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Key Points:

- We analyzed in detail about 400 quasiperiodic (QP) events of DEMETER and corresponding observations of ground Canadian Array for Realtime Investigations of Magnetic Activity magnetometers
- The type of QP emissions can be defined by value of frequency drift of QP elements
- More intense QP events are associated with higher power of Pc 3–4 pulsations

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Quasiperiodic ELF/VLF Emissions Associated With Corresponding Pulsations of the Geomagnetic Field

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Abstract We present a comparison between properties of quasiperiodic (QP) extra low frequency/very low frequency emissions observed by the low-altitude DEMETER spacecraft and ultra-low frequency (ULF) geomagnetic field pulsations measured on the ground by the Canadian Array for Realtime Investigations of Magnetic Activity system of flux-gate magnetometers and by the Sodankylä Geophysical Observatory magnetometer. Altogether, we have analyzed 398 QP events observed at the times when DEMETER was close to the ground-based magnetometers. The modulation periods of the analyzed QP events were larger than 10 s and their frequency bandwidths were larger than 200 Hz. For a part of QP emissions with modulation periods about 30 s, there was a good agreement between the modulation periods and peak frequencies of ULF magnetic field pulsations measured on the ground. These QP emissions appear to be closely associated with coincident geomagnetic pulsations (QP1 type), and they represent ∼18% of the total number of analyzed QP events. No corresponding geomagnetic pulsations were identified in the remaining 82% of QP events (QP2 type). The intensity of QP1 events does not seem to correlate with the intensity of geomagnetic field pulsations, while the intensity of QP2 events increases with the integral intensity of geomagnetic field pulsations. Based on the observed association between QP emissions and geomagnetic field pulsations, we estimate the radial distance of the generation region of QP1 emissions to $L \sim 7$.

1. Introduction

Very-low frequency (VLF) emissions with noise-like spectrum and almost periodically modulated wave amplitudes, which are observed on the ground and in the inner magnetosphere, are known as quasiperiodic (QP) emissions (Kitamura et al., 1969; Sato et al., 1974). In the magnetosphere, these signals were identified as whistler mode waves. These emissions effectively consist of individual bursts which can have no frequency dispersion or their characteristic frequency can increase during evolution of each burst. The modulation period can vary from about 10 s to several minutes, and the frequency range of QP emissions is typically from about 0.5–4 kHz (Sato & Fukunishi, 1981; Smith et al., 1998). QP emissions are mostly dayside phenomena, and they occur over large spatial regions. Their occurrence seems to be limited to regions of closed magnetic lines at L ∼ 2–8. The duration of QP events can be from a few minutes to several hours (Hayosh et al., 2014; Manninen et al., 2014; Němec et al., 2014; Sazhin & Hayakawa, 1994).

A historically used classification of QP emissions is to distinguish the emissions associated (QP type 1) and not associated (QP type 2) with ultra-low frequency (ULF) geomagnetic field pulsations (Sato & Fukunishi, 1981). The association of QP1 emissions with the ULF pulsations of the geomagnetic field was investigated both by space and ground-based instruments (Manninen et al., 2014; Morrison et al., 1994; Němec, Santolík, Pickett, et al., 2013; Oguti et al., 1986; Sato & Kokubun, 1980; Tixier & Cornilleau-Wehrlin, 1986). It has been suggested that compressional component of the ULF waves modulates resonance conditions and growth rate in the source region, which results in the QP modulation of the wave intensity (Manninen et al., 2012; Sato et al., 1974).

The QP2 waves were observed in the absence of strong external periodic disturbances and mechanism of wave amplitude modulation is still under study. It can be related to plasma relaxation oscillations of the cyclotron instability in the wave generation region (Bespalov & Trakhtengerts, 1976; Davidson, 1979) which can turn into stable and self-sustaining oscillations (Bespalov, 1982; Demekhov & Trakhtengerts, 1994; Pasmanik, Demekhov, et al., 2004; Pasmanik et al., 2019). The constant source of energy in such mechanisms can be the injection of energetic electrons into the interaction region by their magnetic drift (Pasmanik, Titova, et al., 2004). It is assumed that energetic electrons have anisotropic velocity distribution. Removal of energetic particles from the interaction region can be due to precipitation of electrons via the loss cone and or drift of particles away from the interaction region across the magnetic field lines (Trakhtengerts et al., 1986).

The occurrence of QP2 emissions can be associated with precipitating high-energy electrons modulated with the same period as QP2 emissions, which has been experimentally demonstrated using low-altitude DEMETER and National Oceanic and Atmospheric Administration spacecraft data (Hayosh et al., 2013; Němec et al., 2021). Titova et al. (2015) studied Van Allen Probes spacecraft measurements and compare changes of the energetic electron flux with periods of the QP modulation. Recent survey by Li et al. (2021) based on Van Allen Probes wave measurements and the energetic electron data obtained by the Polar-orbiting Operational Environmental Satellite present energetic electron precipitation simultaneously with QP emissions.

QP emissions can propagate ducted, unducted, or, at low geomagnetic latitudes, even perpendicular to the Earth's ambient magnetic field (Hayosh et al., 2016; Manninen et al., 2014; Parrot et al., 2016). The unducted propagation can be reason for observations of the same QP event or the same wave modulations at different location over comparatively large region (Bezděková et al., 2020; Němec, Santolík, Parrot, et al., 2013; Němec, Hospodarsky, et al., 2016).

Hayosh et al. (2016) discussed the role of a possible guiding of QP emissions by the plasmapause based on observations of sudden change of propagation direction of QP emissions which takes place at low altitudes and at middle latitudes. This effect has also been analyzed by a ray-tracing simulation of Hanzelka et al. (2017). A study Němec et al. (2018) of QP event observations by the Van Allen Probes spacecraft showed that the events occur primarily, but not always, inside the plasmasphere. However, the overall role of the plasmapause in the formation or modification of QP emissions is not yet well understood. Multipoint measurements of QP events can help to estimate temporal and spatial properties of the emissions (Manninen et al., 2014; Němec, Santolík, Parrot, et al., 2013; Tixier & Cornilleau-Wehrlin, 1986) and/or location of their source (Martinez-Calderon et al., 2016, 2020; Němec, Bezděková, et al., 2016; Němec, Hospodarsky, et al., 2016).

In the present paper, we study QP emissions observed by the low-altitude DEMETER spacecraft along with ground-based measurements of ULF pulsations of the geomagnetic field. The instrumentation and data are described in Section 2. The results are presented in Section 3, and they are discussed in Section 3. A brief summary of the main results is given in Section 4.

2. Data

This paper is based on measurements of the DEMETER spacecraft which operated between 2004 and 2010. The spacecraft orbit was nearly Sun-synchronous, that is, the data were always collected either shortly before the local noon (about 10:30) or shortly before the local midnight (about 22:30). The spacecraft altitude was about 700 km. The measurements were limited to geomagnetic latitudes within about ±65° (Parrot et al., 2006).

QP events observed by DEMETER during the entire spacecraft mission were statistically analyzed by Hayosh et al. (2014). However, as locally measured magnetic field at frequencies below 0.1 Hz is not available in the DEMETER data set, a relation between the analyzed QP events and geomagnetic field pulsations was not analyzed. The lack of local measurements of magnetic field pulsations is resolved in the present study by using the observations performed by the Canadian Array for Realtime Investigations of Magnetic Activity (CARISMA) system of ground-based flux-gate magnetometers (Mann et al., 2008) and Sodankylä Geophysical Observatory (SGO) magnetometer (64.0°N, 107.2°E, $L = 5.3$) which is a part of the IMAGE system of magnetometers (Tanskanen, 2009). A geographic map of the locations of the magnetometers from both Carisma network and Sodankyla station are presented in Figure 1a. The CARISMA array covers a range of longitudes from Dawson City, YK, Canada (220.89°E) to Rankin Inlet, NU, Canada (267.89°E), and a range of latitudes from Taloyoak, NU, Canada (69.54°N) to Osakis, MN, USA (45.87°N). Most of these instruments are located at two meridians known as the "Churchill Line" and "Alberta Line" (marked by the green and blue lines in Figure 1a, respectively).

The resolution of magnetic field measurements is 0.025 nT, and the sampling rate is 8 Hz. The publicly available CARISMA data contain three components of the geomagnetic field with 1 Hz sampling (down-sampled from the measured data sampled at 8 Hz) and they are available since 2005. The time resolution of SGO magnetometer data was 2 Hz. While DEMETER provided observations in a narrow range of longitudes and the apparent

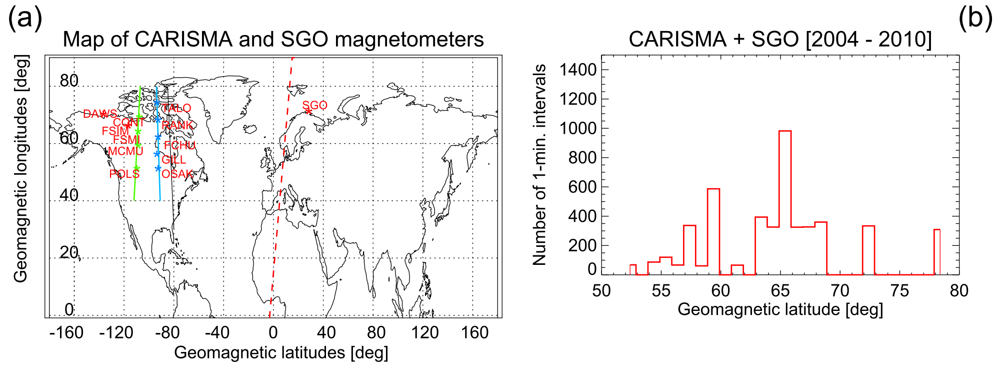

Figure 1. (a) Geographic map showing the locations of the Canadian Array for Realtime Investigations of Magnetic Activity system and Sodankylä Geophysical Observatory (SGO) magnetometers. The dotted red line presents a projection of an example daytime half-orbit trajectory of DEMETER spacecraft during active operation period. (b) Latitudinal distribution of ground-based measurements. The number of 1-min intervals of observations are shown on ordinate axis. The peak of the distribution at the geomagnetic latitude of about 65° is related to the SGO magnetometer measurements.

temporal duration of the observed events was usually rather low, spatially distributed array of magnetometers can be selected to estimate the time duration and spatial extent of geomagnetic field disturbances at larger scales. Figure 1b shows a distribution of CARISMA and SGO magnetic field measurements during the QP events from our data set as a function of the geomagnetic latitude.

We use a list of 2181 QP events observed by DEMETER and compiled by Hayosh et al. (2014). For each of the analyzed QP events we calculated the median value of the modulation period, the median value of the frequency drift, and the maximum intensity of QP elements. Example of frequency-time spectrograms of the power spectral density for a QP event observed by DEMETER on 2 June 2005 is shown in Figure 2.

The event was observed during a single daytime DEMETER pass from the Northern hemisphere to the Southern hemisphere between 19:27 UT and 20:02 UT. A set of QP elements with a modulation period of about 30 s (Northern hemisphere) and 35 s (Southern hemisphere) can be seen, starting at the beginning of the plotted time intervals. The intensity of the QP elements slowly decreases toward lower geomagnetic latitudes in both hemispheres. The data at larger geomagnetic latitudes were not measured (see Section 2).

We identified 398 QP events, from the initial QP event list, which were observed at geomagnetic longitudes within 5° from any CARISMA or SGO magnetometer station. In the case of CARISMA system of magnetometers, this limitation covers a region between 268° and 354° of geomagnetic longitude. Since the primary purpose of our study is to compare properties of QP events observed in the magnetosphere with ULF pulsations detected

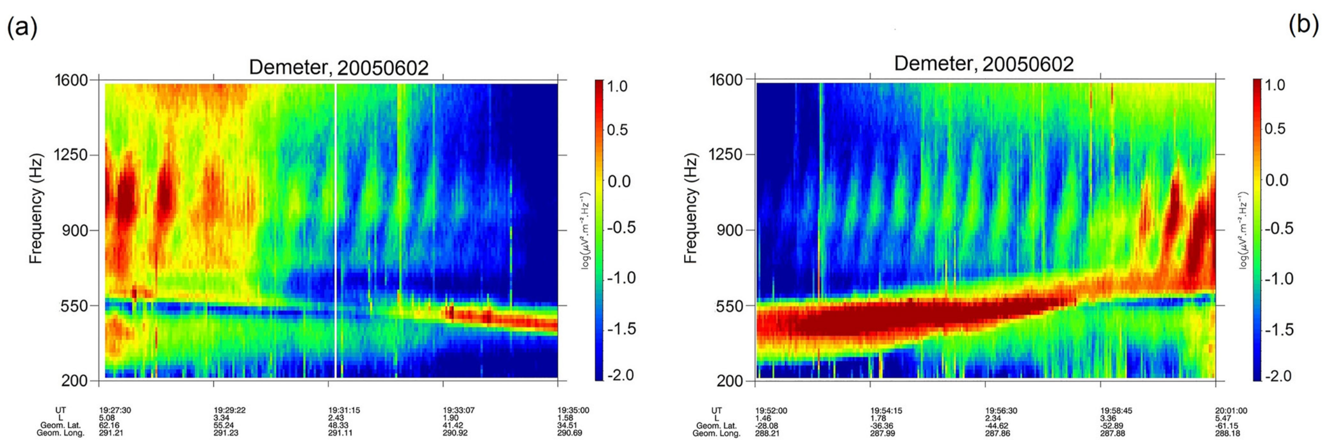

Figure 2. Frequency-time spectrograms of power spectral density of electric field fluctuations corresponding to quasiperiodic (QP) events measured on 2 June 2005 between 19:27 UT and 19:34 UT in the Northern hemisphere (left panel) and between 19.52 UT and 20:02 UT in the Southern hemisphere (right panel). A set of individual QP elements slowly fading out toward lower geomagnetic latitudes can be seen at frequencies between ∼700 and ∼1700 Hz.

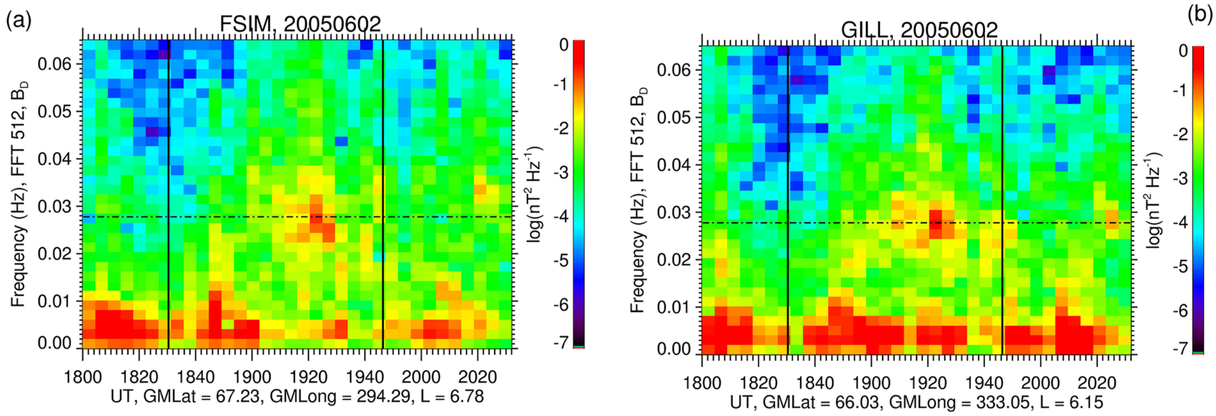

Figure 3. Frequency-time spectrograms of B_D magnetic field component obtained for the time interval of the quasiperiodic (QP) event from Figure 2 (2 June 2005) using (a) the FSIM and (b) the GILL magnetometers data during the same time interval. The black horizontal dashed lines denote the modulation frequency of the QP event. The vertical black lines mark the time interval when the QP event was observed.

simultaneously on the ground, we compare the periods of the most intense ground magnetic field fluctuations with the modulation periods of corresponding QP events.

In order to quantitatively analyze the frequencies of the geomagnetic pulsations during this time interval, we calculate the corresponding frequency-time spectrograms of power spectral density of magnetic field fluctuations. The power spectral density in the frequency range of interest is larger in the B_D-component than in the B_H-component. We thus focus primarily on the power spectra of the B_D geomagnetic field component in a 2 h long time interval centered on the time of the QP event. We use a discrete Fourier transform over 512 samples with 75% overlapping and averaging over 2 neighboring time intervals. Additionally, we calculate averaged frequency spectra of both geomagnetic field components using a shorter 15 min long time interval centered on the time of the QP event. A frequency-time spectrogram of the power spectral density of the fluctuations of the B_D geomagnetic field component corresponding to this time interval is then computed for each of the CARISMA stations. This allows us to identify dominant frequencies of the ULF pulsations at different locations corresponding to individual magnetometer stations.

The frequency-time spectrograms of the B_D geomagnetic field component calculated for the example event from Figure 2 using the data measured by the FSIM magnetometer station (67.23°N, 294.29°E) on 2 June 2005, are shown in Figure 3a. The FSIM station was the closest operating station to spacecraft footprint at the time of the QP event observations. The duration of the QP emission as observed by the DEMETER spacecraft is marked by the two vertical black lines in the figure. The frequency corresponding to the modulation period of the QP emissions is denoted by the black horizontal dashed line. Similar magnetic field perturbations were simultaneously observed also by other CARISMA magnetometers, located over a wide range of longitudes, and even quite far from the footprint of the spacecraft.

As an example, Figure 3b uses the same representation for the data obtained using the GILL magnetometer of the “Churchill line” (66.03°N, 333.05°E), which is located about 40° eastward from the FSIM magnetometer. Again, one can see the enhancement of the power spectral density of magnetic field fluctuations at the times and frequencies corresponding to the QP event.

For both magnetometers, the intensity of geomagnetic field pulsations of both geomagnetic field components at the frequencies between 23 and 32 mHz (corresponding to the periods between about 43 and 31 s) is clearly increased in the time interval between 19:18 UT and 19:32 UT. These frequencies correspond well to the QP event modulation period of ∼35 s in the Northern hemisphere, taking into account that the modulation period of a QP event can vary by about 20% over the event duration (Hayosh et al., 2014; Manninen et al., 2014; Němec, Hospodarsky, et al., 2016).

Since the magnetic field variations are well seen in the “Churchill line” magnetometer data, we present in Figure 4a power spectra of the B_D-component measured by all these stations in order to investigate latitudinal variations of the amplitude of the fluctuations. The spectra were computed for the time interval from 19.20 UT to

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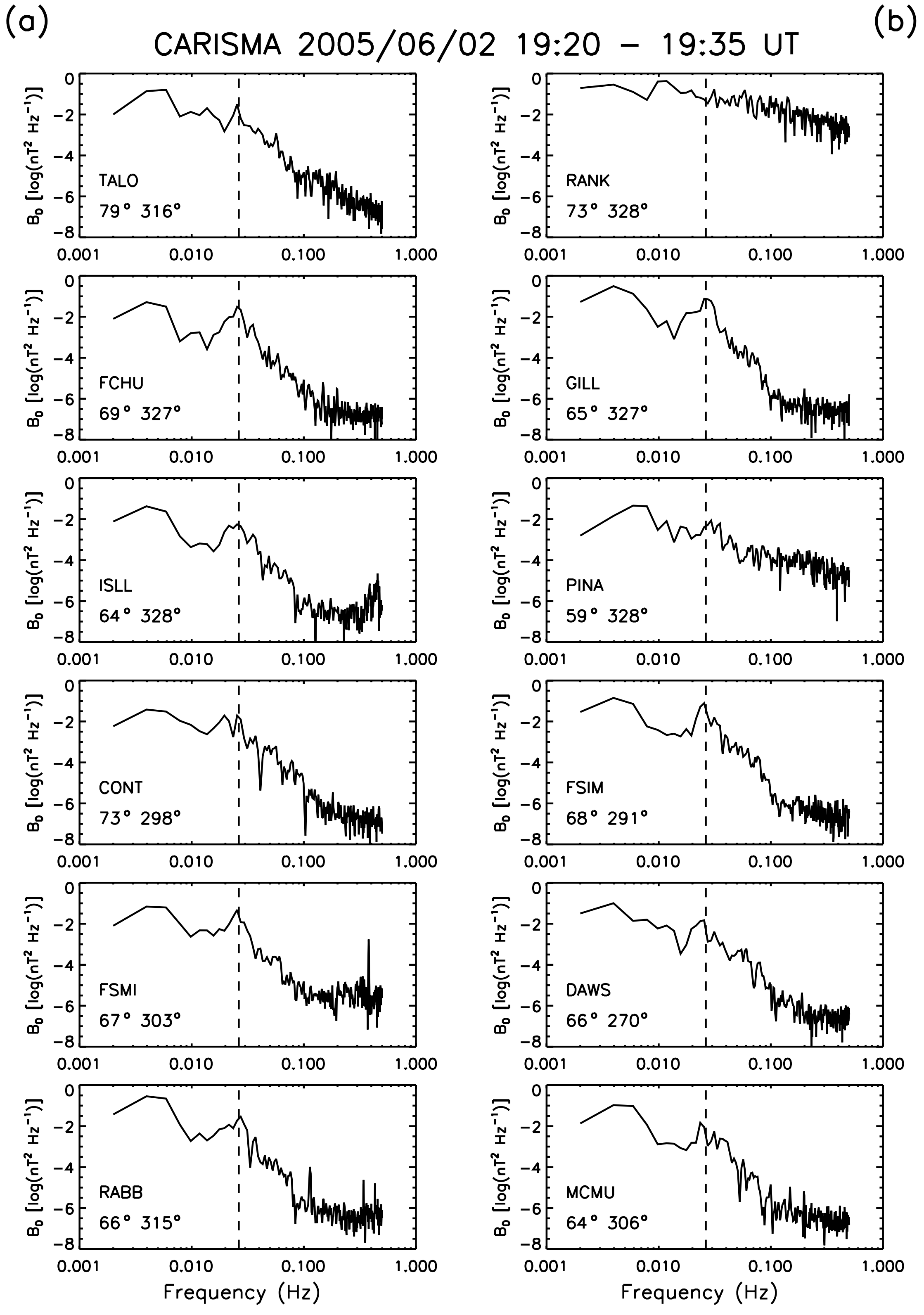

Figure 4. Frequency spectra of the B_D component of the geomagnetic field in the time interval between 19.20 UT and 19.35 UT. (a) Canadian Array for Realtime Investigations of Magnetic Activity (CARISMA) system magnetometers combined in the "Churchill line" chain. (b) CARISMA system magnetometers which are not combined in the chain. The vertical black dashed lines denote the modulation frequency of the quasiperiodic event. The amplitudes of the peaks along with magnetometer coordinates are shown in each panel.

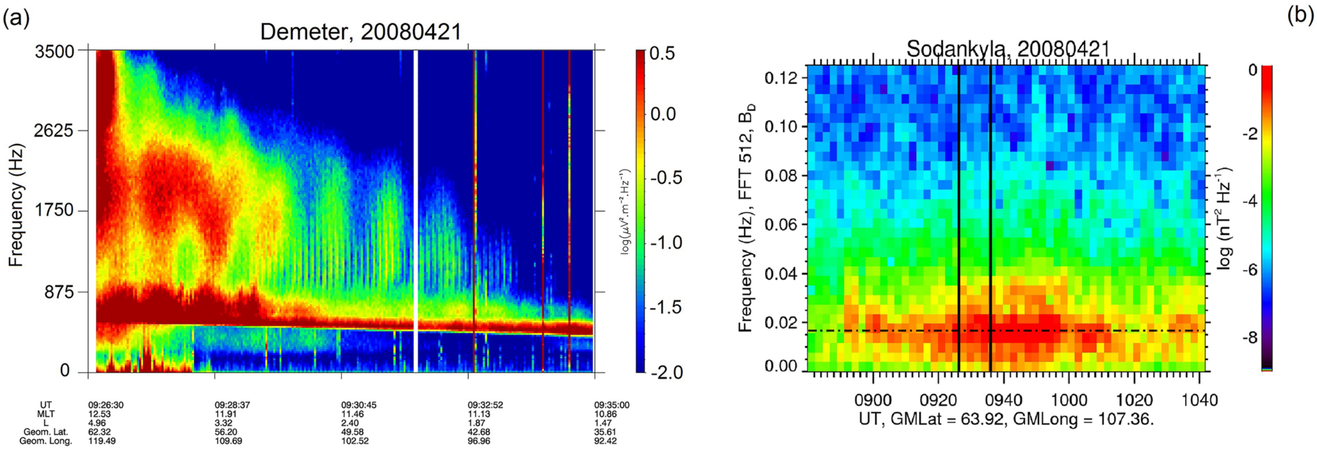

Figure 5. (a) Frequency-time spectrogram of power spectral density of electric field fluctuations corresponding to quasiperiodic (QP) events measured on 21 April 2008 between 9:27 UT and 9:34 UT in the Northern hemisphere. (b) Frequency-time spectrogram of the power spectral density of the B_D magnetic field component measured during the time interval of the QP event by the Sodankylä magnetometer. The black horizontal dashed line denotes the modulation frequency of the QP event. The vertical black lines mark the time interval when the QP event was observed.

19.35 UT, which corresponds to the observations of the QP event from Figure 2 in the Northern hemisphere. The frequency of the QP modulation is marked by the vertical black dotted lines in Figure 4 and the power spectral density measured at the respective frequency is noted in individual panels. In spite of the limited frequency resolution in this frequency range, we can say that three magnetometers located at geomagnetic latitudes between 64° and 69° (FCHU, GILL, and ISLL) and the magnetometer located at a geomagnetic latitude of 79° (TALO) show a clear enhancement of power spectral density within the frequency interval between about 20 and 30 mHz. This frequency range corresponds well to the modulation period of the analyzed QP event. On the other hand, we note that the data measured by the RANK magnetometer at intermediate latitudes do not reveal this spectral peak, for which we do not have any explanation at the moment.

In order to compare the observations of ULF geomagnetic field pulsations at different geomagnetic longitudes, we present in Figure 4b also the measurements of the remaining CARISMA magnetometers which operated on 2 June 2005, those that are not part of the Churchill line. A clear peak of the power spectral density of the B_D component at the frequency which corresponds to the QP modulation period is seen even at the DAWS station which is located at a longitudinal distance of about 58° from the magnetometers of the Churchill line. QP events measured by DEMETER in both hemispheres during a single spacecraft half-orbit (i.e., within about 40 min) indicate that such QP events, as well as the ULF geomagnetic pulsations associated with them, can last in the magnetosphere for a period longer than the half-orbit duration.

Frequency-time spectrograms corresponding to the QP event observed by DEMETER on 21 August 2008 in the Northern hemisphere and the frequency-time spectrogram of the power spectral density of the B_D geomagnetic field component simultaneously measured by the Sodankylä magnetometer are shown in Figure 5. The representation is the same as in Figures 2 and 3, respectively. It can be seen that the Sodankylä magnetometer measures intense ULF geomagnetic field pulsations at the frequency corresponding to modulation period of the QP event, starting at about 09.00 UT and ending at about 10.18 UT. This period (~75 min) is much longer than the duration of the QP emissions observed by DEMETER in the Northern hemisphere (~7 min).

Considering the duration of QP emissions and corresponding ULF geomagnetic field pulsations, we visually inspected all relevant 2 hr long frequency-time spectrograms and frequency spectra centered at the times of the QP events using all the CARISMA and SGO measurements summarized in Figure 1b. We investigated a possible presence of a dominant frequency of geomagnetic field pulsations, and its correspondence to the QP modulation period for all 424 analyzed QP events.

According to a preliminary study of CARISMA magnetic field measurements, the more intense magnetic field fluctuations are observed mostly at frequencies between 0.01 and 0.5 Hz (for some stations lower than 0.05 Hz). Hayosh et al. (2014) reported that the modulation periods of QP events observed by DEMETER are from ~10 to ~100 s, corresponding to the range 0.01–0.1 Hz. Thus, the frequency ranges of both magnetic pulsations

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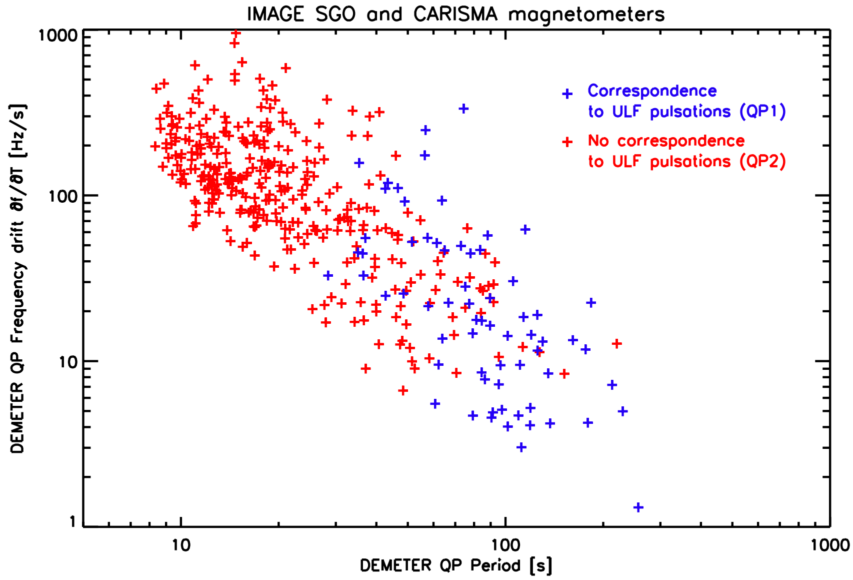

Figure 6. Median frequency drifts of quasiperiodic (QP) events as a function of their modulation periods. The blue crosses correspond to QP events which can be associated with ultra-low frequency (ULF) magnetic field pulsations measured on the ground (QP1). The red crosses correspond to QP events for which no clear association with ULF magnetic field pulsations measured on the ground was found (QP2).

observed on the ground and QP modulation observed by spacecraft correspond quite well to each other. Since according to Hayosh et al. (2014) the modulation period of a QP event can vary by about 20% during the spacecraft observation interval, we selected the frequency interval within ±20% from the value of the QP modulation frequency in each frequency spectrum of the B_D magnetic field component, and we identified the maximum power spectral density value in this frequency interval. Then, for two adjacent frequency intervals of the same frequency bandwidth just below and above the QP modulation frequency interval, we calculated the median values of the power spectral density of B_D, $I_M(B_D)$, and corresponding values of standard deviation, σ. The value of the power spectral density equal to $I_M(B_D) + (3\,\sigma)$ was then used as a background threshold for the power spectral density of the geomagnetic field pulsations. If the power spectral density of magnetic field pulsations at the frequency corresponding to the QP modulation frequency is larger than the background power spectral density of magnetic field pulsations, then we assumed the QP modulation frequency to be dominant. We request the QP modulation frequency to be dominant for at least two ground-based magnetometers in order to claim the QP event to be associated with ULF magnetic field pulsations. Note that the power spectral density of magnetic field pulsations generally decreases with the frequency. However, as the power spectral density at frequencies both just below and above the QP modulation frequency interval is used for the comparison and, moreover, the considered ±20% bandwidth interval is rather narrow, this does not significantly bias the used peak identification criterion. Moreover, we note that the highest frequency part of the spectrum (>~0.1 Hz) is above the maximum frequencies relevant for the QP emissions. The results show that the association has been found for 67 events, that is, 17% of the data set of DEMETER QP events.

QP events with larger modulation periods usually have lower frequency drifts (Hayosh et al., 2014). In Figure 6 we use this property of QP emissions to demonstrate how the data are organized when categorized according to whether or not corresponding ULF magnetic field pulsations are observed on the ground. Specifically, Figure 6 shows a dependence of the median frequency drifts of individual QP events (Hayosh et al., 2014) as a function of their modulation periods. The results obtained for QP events with corresponding ULF magnetic field pulsations measured on the ground (QP1) are shown by the blue crosses. The results obtained for QP events with no corresponding ULF magnetic field pulsations measured on the ground (QP2) are shown by the red crosses. It can be seen that QP1 events have usually longer modulation periods than QP2 events. While the modulation periods of QP1 events are always longer than about 30 s, QP2 events tend to have modulation periods lower than 30 s, but longer periods also occur. Thus QP1 constitute about 64% of the whole number of QP events with modulations period larger than 30 s.

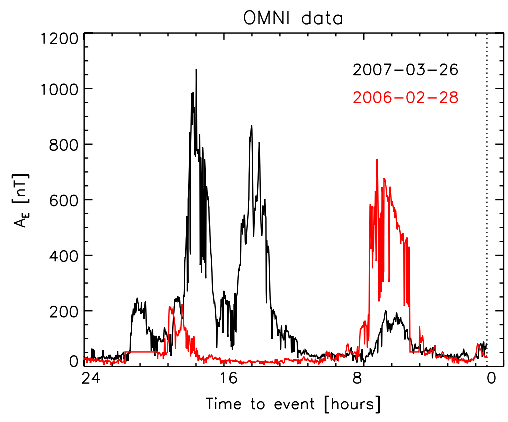

Figure 7. Values of the A_E index as a function of the time relative to the start of quasiperiodic (QP) events (black dotted line on the left) for 24 hr before the times of the QP events for 26 March 2007 (black solid line) and on 28 February 2006 (red line).

In order to further investigate the difference between QP1 and QP2 events, we have verified whether the geomagnetic conditions during the occurrence of QP1 events differ from those during the occurrence of QP2 events. A superposed epoch analysis was used to check the dependence of the values of the A_E index and solar wind dynamic pressure, P_{SW}, as extracted from NASA/GSFC's OMNI data set through OMNI Web http://omniweb.gsfc.nasa.gov/hw.html, on the time relative to the times of the QP1 or QP2 events. The time interval for epoch analysis was selected from 24 hr before to 24 hr after the starting times of the QP events. The activity level of a certain parameter (A_E or P_{SW}) can be described by the presence or absence of some peak value. To make this estimation, we computed 1 hr averages and the corresponding standard deviation (σ) based on 1-min resolution data for 24-hr interval before the beginning of the QP event and compared it with the maximum value within the same interval. If the maximum value was larger than sum of 1-hr averages and $+2\sigma$ values (excluding the 1-hr interval with the maximum value), then we indicated this event as the event with the solar wind or the magnetic activities; in the opposite case, we indicated the event as quite one. Also, checking by eye was made in the case of two or three peaks were observations. We separated the QP1 or QP2 events in quiet and active groups and calculated average A_E and P_{SW} values for each group. Two examples of the A_E profile during a magnetically active period for QP2 event are presented in Figure 7. The maximum values of the index are different and are located on different time intervals from the beginning of the event which is located on time "0" and is indicated by black dotted line. Moreover, the event on 26 March 2007 has two clear peaks and manual check was used to identify this event as active event.

The average values obtained for the A_E index and solar wind pressure variations are shown in Figures 8 and 9, respectively. In the case of A_E index, we separated both types of QP events in quiet (plot is indicated as A_E without peak) or active (A_E with peak) groups and calculated average values and 3σ intervals for each group. These intervals were calculated as the triple standard deviation of the corresponding set of values divided by the square root of the number of the QP events in a given bin. Since there were less QP1 events than QP2 events, we keep in mind that calculated $\pm 3\sigma$ intervals of QP1 events will be larger than for QP2. Moreover, variations of A_E index values are larger in the case of higher magnetic activity.

In the case of lower magnetic activity (Figure 8a), the mean A_E index before a QP event is higher for QP2 than QP1 events, even taking into account the error bar. However, for the interval after the QP event this difference disappears since the mean A_E index after QP2 events decreases to the values of the mean A_E index of QP1 events. For higher magnetic activity, presented on Figure 8b, the situation is similar, that is, the mean A_E index does not change much for QP1 events and fluctuates around 100 nT that is lower than for QP2 events for the entire analyzed time interval of $\pm$24 hr. Moreover, there is a quite clear minimum around the event time. The higher A_E

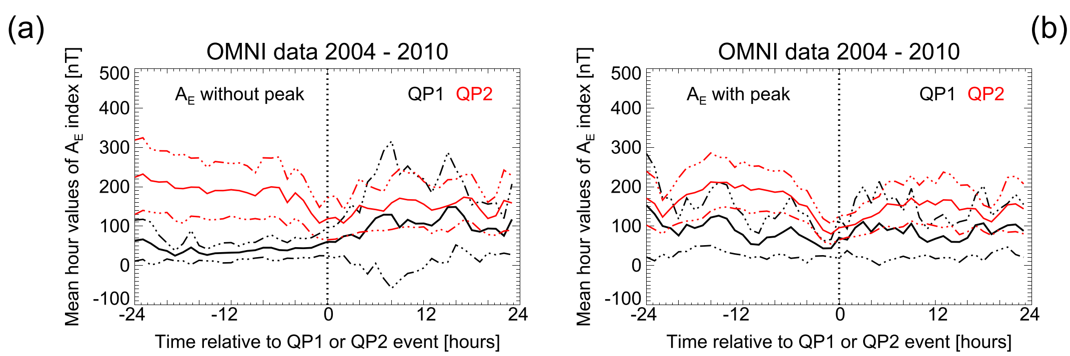

Figure 8. Mean value of the A_E index as a function of the time relative to the start of quiet events (a) and active events (b) for 24 hr before/after the times of the quasiperiodic events. Black and red lines correspond to QP1 and QP2 events, respectively. Thin dash dot lines plotted in both figures correspond to the interval of $\pm 3\sigma$ around the mean values, which are plotted by thick solid lines.

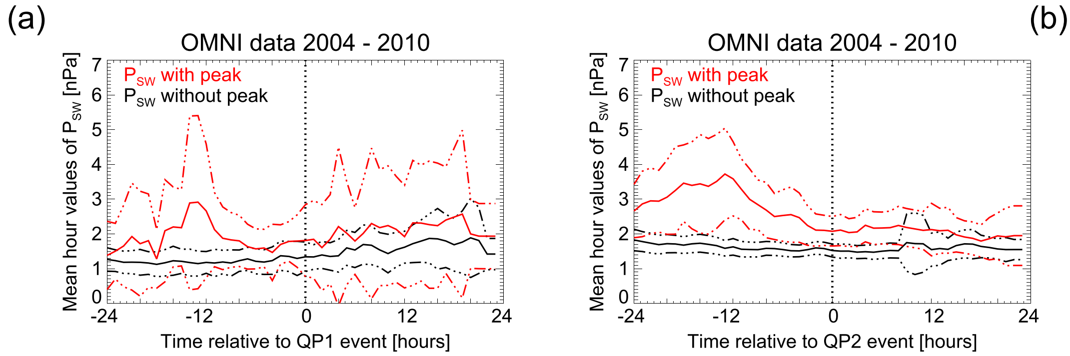

Figure 9. Mean values (thick dotted lines) and 3σ intervals (thin dash-dotted lines) of the solar wind pressure as a function of the time relative to the times of QP1 (a) or QP2 (b) events.

index values before QP2 events can indicate possible relationship between the substorm activity and the generation of QP2 emissions whereas QP1 events are known to be observed during quiet geomagnetic conditions (Sato et al., 1974; Sazhin & Hayakawa, 1994, etc.).

In the case of the analysis of the solar wind pressure we compared the activity level for QP1 or QP2 groups separately. The difference between active and quiet pressure averages for QP1 events (black and red lines respectively on Figure 9a) and both values do not change much during all 48 hr.

For the QP2 events, the pressure average is clearly higher for higher activity (red line on Figure 9b) than for weaker activity during 24 hr before the QP event, and has a clear maximum of ~3 nPa of the higher activity pressure at about 17–12 hr before the event time. At later times with respect to the event, the pressure level decreases and no difference between higher and weaker activity is observed.

The difference in the geomagnetic activity at the times of observations of QP1 and QP2 events can be also indicated directly using the ground measurements of the geomagnetic field pulsations. For this purpose, we use the median of an integral of the power spectral density of geomagnetic field pulsations in the frequency range from 10 to 500 mHz. This corresponds to the modulation periods between about 10 and 200 s, that is, to the same period range as it is typical for the QP events. Note, however, that by integrating over such a broad frequency range, we disregard any relationship between the QP and magnetic pulsation periods, and that we use the ULF power as a proxy of the geomagnetic activity. It is somewhat similar to the so-called ULF index (Kozyreva et al., 2007) but the latter is computed for a narrower frequency range of 2–10 mHz. These results seem to be consistent with the variations of the A_E index around the times of the QP events. As QP1 events are observed during quiet geomagnetic conditions (Sato et al., 1974; Sazhin & Hayakawa, 1994, and etc.), the level of ULF geomagnetic pulsations is expected to be rather low at the times of QP1 events. On the other hand, we observed larger values of the A_E index before the times of the QP2 events, and higher levels of geomagnetic field pulsations may be thus expected.

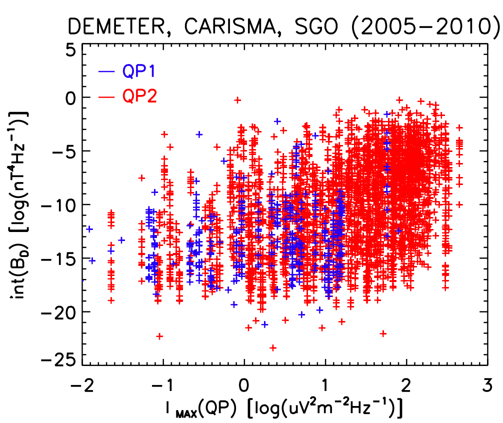

Figure 10. Integral of power spectral density of the B_D-component of the geomagnetic field pulsations in the frequency range 10–500 mHz as a function of corresponding quasiperiodic event intensities. The results obtained for QP1 and QP2 are plotted by the blue and red crosses, respectively.

Figure 10 shows a comparison between the maximum intensity of individual QP elements observed by DEMETER (abscissa axis) and the integral intensity of geomagnetic field fluctuations (ordinate axis) observed by CARISMA and SGO magnetometers in the frequency range 10–500 mHz. In general, the intensity of wave electric field for QP1 (blue crosses) does not change much with the integral intensity of geomagnetic field fluctuations and is lower than the QP2 events intensity (red crosses). This is in agreement with Hayosh et al. (2014) who reported that higher intensities are observed for QP emissions, together with smaller modulations periods. Moreover, the integral intensity of geomagnetic field fluctuations for QP1 events is mostly weaker than $\sim 10^{-10}$ (nT^2/Hz) whereas more intense QP2 events were observed at the times of higher values of the integral intensity of geomagnetic field fluctuations (up to $\sim 10^{-1}$ nT^2/Hz).

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3. Discussion

We found that only the QP events with larger modulation periods are sometimes accompanied by enhanced geomagnetic pulsations at the frequency corresponding to the period of the QP modulation. These magnetic field pulsations associated with QP events were observed simultaneously over an entire region covered by CARISMA magnetometers, that is, extending about 50° in geomagnetic longitude and covering L shells between about 3.5 and 7. It should be noted that the total number of magnetometer measurements at L above 7 is very limited, and thus we cannot make any conclusions about the occurrence of ULF pulsations associated with QP emissions at such high L. For QP events with shorter modulation periods (about 30 s), there generally appears to be no association with simultaneously observed ULF pulsations. The power spectral density of these pulsations does not exhibit a peak at frequencies corresponding to the QP modulation period. We note that the modulation period threshold of about 30 s is strikingly similar to the threshold of about 20 s reported by Bezděková et al. (2019) when analyzing the QP emission properties as a function of solar wind parameters and geomagnetic activity, concluding that short period and long period QP emissions may be generated by two different mechanisms.

The duration of the associated geomagnetic pulsations is usually longer than the duration of QP events as observed by DEMETER in a particular hemisphere (<10 min). This is consistent with the total durations of QP events generally being long, on the order of hours (Sazhin & Hayakawa, 1994; Tixier & Cornilleau-Wehrlin, 1986); the shorter duration of QP events observed by DEMETER is then due to the nearly polar spacecraft orbit and the lack of QP emissions at very low and very high geomagnetic latitudes.

QP1 events and corresponding long-lasting ULF magnetic pulsations are observed simultaneously over a wide range of longitudes and latitudes, that is, the magnetic pulsations with the same period are measured in range of L-shells from 3 to 6. This fact is in agreement with previous studies (Engebretson et al., 1986; Odera et al., 1994; Takahashi & McPherron, 1982). ULF geomagnetic field pulsations can be generated locally in the magnetosphere (as resonant field line oscillations) and after propagation to the ground they can be detected at a distance from the source magnetic field line.

A part of QP1 emissions, seen mostly on lower L shells, can be associated with Pc 3,4 pulsations which occur mostly at $L \sim 2.5$–4.5 with a peak at $L \sim 3$ (Lessard et al., 1999; Odera et al., 1994). The ULF magnetic field pulsations observed on the ground can be caused by compressional waves in the magnetosphere. The periods of QP emissions associated with these pulsations might thus correspond to the periods of compressional waves propagating in the magnetosphere (Hartinger et al., 2012; Southwood & Hughes, 1983). The source of the pulsations is likely in the outer magnetosphere. Solar wind pressure values seem to be larger before QP1 events than before QP2 events, suggesting that the solar wind pressure variations might be responsible for the generation of ULF geomagnetic field pulsations, and, correspondingly, QP1 emissions. Considering that QP emissions may propagate unducted (Hayosh et al., 2016; Němec et al., 2014), it is then possible to observe QP events at L shells significantly different from the L-shell of the source region.

The observed difference in the modulation periods and frequency drifts between QP1 and QP2 events strongly suggests that, although not distinguishable by using exclusively the DEMETER data, the observed QP events have at least two different generation mechanisms. We assume, following former theoretical studies, that the QP1 events can be generated due to the ULF magnetic field pulsations periodically modulating the energetic electron distribution and, thus, the wave growth in the source region.

The QP2 emissions can be qualitatively explained in the frame of models based on the wave generation in the regime of relaxation oscillations in the generation region (Bespalov et al., 2010; Demekhov & Trakhtengerts, 1994; Manninen et al., 2013; Pasmanik, Titova, et al., 2004). In these models the period of ULF geomagnetic field pulsations is not taken into account and still they do obtain a QP modulation of the wave intensity, in agreement with our observations. On the other hand, ULF pulsations can affect QP2 emissions by imposing a modulation with a longer time scale (Bösinger et al., 1996).

One observes that QP1 and QP2 events follow remarkably similar tendency on the diagram in Figure 6, both showing a decrease in the frequency drift with increasing period. It seems not surprising if we recall that the effect of external modulation such as ULF magnetic pulsations the development of quasi-periodic variations in VLF wave intensity can be sufficiently strong only if the modulation frequency coincides with an eigenfrequency of relaxation oscillations in wave-particle system (e.g., Bespalov & Trakhtengerts, 1976). The fact that QP1 emissions have statistically larger periods than QP2 could be explained by the range of characteristic eigenfrequencies of field-line oscillations at the latitudes corresponding to VLF wave generation regions. Indeed, periods below 30 s correspond to fairly low L shells ($L < 4$) where the VLF activity is more typical during active periods, while QP emissions are mostly observed at a low background level of geomagnetic activity.

4. Conclusions

The main aim of the presented paper was to compare modulation periods of QP emissions observed by the low-altitude spacecraft with the ULF geomagnetic field pulsations measured on the ground. Altogether, 398 QP events measured by the low-altitude DEMETER spacecraft along with corresponding measurements of CARISMA and SGO ground based magnetometers have been analyzed.

An agreement between the modulation periods of QP events and peak frequencies of ULF magnetic field pulsations was found for QP events with modulation periods larger than 40 s (approximately 18% of observations). There seems to be no relation between the QP modulation periods and ULF magnetic field pulsations in the remaining QP events.

The value of the A_E index seems to be lower during about 24 hr before QP1 events than for QP2 types. This can indicate that the occurrence of QP2 events is related to a substorm activity. Solar wind dynamic pressure appears to be slightly increased at the times of the QP2 events, while it does not show any well pronounced variation around the times of QP1 events. Maximum intensities of both QP1 and QP2 events are larger at the times of higher ULF pulsations power in the range from 5 to 500 Hz. The pulsations intensities themselves are slightly higher for QP2 events at geomagnetic latitudes > 60°.

Our results show that the behavior of geomagnetic field pulsations is different at the times of QP events with shorter modulation periods (QP2 events) and at the times of QP events with longer modulation periods (both QP1 and QP2 events). The geomagnetic conditions at the times of the event observations are also somewhat different, suggesting that two distinct generation mechanisms exist and should be considered in future theoretical studies.

Data Availability Statement

DEMETER data are accessible from https://sipad-cdpp.cnes.fr.
CARISMA magnetometer data can be downloaded from http://www.carisma.ca.
SGO magnetometer data can be downloaded from http://www.sgo.fi/Data/Magnetometer/magnData.php.
NASA/GSFC's Space Physics Data Facility's OMNIWeb (http://omniweb.gsfc.nasa.gov/hw.html) Service, and OMNI Data.

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