals.

There is a large amount of different wave phenomena in the ionized environment around the Earth. Their analysis is very important, because in nearly collisionless plasma they represent the only possible way of an energy transport. In the presented thesis we have focus on two rather specific phenomena: electromagnetic effects connected with seismic activity and emissions with a line structure. Both of them correspond well to the scientific objectives of the DEMETER satellite. A study of effects connected with seismic activity is very important: they are reported several hours/days before the time of the main shock and there is thus a possibility of their application for a short-term prediction. Emissions with a line structure are very interesting, because they are probably connected with a man-made activity (at least in some cases), although their origin is still not well understood.

We have performed a statistical study of electromagnetic effects connected with seismic activity. Two different methods for their analysis have been used, using in both cases maps of global distribution of electromagnetic emissions in order to eliminate the influence of common natural variations. Our results show that:

1. There is a correlation between intensity of VLF electromagnetic waves in the ionosphere and seismic activity.

2. The effect is observed only during the night. No effect was observed during the day.

3. Intensity of electromagnetic waves in the frequency range 1 – 2 kHz was less intense than normally shortly (0 – 4 hours) before the time of the main shock. The dimensions of the affected area are a few hundreds of kilometers.

4. The effect is stronger for larger earthquakes.

5. The effects is stronger for shallower earthquakes. No effect was observed for deep earthquakes (depth > 40 km).

6. The effect was observed for earthquakes below the continent as well as for earthquakes below the ocean.

7. The effect seems to be shifted by approximately 2 degrees to the West from the epicenters of earthquakes.

Nevertheless, it is necessary to understand that this effect was found by using a large number of data and that the situation for a single earthquake can be rather different. We hope that the results of this analysis will help to understand the effects accompanying the earthquakes.

We have performed a statistical study of electromagnetic events with a line structure. We have shown that they can be classified into three distinct groups: Power Line Harmonic Radiation (PLHR), Magnetospheric Line Radiation (MLR) and electromagnetic harmonic emissions in the ELF range. The most important results that we have obtained for each of them are:

1. Power Line Harmonic Radiation (PLHR):

    - Frequency separation of individual lines forming the events corresponds well to the base frequency of electric power systems below the point of observation (or in the conjugate region).
    - The intensity of events observed during the day is lower than the intensity of events observed during the night. This can be explained using the efficiency of coupling of electromagnetic waves through the ionosphere.

2. Magnetospheric Line Radiation (MLR):

    - There are less events observed above the Atlantic Ocean (to the East of the South-Atlantic anomaly).
    - The events are observed (almost) uniquely inside the plasmasphere.
    - The events are observed after an increase of geomagnetic activity.

3. Electromagnetic harmonic emissions in the ELF range:

    - The waves come from larger radial distances.
    - Generation region of these waves is localized in the equatorial plane.
    - It is possible that these emissions are connected with the "equatorial noise" emissions observed at larger radial distances.

The results that we have obtained are very interesting, because they enabled a better understanding of the studied effects. However, a lot of work remains for the future. The satellite DEMETER is always operational and the amount of data is increasing every day, which is particularly important for the statistical studies of electromagnetic effects connected with seismic activity. Moreover, even if we understand the origin of some of the events with a line structure, the origin of the rest of them is still a mystery.

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