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RESEARCH ARTICLE

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Equatorial noise emissions with quasiperiodic modulation of wave intensity

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Key Points:

- Equatorial noise can exhibit a quasiperiodic modulation of wave intensity
- Events primarily on the dayside at times of enhanced solar wind flow speeds
- Possibly governed by simultaneously observed ULF compressional pulsations

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Abstract Equatorial noise (EN) emissions are electromagnetic wave events at frequencies between the proton cyclotron frequency and the lower hybrid frequency observed in the equatorial region of the inner magnetosphere. They propagate nearly perpendicular to the ambient magnetic field, and they exhibit a harmonic line structure characteristic of the proton cyclotron frequency in the source region. However, they were generally believed to be continuous in time. We investigate more than 2000 EN events observed by the Spatio-Temporal Analysis of Field Fluctuations and Wide-Band Data Plasma Wave investigation instruments on board the Cluster spacecraft, and we show that this is not always the case. A clear quasiperiodic (QP) time modulation of the wave intensity is present in more than 5% of events. We perform a systematic analysis of these EN events with QP modulation of the wave intensity. Such events occur usually in the noon-to-dawn magnetic local time sector. Their occurrence seems to be related to the increased geomagnetic activity, and it is associated with the time intervals of enhanced solar wind flow speeds. The modulation period of these events is on the order of minutes. Compressional ULF magnetic field pulsations with periods about double the modulation periods of EN wave intensity and magnitudes on the order of a few tenths of nanotesla were identified in about 46% of events. We suggest that these compressional magnetic field pulsations might be responsible for the observed QP modulation of EN wave intensity, in analogy to formerly reported VLF whistler mode QP events.

1. Introduction

Equatorial noise (EN) are electromagnetic wave events at frequencies between the proton cyclotron frequency and the lower hybrid frequency, which are routinely observed in the equatorial region of the inner magnetosphere. They typically occur at radial distances between about 2 and 7 R_E and at latitudes within about 10° from the geomagnetic equator [Laakso *et al.*, 1990; Kasahara *et al.*, 1994; Němec *et al.*, 2005], but in some exceptional cases they may extend well beyond these limits both in the radial distance and in latitude [Hrbáčková *et al.*, 2015]. The emissions have magnetic field fluctuations nearly linearly polarized along the ambient magnetic field [Santolík *et al.*, 2004], which corresponds to the wave propagation in the extraordinary mode almost perpendicular to the ambient magnetic field. This is also the reason EN events are limited to frequencies below the lower hybrid frequency, as it is the upper frequency limit for the appropriate wave mode [Stix, 1992]. In the low-frequency limit the extraordinary mode corresponds to the fast magnetosonic mode, and EN emissions are thus sometimes called “magnetosonic waves.”

Although EN emissions appeared as unstructured noise when originally identified in low-resolution data [Russell *et al.*, 1970], later high-resolution measurements revealed that they consist of a complex superposition of many harmonically spaced lines [Gurnett, 1976]. The fine frequency structure is likely linked to the proton cyclotron frequency in the source region, and the EN emissions are believed to be generated by energetic protons with ring-like distribution functions [Curtis and Wu, 1979; Perraut *et al.*, 1982; McClements and Dendy, 1993; McClements *et al.*, 1994; Horne *et al.*, 2000; Liu *et al.*, 2011; Chen *et al.*, 2011], which were observed together with the waves [Perraut *et al.*, 1982; Boardsen *et al.*, 1992; Xiao *et al.*, 2013; Ma *et al.*, 2014].

Ray tracing studies show that EN emissions can cross the plasmopause boundary and propagate over a broad region of magnetic local times (MLTs). This is particularly true inside the plasmasphere, where the emissions can be effectively trapped by sharp gradients of the refractive index [Chen and Thorne, 2012; Kasahara *et al.*, 1994; Xiao *et al.*, 2012]. Results of experimental analyses of azimuthal directions of wave

propagation [Němec *et al.*, 2013a], EN occurrence rate [Hrbáčková *et al.*, 2015], and EN wave intensities [Němec *et al.*, 2015] are consistent with these theoretical predictions, and they demonstrate the importance of the plasmopause boundary for the distribution of EN waves.

Although EN emissions were generally believed to be continuous in time, recent results suggest that some EN events may exhibit a quasiperiodic (QP) time modulation of the wave intensity; i.e., they may effectively consist of nearly periodically occurring wave elements [Fu *et al.*, 2014; Boardson *et al.*, 2014]. Such QP modulation of wave intensity is known to occur in some VLF whistler mode wave events, and the appropriate waves are usually called “quasiperiodic emissions” (see, e.g., a review by Sazhin and Hayakawa [1994]). These emissions, however, typically have frequencies of a few kilohertz, and they are right handed nearly circularly polarized [Němec *et al.*, 2013b, 2013c]. Their modulation periods can range from some 10 s up to a couple of minutes [Carson *et al.*, 1965; Smith *et al.*, 1998], and they occur primarily on the dayside [Morrison *et al.*, 1994; Engebretson *et al.*, 2004; Hayosh *et al.*, 2014]. The generation mechanism of these emissions is still not entirely understood. However, it seems that the QP modulation of the wave intensity could be caused by periodic modulations of resonant conditions in the wave generation region governed by compressional ULF magnetic field pulsations [Chen, 1974; Kimura, 1974; Sato and Fukunishi, 1981; Sazhin, 1987]. In situ measurements of such compressional ULF pulsations associated with VLF whistler mode QP emissions were reported for the first time by Tixier and Cornilleau-Wehrin [1986]. More recently, the compressional ULF pulsations were observed along with VLF whistler mode QP emissions close to the geomagnetic equator [Němec *et al.*, 2013c, 2014], where the generation region is believed to be located [Sato and Kokubun, 1980; Morrison, 1990]. Boardson *et al.* [2014] suggested that ULF magnetic field pulsations might, in analogy to the case of VLF whistler mode QP emissions, periodically modulate the resonant conditions in the wave generation region and be thus responsible for the QP modulation of EN events. However, this mechanism seems to require the ULF pulsations to be strong enough to create sufficiently large periodic variations of the Alfvén speed to turn-on and turn-off the instability, which the authors considered unlikely.

In the present study we investigate a set of more than 2000 EN events identified in the first 10 years of the Cluster spacecraft data [Hrbáčková *et al.*, 2015] for the presence of QP intensity modulation. The identified events with QP modulation of the wave intensity are systematically analyzed, and the most favorable conditions for their occurrence, along with a possible generation mechanism, are discussed. The data set used in the study is described in section 2. The obtained results are presented in section 3. Section 4 contains discussion, and the main results are briefly summarized in section 5.

2. Data Set

Electromagnetic wave data measured by the Cluster spacecraft have been used. The Cluster spacecraft are moving in a formation along elliptical orbits. They were launched in 2000, and they are still operating after more than 14 years. The orbital parameters have changed over the duration of the mission. The equatorial region of the inner magnetosphere, which is of interest for the present study, is typically sampled at radial distances of a few Earth radii. The spectrum analyzer of the Spatio-Temporal Analysis of Field Fluctuations (STAFF-SA) instrument placed on board performs multicomponent measurements of electromagnetic waves in 27 logarithmically spaced channels between 8 Hz and 4 kHz. Spectral matrices are calculated on board using the three orthogonal magnetic field components and two electric field components in the spin plane of the spacecraft. The time resolution of the spectral matrices is 4 s (power spectral densities are determined with a better time resolution of 1 s). The spectral matrices can be used to determine not only the intensity of observed electromagnetic waves but also their polarization and propagation properties. A detailed description of the STAFF-SA instrument was given by Cornilleau-Wehrin *et al.* [1997, 2003].

Apart from the low-resolution multicomponent STAFF-SA data, high-resolution single-component measurements are performed, during selected time intervals, by the Wide-Band Data (WBD) Plasma Wave investigation instruments. In the continuous baseband measurement mode relevant for our study, these provide us with a waveform band-pass filtered in the frequency range of about 70 Hz–9.5 kHz and sampled with the sampling frequency of 27,443 Hz. The WBD instruments measure a single electromagnetic field component at a given time. WBD electric field measurements are used in the present study. For these waveforms, intervals of about 42 s of continuous data are most of the time followed by about 10 s long data gaps when the magnetic field measurements are being made. A detailed description of the WBD instrument was given by Gurnett *et al.* [1997].

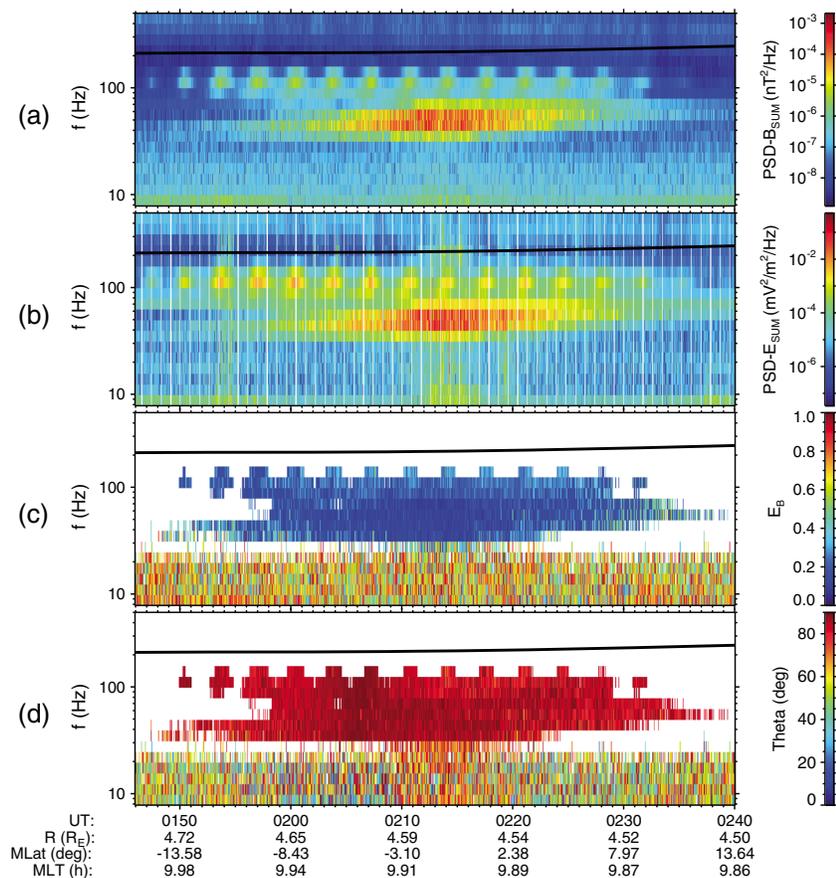


Figure 1. Example of an equatorial noise event with a quasiperiodic modulation of the wave intensity observed by Cluster 1 on 17 October 2005 between 01:46 UT and 02:40 UT. (a) Frequency-time spectrogram of power spectral density of magnetic field fluctuations. (b) Frequency-time spectrogram of power spectral density of electric field fluctuations. (c) Frequency-time plot of the ellipticity of magnetic field fluctuations. (d) Frequency-time plot of the wave normal angle. The overplotted black curves correspond to the upper estimate of the lower hybrid frequency.

In addition to the STAFF-SA and WBD wave measurements, low-frequency variations of the ambient magnetic field are measured on board by the fluxgate magnetometers (FGMs). These provide us with the measurements of the three orthogonal components of the magnetic field [Balogh *et al.*, 1997, 2001]. The time resolution depends on the mode of the instrument, and it is equal to about 4 s (spin resolution) for the FGM data used in the present study.

We have used the list of 2229 EN events identified in the first 10 years of Cluster measurements (2001–2010) by Hrbáčková *et al.* [2015]. This list was compiled after a visual inspection of STAFF-SA data from all Cluster equatorial passages, and it therefore contains all EN events observed by Cluster during the given period of time. We have plotted frequency-time spectrograms of power spectral densities of magnetic and electric field fluctuations corresponding to individual EN events from the list. These have been complemented by frequency-time plots of ellipticity of magnetic field fluctuations and frequency-time plots of wave normal angles, as these propagation parameters are known to clearly distinguish EN emissions [Santolik *et al.*, 2004]. The resulting plots were then visually inspected for a possible presence of EN emissions with a QP modulation of the wave intensity. Altogether, 118 EN events with QP modulation of the wave intensity have been found. This means that the QP modulation of the wave intensity was identified in about 5% of the analyzed EN events.

Examples of EN events with QP modulation of the wave intensity are shown in Figures 1 and 2. The event depicted in Figure 1 was measured by Cluster 1 on 17 October 2005 between 01:46 UT and 02:40 UT. The event depicted in Figure 2 was measured by Cluster 2 on 27 November 2003 between 02:24 UT and 03:16 UT. The format of both figures is the same. Figures 1a and 2a show frequency-time spectrograms

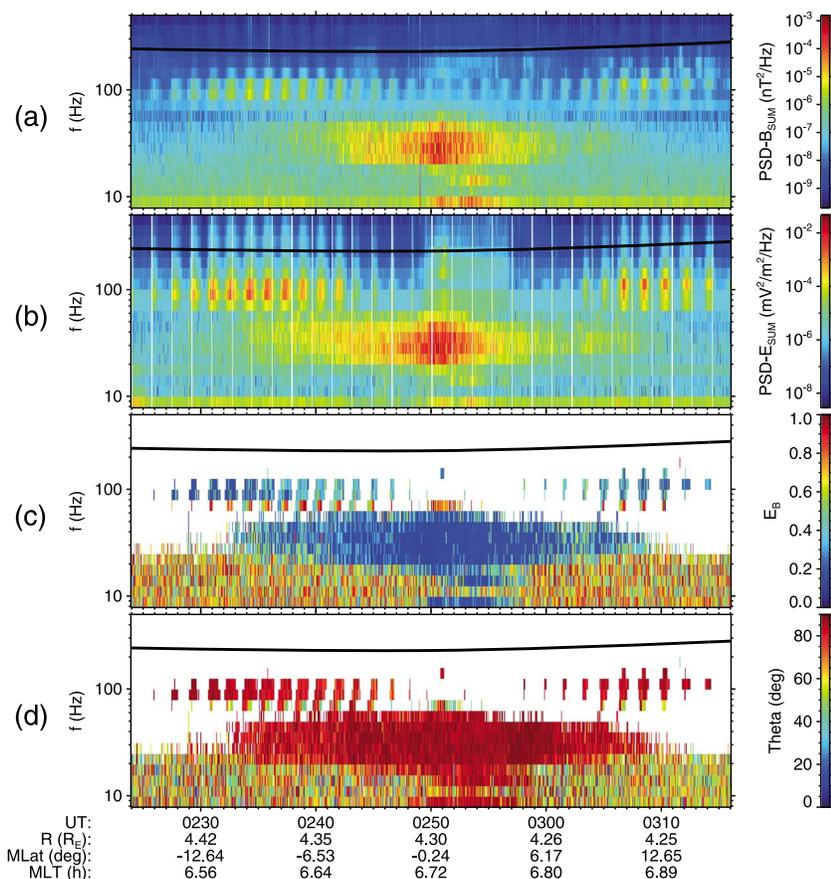


Figure 2. Example of an equatorial noise event with quasiperiodic modulation of wave intensity observed by Cluster 2 on 27 November 2003 between 02:24 UT and 03:16 UT. The used format is the same as in Figure 1.

of power spectral density of magnetic field fluctuations. Figures 1b and 2b show frequency-time spectrograms of power spectral density of electric field fluctuations. Figures 1c and 2c show frequency-time plots of ellipticity of magnetic field fluctuations. The values of ellipticity may range from 0 (linear polarization) to 1 (circular polarization). The values of ellipticity expected for EN events are close to 0, corresponding to a nearly linear polarization of magnetic field fluctuations [e.g., Santolik et al., 2004]. Figures 1d and 2d show frequency-time plots of wave normal angles calculated using the singular value decomposition of the magnetic part of spectral matrices [Santolik et al., 2003]. Wave normal angles may range from 0° (wave vector oriented along the ambient magnetic field) to 90° (wave vector oriented perpendicular to the ambient magnetic field). Wave normal angles expected for EN events are close to 90°, corresponding to the propagation in the equatorial plane nearly perpendicular to the ambient magnetic field. We note that the ellipticity and wave normal angles were determined only for frequency-time intervals with the power spectral density of magnetic field fluctuations larger than $10^{-6} \text{ nT}^2 \text{ Hz}^{-1}$.

Taking into account that EN emissions propagate in the extraordinary mode nearly perpendicular to the ambient magnetic field, they should be limited to frequencies below the lower hybrid frequency [Stix, 1992]. This characteristic frequency depends both on the magnetic field magnitude and the plasma number density. However, its upper estimate (high-density limit, which is approximately valid for our case) can be obtained using exclusively the magnetic field magnitude as the geometric average of proton and electron cyclotron frequencies. These upper estimates of the lower hybrid frequencies are overplotted by the black curves in individual panels of Figures 1 and 2.

Two different types of waves with large intensities and propagation parameters corresponding to those expected for EN can be seen in Figures 1 and 2. First, there are waves at lower frequencies, which are continuous in time and correspond to normal EN events. Second, there are periodically repeating elements at higher frequencies, corresponding to EN with QP modulation of the wave intensity. These are the events

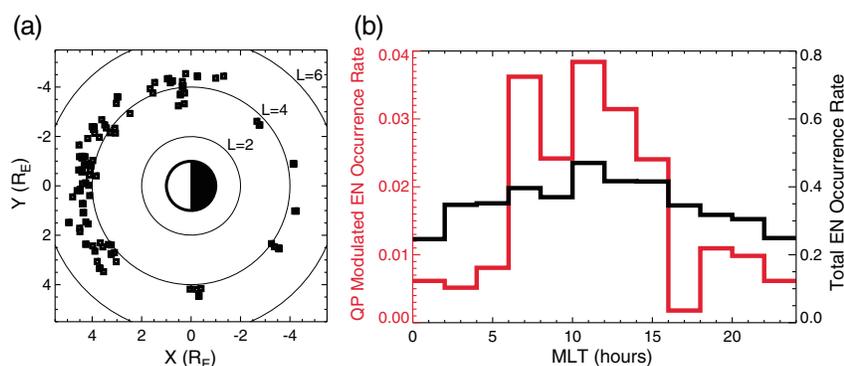


Figure 3. (a) Locations of equatorial noise events with a quasiperiodic modulation of the wave intensity projected on the geomagnetic equatorial plane are shown by the black square symbols. The X and Y axes are in solar magnetic coordinates. The thick solid circle in the middle corresponds to the Earth's surface. Thinner concentric circles correspond to L shells of 2, 4, and 6. (b) Occurrence rate of equatorial noise events with a quasiperiodic modulation of the wave intensity is shown by the red line as a function of magnetic local time. Total occurrence rate of equatorial noise events identified in the Cluster data by Hrbáčková *et al.* [2015] is shown by the black line as a function of magnetic local time. Note that the occurrence rates were calculated from the number of events in each magnetic local time bin using the normalization by the total number of equatorial passages of the Cluster spacecraft at $L < 10$ in a given magnetic local time bin.

which we focus on in the present paper. We note that the occurrence of the EN emissions with QP modulation of the wave intensity at frequencies slightly higher than those of normal continuous EN is a pure coincidence. Out of the total 118 EN events with QP modulation of the wave intensity, 44 events are observed without any continuous EN counterpart, 39 events are observed at frequencies higher than the simultaneously observed continuous EN, 23 events are observed at frequencies lower than the simultaneously observed continuous EN, and in 12 events there are continuous EN emissions both at higher and lower frequencies. It is also noteworthy that while the QP elements occur during all the analyzed time interval in Figure 1 with approximately the same intensity, their intensity is visibly lower in the equatorial region in Figure 2.

3. Results

Locations of identified EN events with QP modulation of the wave intensity projected on the geomagnetic equatorial plane are shown in Figure 3a by black square symbols. The thick solid circle in the middle corresponds to the Earth's surface. The thinner concentric circles correspond to L shells of 2, 4, and 6, inner to outer, respectively. The positive values on the x axis (toward the left) correspond to the orientation toward the Sun. The negative values on the y axis (top) correspond to dawn, and the positive values on the y axis (down) correspond to dusk. It can be seen that EN events with QP modulation of the wave intensity occur predominantly in the noon sector and extend toward the dawn rather than toward the dusk. This is confirmed in Figure 3b, where the occurrence rate of EN events with QP modulation of the wave intensity is shown by the red line as a function of MLT. In order to verify how this distribution differs from the MLT distribution expected for normal EN events, the MLT distribution of all EN events identified in the Cluster data by Hrbáčková *et al.* [2015] is overplotted by the black line. Although the occurrence of normal EN emissions itself exhibits a maximum close to the local noon, it is clear that the noon maximum corresponding to EN events with QP modulation of the wave intensity is much sharper, with the noontime occurrence rate being about 4 times higher than the nighttime occurrence rate. Note that the occurrence rates in Figure 3b were calculated from the number of events in each MLT bin using the normalization by the total number of equatorial passages of the Cluster spacecraft at $L < 10$ in a given MLT bin of 2 h.

Having investigated the MLT distribution of EN events with QP modulation of the wave intensity, we focus on determining the most favorable conditions for them to occur. For this purpose, we have used the superposed epoch analysis; i.e., we have investigated mean/median dependencies of selected controlling parameters as a function of time relative to the central times of the events. Figure 4a shows the median value of the K_p index as a function of time relative to the times of EN events with QP modulation of the wave intensity in red. The increase of the median value of the K_p index about 2 days before the times of the events, which lasts until the event occurrence, indicates that the event occurrence is related to the periods

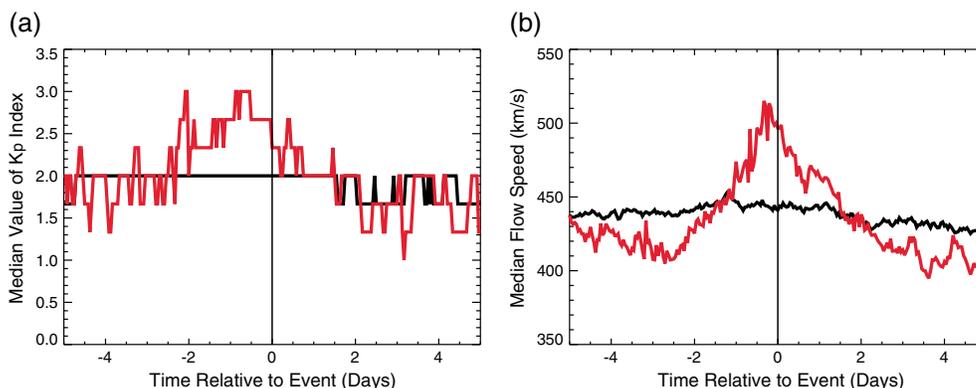


Figure 4. (a) Median value of K_p index as a function of time relative to time of the events. The results obtained for equatorial noise events with a quasiperiodic modulation of the wave intensity are shown in red. The results obtained for all equatorial noise events identified in the Cluster data by Hrbáčková *et al.* [2015] are shown in black. (b) The same as in Figure 4a but for the median value of solar wind flow speed.

of increased geomagnetic activity. In order to demonstrate that this is not the case for EN events, in general, the same results obtained for all EN events from the list of Hrbáčková *et al.* [2015] are plotted in black. No particular dependence of the geomagnetic activity on the time relative to the times of EN events can be seen in this case. On the other hand, the EN occurrence rate increases with the geomagnetic activity [Hrbáčková *et al.*, 2015]. This increase, however, appears to be related to the long-term evolution of the geomagnetic activity (solar maximum versus solar minimum) rather than to the short-term variations expressed by instantaneous values of K_p index analyzed in Figure 4a. The same conclusion is confirmed when using other geomagnetic activity indices, such as Dst or AE , and mean values in place of medians (not shown).

Apart from the analysis of the role of the geomagnetic activity indices, we have used the superposed epoch analysis to identify most favorable solar wind parameters for the events to occur. Solar wind OMNI data have been used (<http://omniweb.gsfc.nasa.gov>). Out of the investigated solar wind parameters (plasma number density, flow speed, dynamic pressure, interplanetary magnetic field B_z component), by far the strongest relation was found between the event occurrence and the solar wind flow speed. The obtained results are shown in Figure 4b using the same format as in Figure 4a. It can be seen that the occurrence of EN events with QP modulation of the wave intensity is statistically related to faster solar wind flows. The median flow speeds shortly before the times of event occurrence reach more than 500 km/s. Similar to Figure 4a, no such dependence is observed for normal EN events. This indicates that the effect is related exclusively to the events with QP modulation of the wave intensity.

Following the analysis performed by Němec *et al.* [2013c] for VLF whistler mode QP emissions at frequencies of a few kilohertz, we manually identified beginning and ending frequencies and times of each of the elements forming EN events with QP modulation of the wave intensity. This has been used to determine

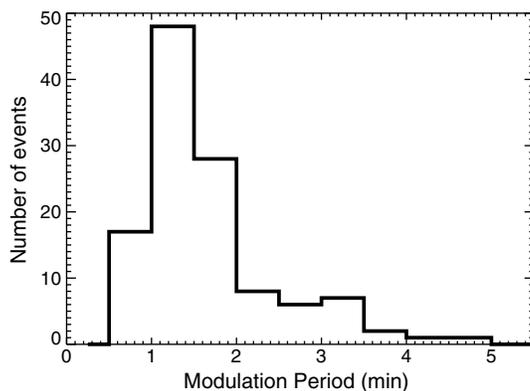


Figure 5. Histogram of modulation periods of equatorial noise events with a quasiperiodic modulation of the wave intensity.

the modulation period of the events, which is defined as the median time separation between consecutive QP elements [Němec *et al.*, 2013c]. A histogram of obtained modulation periods is shown in Figure 5. We note that the modulation periods were evaluated for all Cluster observations separately; i.e., the same event observed by several Cluster spacecraft was considered as several independent events. However, consistent with the results obtained by Němec *et al.* [2013b, 2013c], it is found that if a single event is observed by several Cluster spacecraft, the

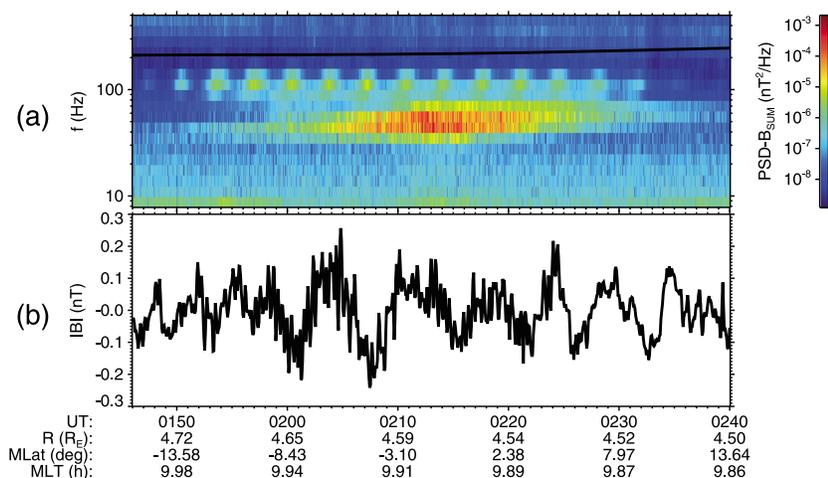


Figure 6. (a) The same as Figure 1a. (b) Deviation of the magnetic field magnitude from the background value (see text).

modulation periods and the overall appearance of the events observed by individual spacecraft are approximately the same (not shown). Figure 5 shows that the modulation periods of the identified events are generally on the order of minutes, with most of the events having modulation periods between 1 and 2 min. It is, however, possible that the lack of events with shorter modulation periods is a result of the visual identification of events. Taking into account that whole EN events were plotted during the identification, which corresponds to time intervals of a few tens of minutes, a very fine modulation of the wave intensity at periods lower than 30 s would not be identified.

Theories that attempt to explain the origin of VLF whistler mode QP emissions are often based on compressional ULF pulsations of magnetic field, which periodically change the resonant conditions in the source region [Coroniti and Kennel, 1970; Kimura, 1974; Sazhin, 1987]. Such compressional ULF pulsations were recently observed along with VLF whistler mode QP emissions close to the equatorial plane [Němec *et al.*, 2013c, 2014], and it was shown that their period corresponds to the modulation period of QP emissions within a factor of 2. It is thus of interest to verify whether similar compressional ULF pulsations occur also at the times of EN events with QP modulation of the wave intensity. As discussed by Němec *et al.* [2014], the magnetic field varies significantly over the analyzed time periods due to the spacecraft movement, and the mean variation of the magnetic field magnitude thus needs to be subtracted in order to reveal a possible presence of rather weak compressional ULF pulsations. We have adopted the approach used by Němec *et al.* [2014]; i.e., we have subtracted the mean trend determined using the Savitzky-Golay smoothing filter of the second order with the length of 128 points (i.e., about 8.5 min).

The resulting deviations of the magnetic field magnitude from the background value were investigated for all 118 EN events with QP modulation of the wave intensity. Compressional ULF pulsations were identified in 54 events, i.e., in about 46%. An example of ULF pulsations which occurred at the time of the example event from Figure 1 is shown in Figure 6. Figure 6a is the same as Figure 1; i.e., it shows the frequency-time spectrogram of power spectral density of magnetic field fluctuations measured by the STAFF-SA instrument. The compressional ULF magnetic field pulsations observed during the given time interval are shown in Figure 6b. Magnitudes of the pulsations are on the order of a few tenths of nanotesla, consistent with the magnitudes of compressional ULF pulsations detected at the times of VLF whistler mode QP emissions [Němec *et al.*, 2013c, 2014]. It can be seen that the period of these pulsations is larger than the modulation period of the EN event in this particular case. However, as the nature of these pulsations is not strictly harmonic, their period cannot be calculated directly by applying the Fourier transform. Instead, we determine their period as the median time separation of peaks in the magnetic field magnitude [Němec *et al.*, 2013c]. It is found that for this particular event the period of compressional ULF pulsations is about 6.6 min, while the modulation period of EN intensity is about 3.4 min.

We note that the observations of compressional ULF magnetic field pulsations along with EN events with QP modulation of the wave intensity do not necessarily imply that the two phenomena are related. It is especially noteworthy that while the modulations of EN wave intensities show, in general, very regular

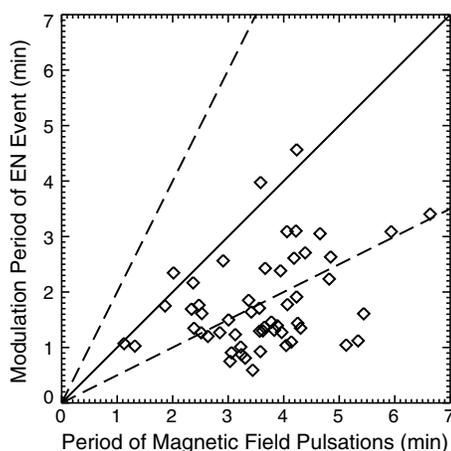


Figure 7. Modulation period of equatorial noise events with quasiperiodic modulation of the wave intensity as a function of the period of ULF magnetic field pulsations observed during the same time intervals. The solid diagonal line corresponds to the situation of the wave intensity modulation period being the same as the period of ULF magnetic field pulsations. The dashed lines above and below the solid black line correspond to the situation of the wave intensity modulation period being equal to twice the period of ULF magnetic field pulsations and to half the period of ULF magnetic field pulsations, respectively.

pulsations observed during the appropriate time intervals. The solid diagonal line corresponds to the situation of the EN modulation period being the same as the period of the ULF magnetic field pulsations. The dashed lines above and below the solid black line correspond to the situation of the EN modulation period being equal to twice the period of the ULF magnetic field pulsations and to half the period of the ULF magnetic field pulsations, respectively. It can be seen that although the scatter of the data points is rather large, the two periods appear to be correlated. The value of the Spearman rank correlation coefficient is equal to about 0.35, and the correlation is 99% significant. However, the two periods are generally not equal, but the period of ULF magnetic field pulsations appears to be on average about twice larger than the modulation period of EN wave intensity. We will discuss this relation more in detail in section 4.

Although called “noise,” EN events are known to exhibit a fine harmonic structure, which is likely related to the proton cyclotron frequency in the source region. This fine frequency structure cannot be seen in the low-resolution STAFF-SA data, but it can be identified in the high-resolution WBD data [Santolik *et al.*, 2002]. It is crucial to verify whether EN emissions with QP modulation of the wave intensity also exhibit such harmonic structure. This would directly point to the same generation mechanism, i.e., the instability of ring-like proton distribution functions in the source region [Xiao *et al.*, 2013; Ma *et al.*, 2014]. The high-resolution WBD data are available for 17 out of 118 EN events with QP modulation of the wave intensity. Detailed frequency-time spectrograms of power spectral density of electric field fluctuations measured by the WBD instrument were analyzed for all these events, and the presence of a harmonic line structure was confirmed in all of them. An example of such a high-resolution frequency-time spectrogram of power spectral density of electric field fluctuations is shown in Figure 8a. The data were measured by Cluster 2 on 23 August 2003 between 23:16 UT and 23:37 UT. We note that cyclic 42 s data intervals of the electric field measurements have been diluted across 10 s data intervals where the magnetic field had been measured instead. Several QP elements with clearly distinguishable harmonic line structure can be seen. Figure 8b shows the frequency-time plot of the ellipticity of magnetic field fluctuations measured by the STAFF-SA instrument during the same time interval, demonstrating that the waves are indeed linearly polarized. Following the approach used in Figures 1 and 2, the values of ellipticity were evaluated only in the frequency-time intervals with power spectral density of magnetic field fluctuations larger than $10^{-6} \text{ nT}^2 \text{ Hz}^{-1}$. We note that this event represents an example of purely QP modulated EN, with no continuous counterpart. We also note that the individual elements forming the event have a form of rising-tone

periodicities, the waveforms of compressional ULF pulsations are typically rather irregular. There is thus no one-to-one correlation between the individual elements of EN emissions and the peaks/valleys of the ULF pulsations. This could indicate that the two phenomena are not related, and their frequent simultaneous observations are a pure coincidence. The disagreement in the observed periodicities might be, however, possibly explained by the spacecraft movement during the observation. Namely, even if the compressional ULF pulsations were perfectly harmonic, a moving spacecraft would see pulsations with varying period, depending on its position on the magnetic field line (see, e.g., Takahashi *et al.* [1987], Korotova *et al.* [2013], and a more detailed discussion in section 4).

It is thus of interest to verify the relation between the modulation periods of EN events and the periods of simultaneously observed compressional ULF magnetic field pulsations in a systematic manner. The obtained results are presented in Figure 7, which shows the modulation period of EN events with QP modulation of the wave intensity as a function of the period of ULF magnetic field

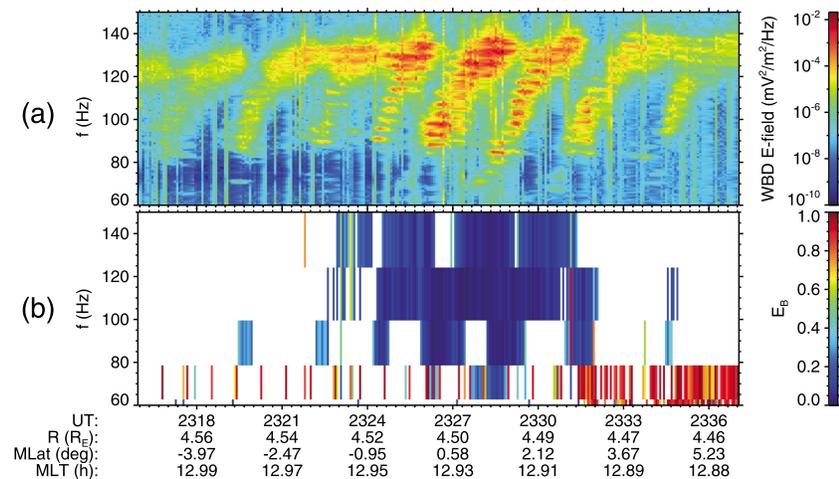


Figure 8. Example of an equatorial noise event with a quasiperiodic modulation of the wave intensity observed by Cluster 2 on 23 August 2003 between 23:16 UT and 23:37 UT, when the high-resolution WBD data were available. (a) Frequency-time spectrogram of power spectral density of electric field fluctuations. (b) Frequency-time plot of the ellipticity of magnetic field fluctuations.

structures (positive sweep rates). This seems to be a common feature of both EN events with QP modulation of the wave intensity (see also case studies by *Fu et al.* [2014] and *Boardsen et al.* [2014]) and VLF whistler mode QP emissions [see, e.g., *Hayosh et al.*, 2014], and it will be discussed more in detail in section 4.

4. Discussion

It has been found that about 5% of EN events observed by the Cluster spacecraft exhibit QP modulation of the wave intensity. This means that the events of this type are surprisingly common, especially when one considers the high occurrence rate of EN events, which is about 60% of Cluster equatorial perigee passages [*Santolík et al.*, 2004].

EN events with QP modulation of the wave intensity were visually identified in the list of all EN events observed by the Cluster spacecraft during the first 10 years of operation [*Hrbáčková et al.*, 2015]. As the frequency-time spectrograms of the entire individual EN events were analyzed during the identification process, i.e., the time interval of a few tens of minutes was plotted at a single time, we would have likely missed any events with modulation periods less than about 30 s. We believe that this imperfect event identification might be possibly responsible for the lack of events with shorter modulation periods in Figure 5. The identified modulation periods on the order of minutes are thus comparable with modulation periods of VLF whistler mode QP emissions observed by the Cluster spacecraft [*Němec et al.*, 2013c]. It is also noteworthy that the two EN events with QP modulation of the wave intensity reported by *Fu et al.* [2014] using Time History of Events and Macroscale Interactions during Substorms data and the event reported by *Boardsen et al.* [2014] using Van Allen Probes data have periods consistent with this range.

EN events with QP modulation of the wave intensity are often observed along with normal continuous EN events. They may have frequencies below or above, with no pattern clearly identifiable in our data set. We believe that these simultaneous observations might be at least in some cases explained by the emissions being generated independently at different locations and only arriving at the spacecraft at the same time. Another curious observation is that the wave propagation parameters of EN events with QP modulation of the wave intensity are sometimes not strictly those expected for EN. Namely, it appears that they do not propagate always strictly perpendicular to the ambient magnetic field, having a nonnegligible parallel component of the wave vector. This might possibly explain the lower intensity of QP modulated EN waves in the equatorial region observed in Figure 2. Specifically, the waves, although probably generated at the equator, might deviate from it during the propagation from the generation region to the observing spacecraft. This can be contrasted with normal continuous EN events, which typically have intensity maxima exactly at the magnetic equator [*Němec et al.*, 2006].

The events are found to occur primarily in the noon-to-dawn MLT sector. This MLT distribution is consistent with the primarily dayside occurrence of VLF whistler mode QP emissions [Morrison *et al.*, 1994; Engebretson *et al.*, 2004] and with the occurrence of harmonic field line oscillations in the Pc3–Pc4 frequency range [Takahashi and McPherron, 1982], which we suggest might be responsible for the QP modulation of the wave intensity. The observations of ULF compressional magnetic field pulsations at the times of 54 events seem to support this hypothesis. The absence of the observations of compressional ULF magnetic field pulsations in the remaining 64 EN events with QP modulation of the wave intensity can be explained by the propagation of EN emissions. Taking into account that they may propagate from distant source regions [Santolik *et al.*, 2002], it is well possible that the compressional pulsations were present in the regions of their generation, while being absent at the observation points. We note that these experimental results do not exclude the possibility that the ULF magnetic field pulsations and EN events with QP modulation of the wave intensity are two unrelated phenomena, and their frequent simultaneous observations are a pure coincidence. However, the hypothesis of the ULF pulsations being responsible for the QP modulation of EN is tempting. It would explain both the primarily daytime occurrence of the events, and their relation to the increased solar wind speeds, as these can serve as external source of harmonic field line oscillations [e.g., Takahashi *et al.*, 1984].

As for the relation between the periods of compressional ULF magnetic field pulsations and the periods of QP modulation of EN wave intensity, periods of compressional ULF magnetic field pulsations appear to be systematically larger, on average, by a factor of about 2. This relation is similar to one of the VLF whistler mode QP events reported by Němec *et al.* [2014], and it may be possibly explained in the same way. The basic idea is the one used in the model by Takahashi *et al.* [1987] to explain nonsinusoidal waveforms of compressional ULF magnetic pulsations observed by spacecraft in the equatorial region of the magnetosphere [Higuchi *et al.*, 1986], which was shown to be in excellent agreement with observations. They started with an antisymmetric standing wave model for a compressional wave (node at the magnetic equator). Then they extended this model by assuming that the equatorial node is not stationary, but its position harmonically varies with the period equal to the period of the compressional wave. Such a simple extension of the model results in the magnetic field waveform being significantly dependent on the position of the observer [see Takahashi *et al.*, 1987, Figure 2], which can possibly explain irregular waveforms of the ULF pulsations observed by the Cluster spacecraft at the times of EN events with QP modulation of the wave intensity.

It is important to note that according to the model of Takahashi *et al.* [1987], an observer located exactly at the geomagnetic equator would see two compressions per cycle. This directly stems from the equations given by Takahashi *et al.* [1987], but it can be also understood intuitively using a schematic picture provided by Korotova *et al.* [2013] (see their Figure 6). Specifically, imagine the node located in the north at a time in the wave cycle when the region south of it is compressed. If the node moves southward in phase with the wave, an observer at the geomagnetic equator would see another compression when the field north of the node is compressed. Assuming that the generation region of EN is located exactly at the magnetic equator [Němec *et al.*, 2006], the generation region would thus effectively “see” the compressions with half the real period of ULF pulsations. The exact shape of the ULF magnetic waveform observed by the spacecraft then depends on its movement with respect to the node.

The obtained results show that EN emissions with QP modulation of the wave intensity are in many aspects remarkably similar to VLF whistler mode QP emissions. This suggests that the modulation mechanism might be analogous for both types of emissions but acting at different frequencies and in different wave modes. However, a theoretical model which would confirm this hypothesis is still to be developed. Most importantly, the observed amplitudes of compressional ULF magnetic field pulsations are rather small, and it remains to be verified whether they may or they may not efficiently modulate the resonant conditions in the source region. A crude estimate based exclusively on the modulation of the Alfvén speed would suggest that they may not [Boardsen *et al.*, 2014], but a more refined theory is clearly needed to investigate this possibility properly.

Another possible generation mechanism of EN events with QP modulation of the wave intensity suggested by Boardsen *et al.* [2014] is an analogy with the electron cyclotron maser [Trakhtengerts, 1995; Pasmanik *et al.*, 2004a, 2004b]. The mechanism is based on the periodic evolution of the particle distribution in the source region due to the interplay between the wave instability and external particle sources. Importantly, it does not require the presence of magnetic field pulsations to operate, and it can therefore be used to

explain the observations of VLF whistler mode QP emissions of the so-called type 2, i.e., the emissions for which no corresponding magnetic field pulsations were observed [Sato *et al.*, 1974; Sato and Kokubun, 1980, 1981; Sato and Fukunishi, 1981]. Nevertheless, type 1 (with magnetic field pulsations) and type 2 (without magnetic field pulsations) VLF whistler mode QP emissions were classified using ground-based observations. However, Tixier and Cornilleau-Wehrin [1986] analyzed simultaneous observations on board a satellite and on the ground, and they proposed that QP emissions of type 1 and of type 2 may actually be the same phenomenon. The point is that the ULF magnetic pulsations may be always present in the source region, but they make it to the ground only if their period corresponds to the eigenfrequency of a given field line. In any case, the electron cyclotron maser analogy suggested by Boardsen *et al.* [2014] seems to be a plausible mechanism for the generation of EN events with QP modulation of the wave intensity. A more elaborated theory of this analogy is, however, again needed.

The third possible mechanism of the generation of EN events with QP modulation of the wave intensity was suggested by Fu *et al.* [2014]. They used an analogy with the nonlinear wave-particle interactions involved in the generation of wave elements of both chorus [Omura and Summers, 2006] and electromagnetic ion cyclotron [Omura *et al.*, 2006] waves, and they suggested that a similar nonlinear mechanism might be responsible for the generation of individual EN elements. However, in our understanding this generation mechanism would probably not be consistent with the fine harmonic structure of EN emissions, which persists even in the QP modulation.

The last point that we would like to comment concerns the observed rising-tone structures (positive sweep rates) of individual QP elements forming the modulated EN events. Interestingly enough, this feature seems to be consistent with most VLF whistler mode QP emissions [Hayosh *et al.*, 2014]. As pointed out by Boardsen *et al.* [2014], this is at least partially due to the dispersion. Specifically, the group velocity of EN emissions decreases with increasing frequency, and it reaches zero at the lower hybrid frequency. Assuming that the waves are not observed exactly at their source region, this results in lower frequency parts of QP elements arriving to the observer sooner than the higher-frequency parts of QP elements, forming thus rising-tone structures [see Boardsen *et al.*, 2014, Figure 1]. However, the authors concluded that this effect is likely not sufficient to explain the observed time delays of the event they analyzed; i.e., the rising-tone structure is probably generated already in the source region. This would be the case both for the nonlinear wave-particle interaction mechanism suggested by Fu *et al.* [2014] and for the electron cyclotron maser analogy suggested by Boardsen *et al.* [2014]. The modulation mechanism based on compressional ULF magnetic field pulsations was argued by Boardsen *et al.* [2014] to produce rising-tone structures only for unrealistically large ULF wave amplitudes. However, we again note that a more refined theory is needed to investigate this condition properly.

Since the generation of EN emissions has been recently extensively studied [Chen *et al.*, 2010; Liu *et al.*, 2011; Xiao *et al.*, 2013; Ma *et al.*, 2014], we believe that a full theoretical explanation of the origin of the QP modulation might be found in the near future.

5. Conclusions

Although EN events were generally believed to be continuous in time, we have shown that about 5% of more than 2000 EN events detected by Cluster between 2001 and 2010 exhibit a QP modulation of the wave intensity. We have performed a systematic analysis of EN events with this QP modulation. The events were found to occur usually in the noon-to-dawn MLT sector. Moreover, we have shown that the events occur predominantly in relation to the enhanced geomagnetic activity and particularly during the time intervals of increased solar wind flow speed. These occurrence characteristics are similar to the ones of harmonic field line oscillations in the Pc3–Pc4 frequency range. Modulation periods of the events were generally on the order of minutes. Compressional ULF magnetic field pulsations were identified at the times of about 46% of the events. Their periods were typically about double the modulation periods of EN events, and their magnitudes were on the order of a few tenths of nanotesla. We have suggested that these compressional magnetic field pulsations might be responsible for the observed QP modulation of EN intensity, in analogy to the VLF whistler mode QP events at frequencies of a few kilohertz. However, we note that it is only a hypothesis, and a full theoretical explanation of the origin of these events is still missing. Most importantly, the suggested generation mechanisms based on nonlinear wave-particle interactions [Fu *et al.*, 2014] and an analogy with the electron cyclotron maser [Boardsen *et al.*, 2014] should not be ruled out but carefully

verified. The analysis of 17 events for which high-resolution WBD data were available revealed that EN emissions with QP modulation of the wave intensity exhibit a harmonic line structure similar to normal continuous EN events. This clearly suggests that the generation mechanism of QP modulated EN is tightly related to the generation mechanism of normal continuous EN, i.e., the instability of ring-like proton distribution functions. Finally, the individual QP elements forming the events have rising-tone structures (positive sweep rates), which is an additional characteristic that should be considered when developing a theoretical model for these emissions. Although it is far beyond the scope of the presented observational paper, we optimistically believe that such a model might be developed by the scientific community in the near future.

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