Detailed properties of magnetospheric line radiation events observed by the DEMETER spacecraft

F Němec, Michel Parrot, O Santolík

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Detailed properties of magnetospheric line radiation events observed by the DEMETER spacecraft

F. Němec,[1] M. Parrot,[2] and O. Santolík[1,3]

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[1] Magnetospheric line radiation (MLR) events are electromagnetic waves in the frequency range of about 1–8 kHz observed in the inner magnetosphere that, when presented in a form of frequency-time spectrograms, consist of several nearly parallel and almost equidistant intense lines. Although many observations of these events have been reported using ground-based instruments and a survey of a large data set based on low-altitude satellite data has been published recently, their origin remains unclear. We use low-altitude satellite observations of MLR events to study their detailed properties, namely, the frequency spacing of individual lines and their frequency drift. Since the satellite, unlike ground observatories, is moving, it allows us to analyze the properties of the events as a function of the position, especially L-shell. We show that neither the frequency spacing of the events nor their frequency drift varies significantly with the L-shell where the event is observed. Moreover, the frequency drift is generally positive. The individual lines forming the events cannot be explained as harmonics of the base frequency equal to the frequency spacing. We suggest that a possible generation mechanism might be an interaction between a wave of a carrier frequency and an additional wave with the frequency equal to the observed frequency spacing. We cannot exclude that it comes from human activity (power lines), but a magnetospheric origin is more likely. We suggest that the emissions might be guided by the plasmasphere inner boundary before they deviate to lower L-shells at altitudes of a few thousands of kilometers.

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1. Introduction

[2] Frequency-time spectrograms of VLF electromagnetic waves observed in the inner magnetosphere sometimes consist of several clearly defined lines. These lines are usually nearly equidistant in frequency and they may exhibit a rather slow frequency drift. Such emissions typically occur in the frequency range between about 1 and 8 kHz and they are called magnetospheric line radiation (MLR). Although MLR events have been reported both in ground observations [e.g., *Rodger et al.*, 1999, 2000a, 2000b; *Manninen*, 2005] and low-altitude satellite data [e.g., *Bell et al.*, 1982; *Rodger et al.*, 1995; *Parrot et al.*, 2005; *Němec et al.*, 2007a, 2009], their origin remains unclear. However, their role may be rather important as they can trigger emissions and influence the particles in the radiation belts [e.g., *Matthews and Yearby*, 1981; *Parrot and Němec*, 2009].

[3] *Rodger et al.* [1999] analyzed ground-based measurements of MLR events performed at Halley, Antarctica (75°30′S, 26°54′W, $L \approx 4.3$). They focused on the analysis of the frequency spacing between the individual lines forming the events and their frequency drift. They found that the MLR lines rise in frequency about as often as they fall and that the frequency spacing does not preferentially show spacings near harmonics of electrical transmission frequencies, either 50 Hz or 60 Hz. It has been concluded that a roughly exponential form of the distribution of MLR line spacings suggests that a generation mechanism of MLR events is most likely different than power line harmonic radiation (PLHR, an electromagnetic radiation from electric power systems on the ground). *Rodger et al.* [2000a] presented results of a survey undertaken on the basis of MLR measurements at the Halley station, specifically focusing on whether there is a link between MLR and PLHR. Again, they concluded that MLR is a natural VLF emission and is not primarily caused by PLHR. Finally, temporal properties of MLR observed at Halley, Antarctica, have been studied by *Rodger et al.* [2000b]. They have shown that the average duration of a typical MLR event at Halley is about 30 min. The occurrence of MLR events has been found to be weakly

[1]Faculty of Mathematics and Physics, Charles University in Prague, Prague, Czech Republic.
[2]Laboratoire de Physique et Chimie de l'Environnement et de l'Espace, Centre National de la Recherche Scientifique, Orléans, France.
[3]Institute of Atmospheric Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic.

Corresponding Author: F. Němec, Faculty of Mathematics and Physics, Charles University in Prague, V Holesovickach 2, Prague 18000, Czech Republic. (frantisek.nemec@gmail.com)

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linked to geomagnetic activity but only 24–48 hours after very large storms ($Kp > 6$). No dependence of MLR occurrence rates upon the instantaneous levels of geomagnetic activity has been found. The diurnal occurrence of MLR events was found to be twin-peaked, indicating a possible association with a combination of chorus and midlatitude hiss.

[4] The first systematic survey of satellite observations of line radiation events was presented by *Rodger et al.* [1995] using the ISIS 1 and 2 spacecraft. They reported two distinct classes of events. The first class consisted of lines which were characterized by a broadband appearance and by frequency drifts of a few tens of hertz per minute. The frequency spacings of these events were found to be essentially random, with no relation to the multiples of 50 or 60 Hz. Principally only these events are called MLR. The second class of events consisted of lines with a very narrow bandwidth and a zero frequency drift, which appeared to lie close to harmonics of 50 or 60 Hz. *Němec et al.* [2007a] performed a detailed comparison of the two classes of events using the data from the DEMETER satellite. The second class of events was shown to be directly related to electromagnetic radiation from electric power systems on the ground [*Němec et al.*, 2006, 2007b, 2008].

[5] *Parrot et al.* [2007] analyzed simultaneous observations on board the DEMETER satellite and on the ground of a large-scale MLR event. They demonstrated that the event lasted for as long as 2 hours and spanned over a large area in the Northern Hemisphere (≈7,400,000 km^2). Results of a survey of MLR events observed by the DEMETER spacecraft were reported by *Němec et al.* [2009]. They found that MLR events occur more often during the day than during the night and usually during, or after, periods of higher magnetic activity. The total frequency bandwidth of the events was below 2 kHz in the majority of cases. The events were found to occur mostly at $L > 2$ and they occurred primarily inside the plasmasphere. The number of events detected over the Atlantic Ocean was lower than elsewhere on the globe. A lack of energetic electrons east of the South Atlantic geomagnetic anomaly was suggested as a possible explanation. Finally, a possibility that MLR events might be triggered by PLHR was discussed and an event supporting this hypothesis was presented.

[6] In this paper we extend the results obtained by *Němec et al.* [2009], focusing on detailed properties of MLR events observed by the DEMETER spacecraft. As compared to the previous study, we use a slightly larger data set and we investigate the frequency drift and the frequency spacing of individual lines forming the events rather than their occurrence. Section 2 describes the DEMETER satellite and the identification of MLR events, as well as a procedure that we have used to determine their frequency spacing and frequency drift. The results that we have obtained are presented in section 3 and discussed in section 4. Finally, section 5 contains a brief summary.

2. Data Set

2.1. DEMETER Satellite and Identification of Events

[7] DEMETER was a low-altitude French satellite launched in June 2004 on a nearly Sun-synchronous (10:30 and 22:30 LT) circular orbit with an altitude of about 710 km. The altitude of the orbit was decreased to 660 km in December 2005 and the mission came to the end in December 2010. The satellite operated in two different modes, called burst and survey. During the burst mode more detailed data were collected, but it was active only above areas of special interest. The survey mode was active all the time at geomagnetic latitudes lower than 65 degrees. The wave instruments provided both electric and magnetic field measurements. In the VLF range (up to 20 kHz), a waveform of one electric and one magnetic field component was measured in the burst mode and a power spectrum of one electric and one magnetic field component with a predefined frequency resolution (19.53 Hz) was calculated on board in the survey mode. In the ELF range (up to 1250 Hz), waveforms of all the six electromagnetic field components were measured in the burst mode. A more detailed description of the satellite, the wave instruments on board and the data analysis can be found in *Parrot* [2006], *Parrot et al.* [2006], *Berthelier et al.* [2006], and *Santolík et al.* [2006].

[8] We have used the survey mode electric field data for most of the study. However, the burst mode data have been used whenever available in order to improve the frequency resolution. We have used the list of MLR events compiled by *Němec et al.* [2009] extended till the end of September 2008. MLR events were visually identified in the frequency-time spectrograms corresponding to individual satellite half-orbits. A constant frequency range (1 to 8 kHz) and a fixed power scale (10^{-3} to 10^{2} μV^2 m^{-2} Hz^{-1}) have been used. An example of such a frequency-time spectrogram is shown in Figure 1. It contains two MLR events, observed between about 21:19 UT and 21:24 UT and between 21:44 UT and 21:49 UT in the frequency range from about 2800 to 3400 Hz. Altogether, 727 MLR events have been identified in 604 half-orbits (out of 37450 half-orbits analyzed in total).

2.2. Determining Frequency Spacing and Drift

[9] Although the frequency resolution of the data in the survey mode is limited (19.53 Hz), it is usually good enough to enable an identification of individual lines forming the events. We have visually identified these lines in all the events and manually approximated them by straight lines using the mouse pointer on the computer screen. We have chosen this manual approach since the frequency-time spectrograms corresponding to the events are typically rather noisy, preventing any automatic identification of the lines. The result of the straight-line-approximation procedure applied to the example event from Figure 1 is shown in Figure 2. The frequency-time spectrograms presented in the figure represent a zoomed view of the overall spectrogram from Figure 1. The over-plotted black dashed lines correspond to the above described straight line approximations of the individual lines forming the events. Altogether, we were able to identify and approximate the individual lines forming 653 events, i.e. there were 74 MLR events in our data set that were too noisy to perform the procedure. Only the 653 events for which the procedure could be successfully applied will be analyzed further. Among these, 37 events occurred while the burst mode was active and data with a better frequency resolution were therefore available.

[10] The straight line approximations of individual lines forming MLR events have been used to determine the frequency spacing and the frequency drift of the events. First, the frequency drift of each line has been calculated. Since

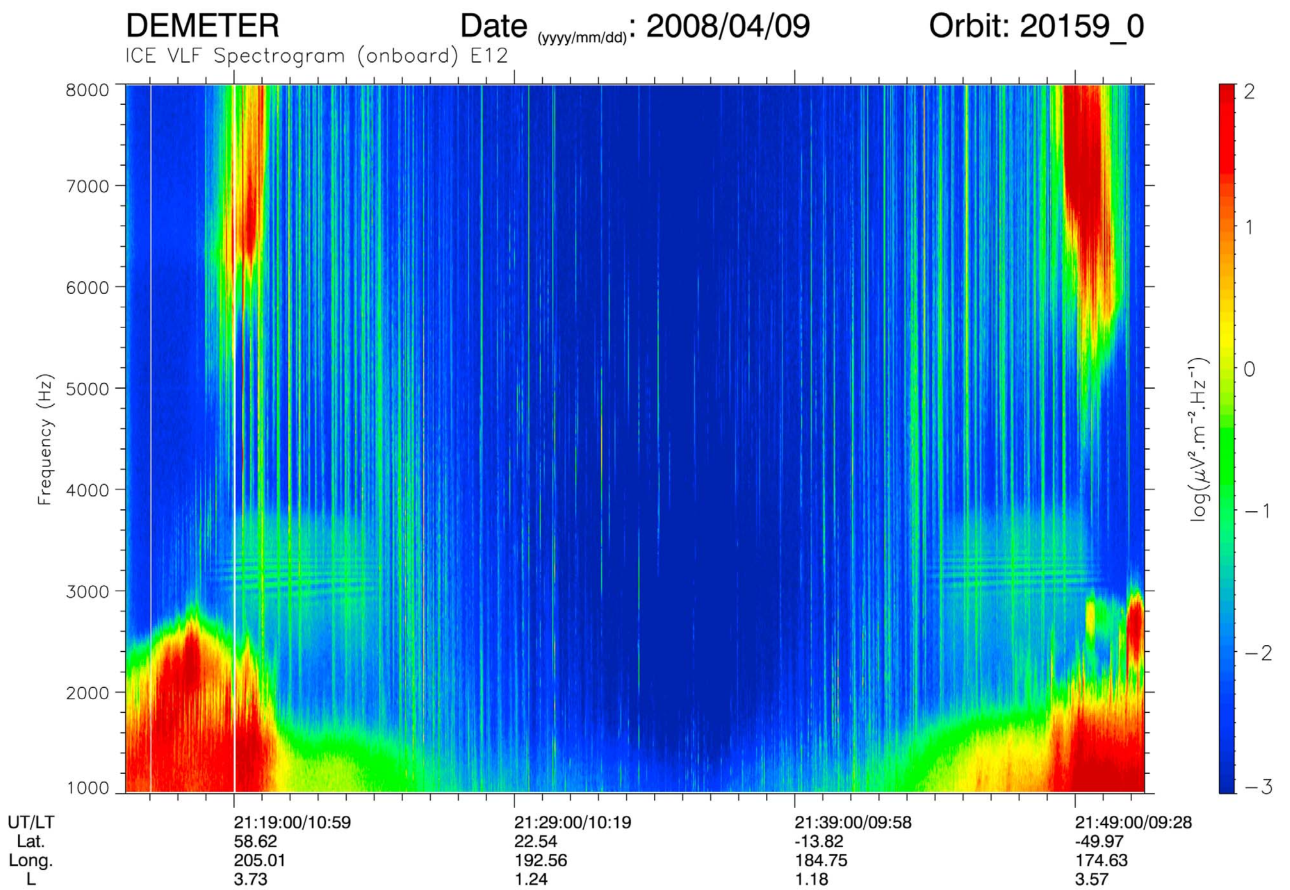

Figure 1. An example of a frequency-time spectrogram of a single half-orbit used for the identification of magnetospheric line radiation (MLR) events. Two MLR events at frequencies between about 2800 and 3400 Hz can be seen. The first MLR event was detected between about 21:19 UT and 21:24 UT. The second MLR event was detected between about 21:44 UT and 21:49 UT. The events occur close to the magnetically conjugate regions.

the lines forming MLR events are in general approximately parallel, we can define a frequency drift of an event as an arithmetic average of the frequency drifts of the individual lines. This average frequency drift trend is then subtracted from the straight approximation lines and the frequencies of the resulting residual lines are calculated as arithmetic averages of their beginning and ending frequencies. The frequencies of the residual lines are then fitted by a linear regression as a function of the integer index number attributed successively to each individual line in order to

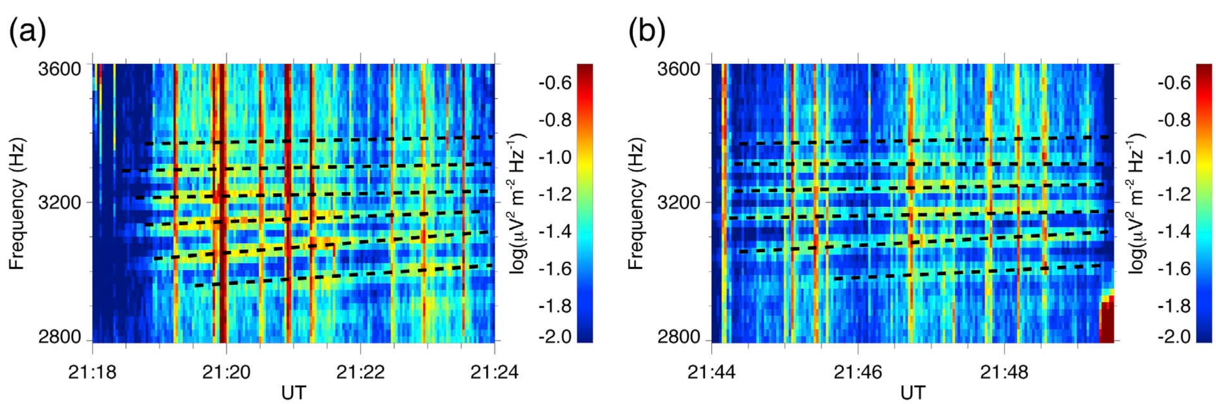

Figure 2. Detailed frequency-time spectrograms corresponding to the two MLR events from Figure 1. The straight lines manually found to approximate the individual lines forming the events are over-plotted by the black dashed lines.

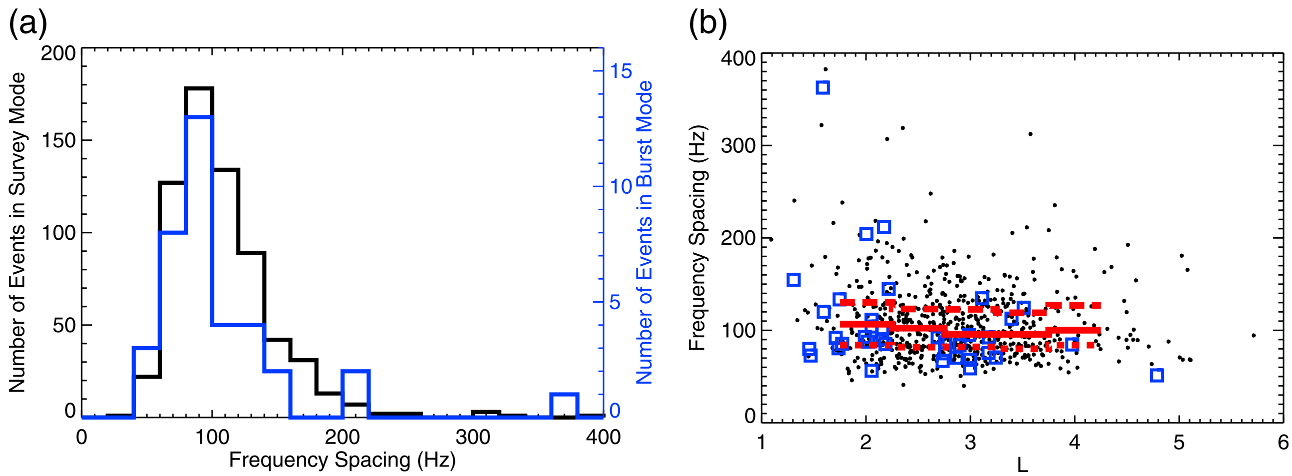

Figure 3. (a) Histograms of frequency spacing of individual lines forming the events. The histogram obtained using the survey mode data is plotted by the black line, using the scale on the left. The histogram based on 37 events for which the burst mode data were available is plotted by the blue line, using the scale on the right. (b) Frequency spacing of individual lines forming the events as a function of their central L-shell. The results obtained using the survey mode data are plotted by the black points. The results obtained for a few events for which the burst mode data were available are plotted by the blue squares. The red lines show the median value (solid) and the 0.25 and 0.75 quartiles (dotted and dashed, respectively).

determine the frequency spacing. The values of the frequency drift obtained for the two MLR events from Figure 2 were 0.13 Hz s^{-1} and 0.09 Hz s^{-1} and the values of the frequency spacing were 77.6 Hz and 76.4 Hz, respectively. The precision of these results is obviously limited by the frequency resolution of the instrument and, moreover, by the fact that the lines forming the events are neither perfectly straight nor exactly parallel. However, since each MLR event consists of several lines and we are interested in average characteristics, the relevant inaccuracies decrease accordingly. Consequently, the two parameters express to a good degree basic detailed properties of MLR events.

[11] Concerning the 37 events for which the burst mode data were available, an alternative approach to determine the frequency spacing and the frequency drift has been used. Frequency spectra with a frequency resolution of 2.44 Hz were calculated for the time intervals corresponding to the beginning and to the end of the MLR events in the burst mode. The peaks in the spectra have been visually identified and the frequency intervals corresponding to the individual peaks have been manually determined using the mouse pointer on the computer screen. Each of the spectral peaks has been then fitted in the appropriate frequency interval by a Gaussian function and the central frequency of the peak has been defined as the central frequency of this Gaussian fit. Knowing the central frequencies of the individual spectral peaks—i.e. knowing the beginning and ending frequencies of the MLR lines—the frequency drifts of the MLR lines have been calculated. The average frequency drift has been determined for each of the MLR events as the average frequency drift of the individual lines forming the event. The average frequency spacing of the lines forming an MLR event has been calculated using a linear regression of the peak central frequencies, separately for the beginning and for the end of the event in the burst mode. The final frequency spacing of the event has been determined as the arithmetic average of the two frequency spacings.

[12] Since the frequency drift and the frequency spacing of the events in the burst mode were determined independently of the events in the survey mode, we can verify the accuracy of the obtained characteristics by their comparison. For frequency spacings, the maximum difference is equal to 41 Hz, the mean difference is equal to 9 Hz and the median difference is equal to 5 Hz. For frequency drifts, the maximum difference is equal to 1.2 Hz s^{-1}, the mean difference is equal to 0.2 Hz s^{-1} and the median difference is equal to 0.1 Hz s^{-1}. Taking into account these results, we can roughly estimate the accuracy of the determined frequency drifts to be about 0.1–0.2 Hz s^{-1} and the accuracy of the determined frequency spacings to be about 5–9 Hz.

3. Results

3.1. Frequency Spacing and Drift

[13] A histogram of the frequency spacings of the MLR events observed during the survey mode is shown in Figure 3a by the black solid line, using the scale on the left. A histogram of the frequency spacings of the MLR events for which the burst mode data were available is plotted by the blue solid line, using the scale on the right. It can be seen that most of the events have frequency spacing close to 100 Hz. The distribution is asymmetric, with a tail extending above 200 Hz. Although the altitude of the DEMETER spacecraft is about constant, the geomagnetic latitude—and therefore also the L-shell—changes. Consequently, it is possible to study the frequency spacing as a function of the L-shell of MLR events. Since a typical time duration of an MLR event observed by the DEMETER spacecraft is a few minutes, the L-shell of the satellite may change considerably during a single observation. We define a central L-shell of an event as the L-shell corresponding to the central time of its observation. Figure 3b shows the frequency spacings of individual lines forming the events as a function of their central L-shells. The results obtained using the survey mode

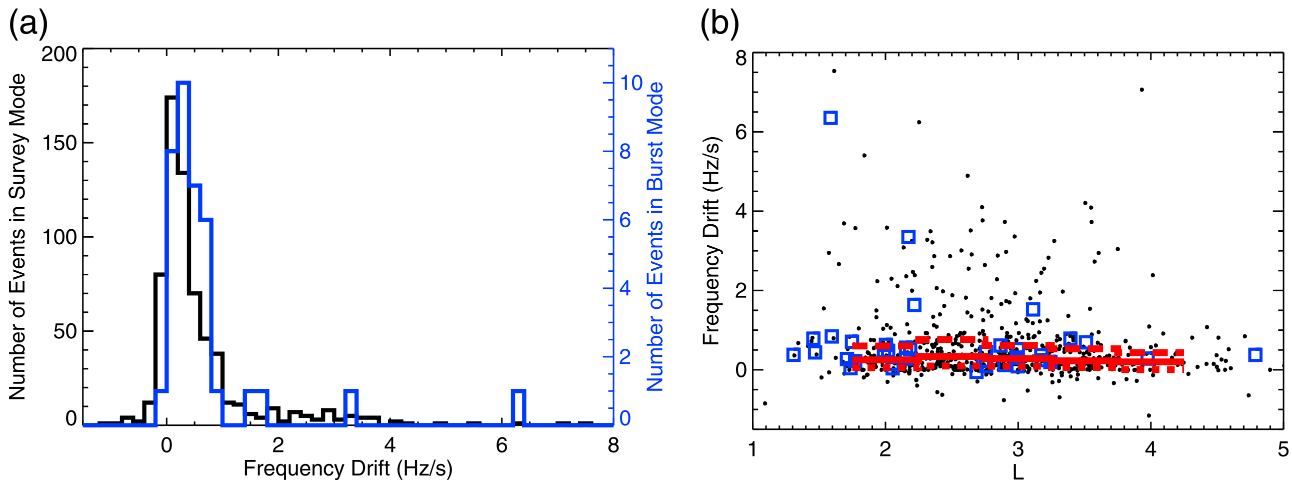

Figure 4. (a) Histograms of average frequency drifts of the analyzed events. The histogram obtained using the survey mode data is plotted by the black line, using the scale on the left. The histogram based on a few events for which the burst mode data were available is plotted by the blue line, using the scale on the right. (b) Average frequency drift of the events as a function of their central L-shell. The format of the figure is the same as that of Figure 3b.

data are plotted by the black points. The results obtained for the MLR events for which the burst mode data were available are plotted by the blue squares. The red lines represent the median value (solid) and 0.25 and 0.75 quartiles (dotted and dashed, respectively) calculated using the survey mode results. It can be seen that the frequency spacing is independent of the L-shell of the satellite at the time of the observation. This is in agreement with our qualitative experience that even long-lasting MLR events that span over several L-shells can be typically reasonably well approximated by a set of nearly parallel lines.

[14] Figure 4 uses the same representation as Figure 3, but it is devoted to the analysis of the frequency drift of MLR events. Figure 4a shows that the frequency drift is typically about 0.5 Hz s^{-1}. It can be both positive and negative. However, the positive values of frequency drift are much more frequent. Out of 653 events in the survey mode, 553 events had a positive frequency drift, 31 events had a zero frequency drift and 69 events exhibited a negative frequency drift. Out of 37 events for which the burst mode data were available, 36 events had a positive frequency drift, while only 1 event exhibited a negative frequency drift. Figure 4b presents an analysis of the frequency drift as a function of the L-shell the events. No clear dependence of the frequency drift on the L-shell of the events has been found. Again, this is in agreement with our qualitative experience that even long-lasting MLR events spanning over several L-shells can be approximated by a set of straight lines.

[15] Having shown that neither the frequency spacing nor the frequency drift depends significantly on the L-shell of the satellite at the time of the observation, we continue to study a dependence of these two basic characteristics of the inner structure of MLR events on other parameters. Figure 5 shows the frequency spacing between the individual lines forming the events as a function of the central frequency of the events. The format used is the same as in Figures 3b and 4b. It can be seen that the median frequency spacing tends to slightly increase with the central frequency of the events. However, the scatter of the data is rather large. Moreover, it should be noted that the frequency spacing increases with the central frequency of the events much slower than what would correspond to a generation at about the same harmonic numbers of the base frequency equal to the frequency spacing. Namely, the median frequency spacing of the events with central frequencies of about 1500 Hz is equal to about 75 Hz and the median frequency spacing of the events with central frequencies of about 4500 Hz is equal to about 129 Hz. This means that while the central frequency of the events is 3 times larger, the median frequency spacing increased only about 1.7 times.

[16] We can further verify the possibility that the frequencies of the individual lines forming the events correspond to harmonics of the base frequency equal to the frequency spacing by analyzing MLR events formed by the lines whose frequencies increase significantly over the time

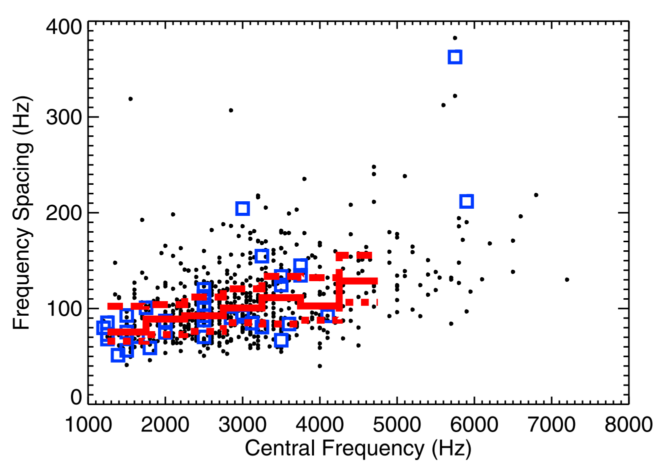

Figure 5. Frequency spacing of individual lines forming the events as a function of their central frequency. The format of the figure is the same as that of Figure 3b.

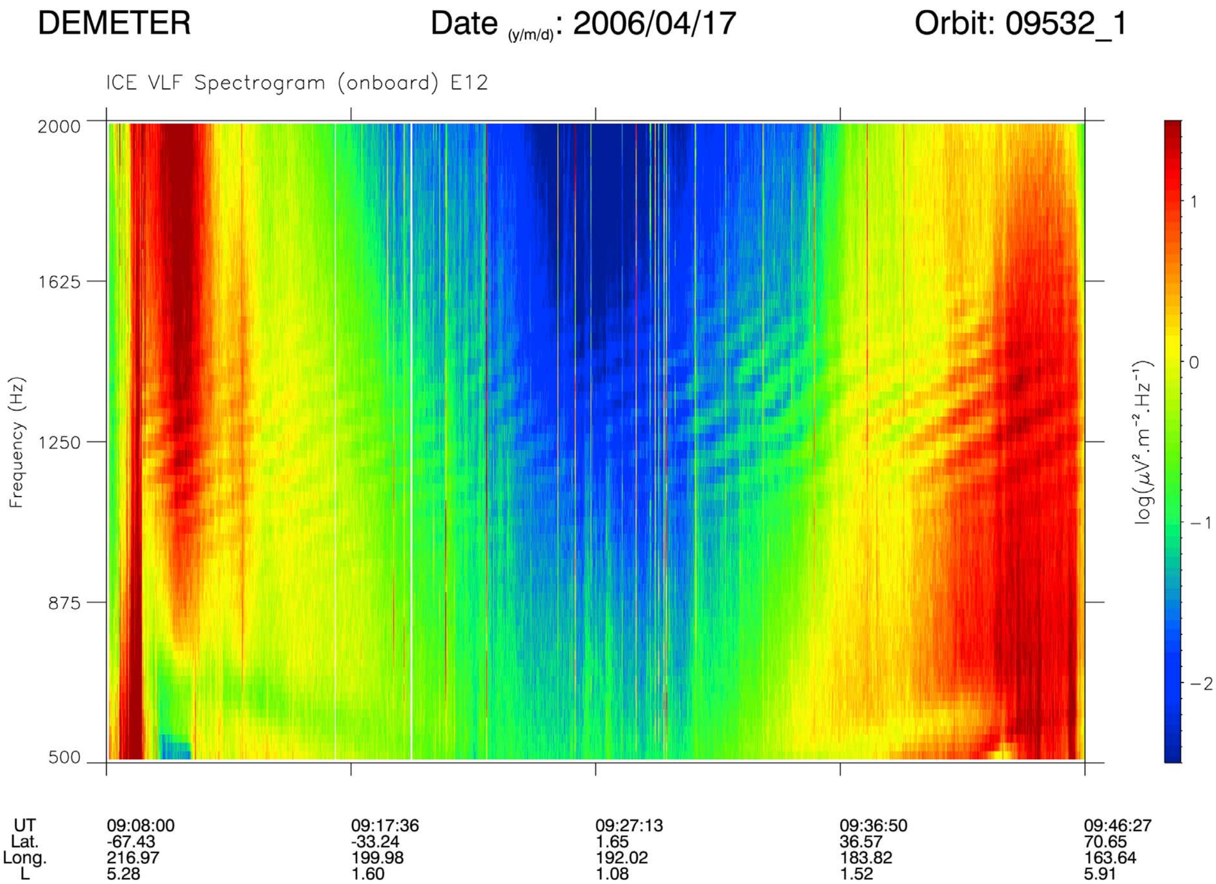

Figure 6. Frequency-time spectrogram of an MLR event that is formed by the lines whose frequencies increase significantly over the time duration of the event.

duration of the events. An example of such an event is shown in Figure 6. If the lines forming the event corresponded to the harmonics of the frequency spacing, the frequencies of the lines should be directly proportional to the frequency spacing. However, this is not observed. Although the frequencies of the lines increase significantly, the frequency spacing remains about the same during all the event. This qualitative observation can be quantified by checking the ratio of the frequency spacing at the end and at the beginning of a chosen time interval as a function of the relative change of the frequencies of the lines over the time interval. The results obtained for 11 MLR events formed by the lines whose frequencies increase significantly enough to enable this type of analysis are shown in Figure 7. The dashed line shows a linear dependence that would be expected if the individual lines corresponded to harmonics of the base frequency equal to the frequency spacing. The solid line shows a dependence corresponding to a constant frequency spacing. It can be seen that the results are in agreement with our qualitative impression from Figure 7; although the frequencies of the lines change quite significantly during the events, their frequency spacings remain about constant.

[17] Finally, the median frequency spacing between the individual lines forming the events seems to be slightly larger during the disturbed periods, when the plasmasphere is more compressed. This is demonstrated in Figure 8 that shows the frequency spacings of MLR events as a function of the model location of the plasmapause determined using the empirical model by *Moldwin et al.* [2002]. Again, it should be noted that the scatter of the data is rather large.

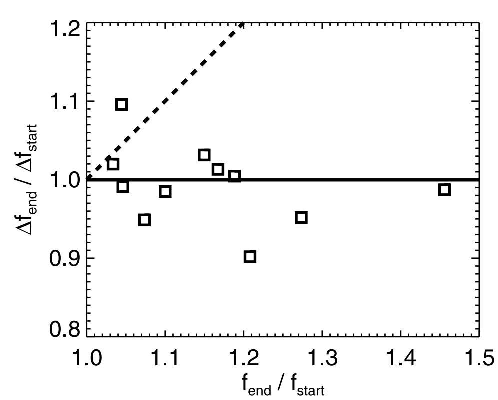

Figure 7. Ratio of the frequency spacing at the end and at the beginning of 11 MLR events that are formed by the lines whose frequencies increase significantly over the time duration of the events as a function of the relative change of their frequency. The dashed line shows the dependence expected for the generation at harmonics of the base frequency equal to the frequency spacing. The solid line shows the dependence corresponding to a constant frequency spacing.

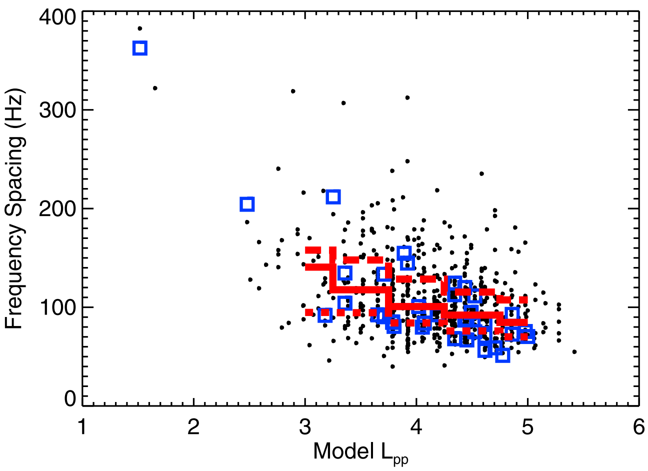

Figure 8. Frequency spacing of the individual lines forming the events as a function of the model location of the plasmapause. The format of the figure is the same as that of Figure 3b.

Moreover, since the empirical model of the plasmapause location is based primarily on 12 hour history of Kp index, a similar dependence is obtained also if only Kp index at the time of the observation is considered. No significant difference has been found between the events observed during the day and during the night (not shown).

4. Discussion

[18] The database of the MLR events used was based on the data set from our previous study [*Němec et al.*, 2009] that we have extended till the end of September 2008 (i.e. we have added about 1 year of data). The events were visually identified in frequency-time spectrograms of individual half-orbits of DEMETER data and all the drawbacks discussed by *Němec et al.* [2009] related to this procedure apply also to the presented paper. Namely, the identification of events is necessarily somewhat subjective and depends on the individual feeling of the observer. Following *Němec et al.* [2009], this was at least partially solved by using a constant color scale of the power spectral density all over the analyzed data set and the data were inspected twice, independently.

[19] Another crucial point concerning the data set analyzed in the presented study is the procedure used to determine the frequency spacing and the frequency drift of MLR events. The individual lines forming the events were visually identified in frequency-time spectrograms. It was assumed that the MLR events consist of straight lines, i.e., that their frequency drift is constant. Although there have been MLR events reported for which this approximation completely fails [*Rodger et al.*, 1999], it typically works well for the MLR events observed by the DEMETER spacecraft. The fact that the individual lines forming the events were identified separately for the events in the survey mode and for the 37 events for which the burst mode data are available allows us to verify the validity of the applied procedure and to estimate the corresponding errors by comparing the two data sets. A typical difference between the frequency drift determined using the survey mode data and the frequency drift determined using the burst mode data is about 0.1–0.2 Hz s^{-1}. A typical difference between the frequency spacing determined using the survey mode data and the frequency spacing determined using the burst mode data is about 5–9 Hz. Taking into account that these inaccuracies are small compared to the absolute values of parameters in the analyzed dependencies, the determined frequency spacings and frequency drifts can be considered as rather robust characteristics of detailed properties of MLR events.

[20] The obtained histograms of frequency spacings and frequency drifts from Figures 3a and 4a can be directly compared with the results obtained by *Rodger et al.* [1999] using ground-based measurements at $L \approx 4.3$ (see their Figures 5 and 4, respectively). Concerning the frequency spacing between individual lines forming the events, the distribution that we have obtained is qualitatively rather similar to that obtained by *Rodger et al.* [1999], i.e., asymmetric distribution with a roughly exponential decrease at large values of frequency spacings. However, there are significant quantitative differences, especially at frequencies lower than about 100 Hz. While our distribution of frequency spacings peaks at about 100 Hz and no MLR events with frequency spacing lower than 40 Hz have been observed, the distribution of *Rodger et al.* [1999] peaks at about 50 Hz and extends down to the frequency spacings as low as 20 Hz. This difference in the obtained distributions can be most likely explained by the limited frequency resolution. The MLR events analyzed in our study were identified in the VLF data measured in the survey mode. The frequency resolution of these data is only 19.53 Hz, and, depending on the frequencies of the MLR lines relative to the central frequencies of the frequency bins of the electric field instrument, frequency spacings up to 60 Hz may be too low to be distinguished. Events with the frequency spacing below or only slightly larger than this minimum frequency spacing were likely to be missed during the identification process. The frequency resolution of the study by *Rodger et al.* [1999] was significantly better than ours, being equal to about ±7 Hz. This allowed them to check if the line spacings preferentially show spacings near harmonics of electrical transmission frequencies, either 50 Hz or 60 Hz, and they reported that this is not the case. The frequency resolution of our data is not sufficient to perform such kind of analysis.

[21] Concerning the frequency drift of MLR lines, the absolute values of the frequency drifts that we have obtained are in agreement with the absolute values of the frequency drifts obtained by *Rodger et al.* [1999]. However, although the frequency drifts observed by the DEMETER spacecraft are generally positive, *Rodger et al.* [1999] reported that in the Halley data the proportion of events showing upward drift is almost equal to that with downward drift. We do not have any explanation for this striking difference at the moment. It might be argued that the situation at the geomagnetic longitudes of Halley may be affected by the South Atlantic geomagnetic anomaly. However, neither the frequency drifts nor the frequency spacings of MLR events observed by DEMETER seem to depend on the geomagnetic longitude (not shown). Nevertheless, one must consider that while the frequency drift observed by the ground-based instruments corresponds to the "real" frequency drift, i.e., to the change of the frequency purely as a function of time, the frequency drift observed by a satellite is also affected by the

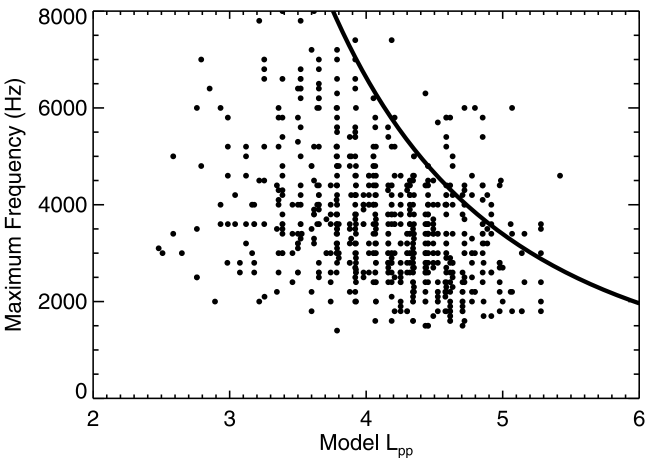

Figure 9. Maximum frequency of MLR events as a function of the model location of the plasmapause. One half of the equatorial electron cyclotron frequency at the plasmapause distance is over-plotted by the thick solid line.

fact that the satellite is moving, i.e., a spatial dependence of the frequency must be taken into account. Anyway, it is difficult to imagine such a spatial dependence of the frequencies of the MLR lines that would explain the always positive frequency drift observed. Namely, during a single half-orbit the satellite moves from large geomagnetic latitudes (i.e., large L-shells) through the geomagnetic equator (i.e., very low L-shells) to the large geomagnetic latitudes in the opposite hemisphere. This means that a possible dependence of the line frequencies on the L-shell cannot explain the observed behavior. Moreover, sometimes there are two MLR events observed during the same half-orbit, located in the geomagnetically conjugate regions, that both exhibit a positive frequency drift (see, e.g., Figure 6 and the event presented by *Němec et al.* [2009, Figure 1]). This means that the slope of the lines observed in the conjugate regions does not correspond to bouncing of waves between the hemispheres. It may indicate that the mostly positive frequency drift of the MLR events observed by DEMETER is really the change of the frequency as a function of time in the source, not a spatial effect induced by the spacecraft motion.

[22] As demonstrated by Figures 3b and 4b, neither the frequency spacing of the individual lines forming the events nor their frequency drift depend significantly on the L-shell of the satellite at the time of the observation. This indicates that the properties of MLR events are independent of the source L-shell. Moreover, the L-shell of the satellite at the time of observation can be hypothetically very different from the source L-shell, if the waves propagate unducted over a long propagation path. In the absence of a significant Landau damping, the waves from a single source may illuminate a large area spanning over a significant range of L-shells. Ray tracing results [*Inan and Bell*, 1977] show that waves can be guided along the inner boundary of the plasmapause. Such kind of guiding seems to be necessary to explain how the MLR events can reach the ground. Moreover, since the guided waves are found to deviate inward at altitudes of about 4000 to 6000 km and to reach the ionosphere at lower L-values [*Inan and Bell*, 1977], such a scheme might possibly explain the L-extent of the MLR events as well as why they are limited within the plasmasphere [*Němec et al.*, 2009].

[23] Only the waves with frequencies lower than one half of the minimum electron cyclotron frequency along the raypath can be ducted by density enhancements [*Smith*, 1961; *Carpenter*, 1968]. The upper frequency limit for waves guided by the plasmapause inner boundary is found to be even slightly lower [*Inan and Bell*, 1977]. The suggested guiding of MLR by the plasmapause boundary is therefore in agreement with the fact that the maximum frequencies of the events are in most cases lower than one half of the equatorial electron cyclotron frequency at L_{pp}, where L_{pp} is the estimated location of the plasmapause. This can be seen in Figure 9 that shows the maximum frequencies of the MLR events observed by the DEMETER spacecraft as a function of the model location of the plasmapause determined using the empirical model of *Moldwin et al.* [2002]. One half of the equatorial electron cyclotron frequency calculated using a dipole magnetic field model at the radial distance of the plasmapause is over-plotted by a thick solid line. The minimum frequencies of MLR events are—with the exception of a few events that can be most likely explained by an inaccuracy of the used plasmapause location model—lower than the upper frequency limit for ducting/guiding.

[24] An additional supporting argument for the hypothesis that MLR events are guided by the plasmapause inner boundary may come from a detailed wave analysis. One electric and one magnetic field component measured by the DEMETER spacecraft in the VLF range are not sufficient to perform a detailed wave analysis, i.e., to determine the polarization properties of the electromagnetic waves and to calculate where they are coming from. However, the waveforms of all the six electromagnetic field components are measured during the burst mode below 1 kHz, which allows us to perform such kind of analysis [see, e.g., *Santolík et al.*, 2006, and references therein]. Among all the identified MLR events, only one event occurred during the burst mode at sufficiently low frequencies to be close to this limit. The results show that the waves are coming from lower geomagnetic latitudes and larger radial distances. However, they cannot be considered as entirely reliable, because the waves are measured at the upper limit of the frequency range of the instrument.

[25] Concerning the generation mechanism of MLR events, the available data clearly show that the individual lines forming an MLR event do not correspond to the harmonics of the base frequency equal to the frequency spacing (Figure 7). We suggest that a possible generation mechanism might be an interaction between a wave of a carrier frequency drifting in time and an additional wave with a nearly constant frequency equal to the observed frequency spacing. Results depicted in Figure 5 would then suggest that there is a weak correlation between the frequencies of the two waves, with larger carrier frequencies more likely interacting with higher frequency waves. However, we would like to underline that this is merely a suggestion and that we are still far from aiming for a comprehensive model of MLR.

[26] The results depicted in Figure 8 suggest that the MLR events generated during the disturbed periods, when the plasmasphere is compressed, have larger frequency spacings. This is possibly related to the change of the source location. Since the frequency spacing might hypothetically

be related to the cyclotron frequencies at the source location, the increase of the frequency spacing could indicate that the source of the emissions is located at lower radial distances.

[27] A detailed theoretical understanding of the generation mechanism of MLR events is needed in order to explain all the observed dependencies. Although this is definitely beyond the scope of the presented paper, the experimental relations that we have found using a large amount of satellite data measured at different L-shells and during various geomagnetic conditions should facilitate this future work.

5. Conclusions

[28] Results of a systematic study of detailed properties of MLR events observed by a low-altitude satellite have been presented. We have used the data set of *Němec et al.* [2009] extended till the end of September 2008, which corresponds to about 4 years of data altogether. According to our knowledge, this represents the largest satellite database of MLR events collected to date. We have focused on the analysis of the frequency spacing of individual lines forming the events and their frequency drift. We have shown that the individual lines forming the events cannot be explained as harmonics of the base frequency equal to the frequency spacing. We have suggested that a possible generation mechanism of MLR events might be an interaction between a wave of a carrier frequency and an additional wave with the frequency equal to the observed frequency spacing. The events observed during periods of increased geomagnetic activity, when the plasmasphere is compressed, tend to have larger frequency spacing. The magnetospheric origin is therefore likely, although our data set does not allow us to exclude that the waves are generated from power lines (see the case reported by *Němec et al.* [2009], which indicates that such a generation might be at least sometimes possible). We have also shown that neither the frequency drift nor the frequency spacing depends significantly on the L-shell where the event was observed. Moreover, the frequency drift is generally positive, i.e., the slope of the lines observed in the conjugate regions does not correspond to bouncing of waves between the hemispheres. We have hypothesized that the waves propagate at least part of their propagation path unducted, so that a single source can, in the absence of a significant wave damping, possibly illuminate a large area spanning over a significant range of L-shells. These waves might be guided along the inner plasmapause boundary before they deviate to lower L-shells at altitudes of a few thousands of kilometers [*Inan and Bell*, 1977].

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