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Surface waves and field line resonances: A THEMIS case study

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[1] Using magnetic field and plasma observations from four of the five Time History of Events and Macroscale Interactions during Substorms (THEMIS) spacecraft, a surface wave at the dawn flank of the magnetopause was identified on 25 April 2007. The wave had an amplitude of about 1 R_E and propagated tailward with a velocity of about 190–240 km/s. Its azimuthal wavelength was in the range of 9–11 R_E. Magnetosheath velocity values support the hypothesis that this surface wave was generated by the Kelvin-Helmholtz instability. Simultaneously, an ultralow-frequency (ULF) pulsation event was detected by the fifth THEMIS spacecraft deeper in the magnetosphere, at a distance of about 5–7 R_E from the magnetopause. This ULF event showed all the signatures predicted for waves generated by the classical field line resonance process. Frequency and phases of the detected ULF oscillations were found to be in close agreement with the magnetopause surface periodic disturbances. We conclude that the observed ULF wave event was most likely directly generated by the magnetopause surface wave and thus represents one of the few known manifestations of the classical field line resonance process in space directly observed, a conclusion made possible due to the special configuration of the THEMIS mission and its five spacecraft.

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1. Introduction

[2] Ultralow-frequency (ULF) pulsations in the period range from 1 s to more then 600 s are one of the modes via which the magnetosphere reacts to solar wind dynamics and associated instabilities of the magnetospheric system. One of the paradigms of ULF pulsation theory is the resonant coupling of a compressional surface wave with toroidal oscillations somewhere deeper in the magnetosphere. This field line resonance (FLR) mechanism was first suggested by *Tamao* [1965] and later used by *Southwood* [1974] and *Chen and Hasegawa* [1974] to interpret observational results by *Samson et al.* [1971]. A basic ingredient of the process is the resonant interaction of a compressional mode, spatially decaying toward the inner magnetosphere, and its coupling to a localized Alfvénic perturbation at a point where the local field line shell eigenfrequency equals the frequency of the driving surface wave. The typical characteristics of a global FLR are predominantly toroidal magnetic field oscillations, localized in radial direction within the magnetosphere. Across the position of maximum field amplitude, the phase of the toroidal component changes by 180° and the direction of polarization is reversed [e.g., *Nishida*, 1978]. The spatially decaying surface mode is thought to be generated by the Kelvin-Helmholtz instability (KHI) of the dawn and dusk magnetopause [e.g., *Southwood*, 1968; *Pu and Kivelson*, 1983; *Fujita et al.*, 1996], conditions for which are best when passing through a high-speed solar wind stream [e.g., *Seon et al.*, 1995; *Engebretson et al.*, 1998]. A ULF pulsation generated by the described resonant coupling between a compressional surface wave and a toroidally polarized and spatially confined Alfvenic perturbation we define here as a classical field line resonance.

[3] At the ground and in the ionosphere field line resonance associated oscillations are usually identified as latitudinally localized oscillations of the H component of the magnetic field [e.g., *Samson et al.*, 1971; *Green*, 1982; *Glassmeier*, 1988; *Mathie et al.*, 1999a; *Rae et al.*, 2005] or in the NS component of the ionospheric electric field [e.g., *Walker et al.*, 1979; *Fenrich et al.*, 1995], associated with a 180° phase shift across this resonantly oscillating field line

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shell. In space, however, direct observations of field line resonances are very sparse. As direct observations we define spatially and temporally resolved observations of wavefields exhibiting typical spatial and temporal characteristics of field line resonances.

[4] Further possibilities to drive discrete frequency perturbations with frequencies in the ULF range are cavity and waveguide modes [e.g., *Mann et al.*, 1999; *Mills et al.*, 1999], sudden impulses of the solar wind [e.g., *Saito and Matsushita*, 1967; *Kivelson and Southwood*, 1985], and quasiperiodic changes of the solar wind dynamic pressure [e.g., *Kepko and Spence*, 2003].

[5] The waveguide theory predicts that the magnetosphere can act as a cavity which traps discrete frequency compressional mode energy between the magnetosphere boundary and the reflection region inside the magnetosphere [e.g., *Mann et al.*, 1999]. Most of the events analyzed by [e.g., *Mathie et al.*, 1999b] using ground based observations can be explained in terms of such waveguide modes and agree closely with the theory proposed by *Samson et al.* [1992] and *Mann et al.* [1999], having discrete frequencies of oscillation. CLUSTER measurements [*Mann et al.*, 2002] furthermore support the hypothesis that, during intervals of fast solar wind speed, the KHI can excite magnetospheric waveguide modes which bathe the flank magnetosphere with discrete frequency ULF wave power and drive large amplitude resonant ULF pulsations.

[6] Probably the best documented example of a KHI-driven resonant ULF pulsation in space is the long-lasting event of 25 November 2001, reported about and analyzed in detail by *Rae et al.* [2005]. Multipoint observations from the CLUSTER and POLAR spacecraft allow one to demonstrate that KHI-driven surface waves drive resonant field line oscillations. The data presented in this study provide evidence for an observational link between wave activity at the magnetopause, in the magnetosphere, and in the ionosphere. The 25 November 2001 event certainly qualifies to directly demonstrate the functionality of the classical field line resonance process.

[7] Earlier studies by, e.g., *Singer* [1982] also reported radially localized, but poloidally polarized ULF waves using ISEE1 and ISEE2 observations and that allowed one to estimate the resonance region width to be about 0.7 RE. *Cramm et al.* [2000] also reported such localized poloidal modes close to the plasmapause and were able to demonstrate a significant phase variation across such a localized ULF wave event. But these events do not represent classical field line resonances, as the observed poloidal polarization was not in agreement with the theoretically expected toroidal polarization [*Southwood*, 1974]. However, such spatially localized and poloidally polarized waves are related to spatial variations of the Alfvén wave velocity close to the plasmapause [e.g., *Klimushkin et al.*, 2004; *Schäfer et al.*, 2007] or are excited by ring current ions on the dusk side of the magnetosphere [e.g., *Hudson et al.*, 2004].

[8] Further very convincing evidence for resonant toroidal oscillations in the dawn and dusk magnetosphere sectors was provided by *Engebretson et al.* [1986], who presented harmonically structured toroidal ULF waves with frequencies changing with magnetic latitude, much as expected for classical field line resonances. However, sudden changes of the solar wind dynamic pressure, that is wideband perturbations, are discussed as an alternative to the KHI source mechanism [e.g., *Kivelson and Southwood*, 1985; *Sinha and Rajaram*, 2003]. Such perturbations can generate natural modes of the magnetospheric resonator with the polarization depending on the propagation direction and magnetic field disturbance vector [*Agapitov and Cheremnykh*, 2008]. In their paper, these authors analyze periodic pulsations associated with sudden impulse in spacecraft magnetic field measurements and in ground based measurements at the magnetic conjugated point. Also, ULF pulsations with different frequencies were observed simultaneously on different magnetic latitudes after a sudden impulse [e.g., *Glassmeier et al.*, 1984]. The existence of such spectral maxima affirms the magnetospheric property of selecting particular spectral peaks with global modes coupling to corresponding local field line shell oscillations. Qualitative confirmation of the experimental results were obtained extensive numerical modeling in a dipole magnetosphere [e.g., *Lysak and Lee*, 1992].

[9] Nevertheless, the many observations of FLRs at the ground and in the ionosphere on the one hand and the sparsity of space observations of classical field line resonances on the other hand is worthwhile to be noted. Here, we present observations from the five Time History of Events and Macroscale Interactions during Substorms (THEMIS) spacecraft [*Angelopoulos*, 2008], traversing the dusk magnetosphere on a highly elliptic orbit with the spacecraft very often aligned in almost radial direction during the coast phase of the mission. Such radial conjugations are ideal for studying surface waves and associated field line resonances. We consider global ULF pulsations in a study similar to *Mann et al.* [2002] and *Rae et al.* [2005] with detail analysis of the magnetopause surface perturbations. The simultaneous analysis of magnetopause perturbation and ULF waves inside the magnetosphere gave an opportunity to explain the properties of observed ULF waves and distinguish the different possible generation mechanisms.

2. Observations

[10] THEMIS consists of five identically instrumented spacecraft, launched on 17 February 2007. The main goal of this mission is to conduct multipoint investigations of the substorm phenomena in the tail of the terrestrial magnetosphere [*Sibeck and Angelopoulos*, 2008]. During the coast phase of the mission between 17 February 2007 and 15 September 2007 all five THEMIS spacecraft were lined up in the same orbit with a 15.4 R_E apogee and a 1.3 R_E perigee. Orbit inclination to the ecliptic plane is 13.7°. The relative THEMIS spacecraft positioning were nearly radially aligned. During the year 2007 the THEMIS system orbit apogee rotated through the day side of the Earth's magnetosphere, such that in April 2007 the orbit skimmed the dusk magnetopause.

[11] For the current study, fluxgate magnetometer (FGM) observations [*Auster et al.*, 2008] and plasma measurements of the electrostatic analyzers (ESA) [*McFadden et al.*, 2008] were analyzed. We use spin averaged magnetic field data with a 3 s resolution to describe the ULF wavefield and plasma moments with a 3 s and a 3 min resolution to identify magnetopause crossings.

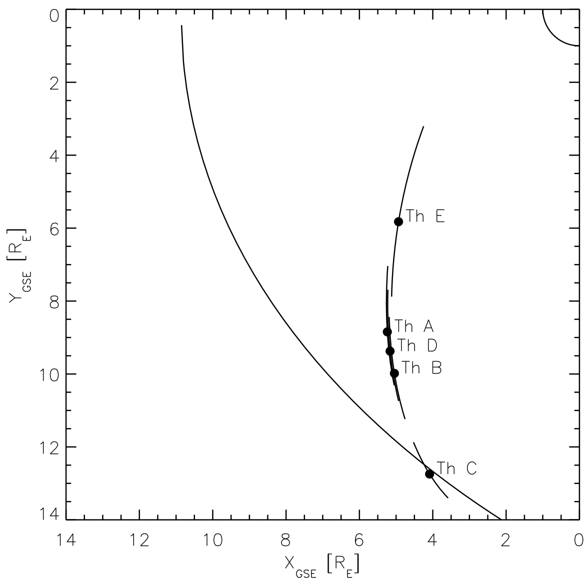

Figure 1. Like pearls on a string: The five THEMIS spacecraft on 25 April 2007, 1200–1500. The dots indicate the s/c positions at 1330. The magnetopause shown is based on the *Fairfield* [1971] model.

[12] The time interval from 17 February 2007 until 15 September 2007 has been inspected for localized toroidal magnetic field oscillations reminiscent of field line resonances. About 150 events where the five spacecraft were in almost radial alignment could be analyzed. During one such conjunction a localized toroidal oscillation has been identified associated with clear magnetopause surface periodic motion. This ULF event occurred on 25 April 2007 between 1200 UT and 1500 UT, a time interval during which the THEMIS spacecraft Th A, Th B, Th C, and Th D carried out observations near the magnetopause, detecting numerous crossings of the magnetopause boundary (Figure 1). The sparsity of observations of concurrent magnetopause oscillations and resonant field line oscillations motivates the current detailed case study.

[13] During this interval the solar wind was very quiet with the dynamic pressure monotonically decreasing from 2.4 to 2.0 nPa (data not shown here). At 1430 UT the pressure decreased further from 2.0 to 1.5 nPa in discrete steps. Figure 2 shows the components of the magnetic field measured by the Th A, Th B, Th C, Th D, and Th E spacecraft; geocentric solar ecliptic coordinates (GSE) are used. For Th E the magnetic field perturbations in magnetic field-aligned coordinate system are shown. The observed multiple crossings of the magnetopause are interpreted as quasiperiodic oscillations of the boundary surface superposed on the background of the slow change of the magnetopause position due to the decrease of the solar wind dynamic pressure.

[14] The magnetopause normal directions were computed for each observed crossing using magnetic field data and the minimum variance technique (MVAB) [e.g., *Paschmann and Daly*, 1998]; they are partially displayed in Figure 3. In Figure 3 the outbound and inbound crossing normal directions of Th A, Th B, Th C, and Th D are shown with local boundary plane observed during the spacecraft crossings. The magnetopause crossing times are listed. The schematic reconstruction of the MP surface perturbation based on results MVAB is shown at the top of Figure 3. The outbound and inbound crossing normal directions are found to be clustered in two groups (Figure 3). The alignment is almost in the Y_{GSE} direction. This suggests that the observed magnetopause motion originated from a two-dimensional, tailward propagating, and quasiperiodic magnetopause surface undulation.

[15] Analysis of the time delay between crossings observed by the different spacecraft allows one to determine the propagation velocity of the magnetopause surface. To determine the time of each crossing the magnetic field data were transformed into a minimum variance system with the minimum variance direction defining the boundary normal. The magnetic field component in the MP coordinate system with maximal variation is fitted by the function $a_3 + a_2 * \tanh((t - a_0)/a_1)$. The crossing times are determined by the a_0 coefficient. From the differences in crossing times and the known separation vectors of the spacecraft the propagation velocity of the boundary perturbation could be computed for several crossings and, hence, the phase speed of the wave could be estimated as 190–240 km/s. The wavelength in azimuthal direction could be estimated by multiplication of the wave velocity and the observed period of the magnetopause oscillation with 9–11 R_E.

[16] A possible source of the observed surface wave train are surface disturbances in the near subsolar magnetopause drifting tailward with the magnetosheath plasma flow. The amplitude of these disturbances can sufficiently increase due to the KHI of the flank boundary. To analyze this further we consider the simple case of an incompressible plasma in which the group and phase velocity of the driven boundary waves, are parallel to the magnetopause [e.g., *Pu and Kivelson*, 1983; *Fujita et al.*, 1996]. Using the standard assumption that the boundary thickness is much smaller than the wavelength of the driven boundary waves the necessary condition for onset of the KHI and wave growth is given by critical velocity $\vec{v}_{cr}$ [*Walker*, 1981]:

$$\left(\vec{v}_{cr} \cdot \vec{k}\right)^2 = \frac{\rho_1 + \rho_2}{\mu_0\, \rho_1\, \rho_2} \left[\left(\vec{B}_1 \cdot \vec{k}\right)^2 + \left(\vec{B}_2 \cdot \vec{k}\right)^2\right], \qquad (1)$$

where ρ, $\vec{B}$, and $\vec{k}$ denote the mass density, magnetic field, and the wave number vector, respectively; indices "1" and "2" denote corresponding values in the magnetosheath and the magnetosphere. If the velocity of the magnetosheath plasma flow exceeds the critical velocity v_{cr}, surface waves can be generated or intensified. We have tested this necessary condition near the magnetopause boundary to determine whether conditions are suitable for KHI: the condition was satisfied during the time interval studied here. The critical velocity according to (1) obtained from magnetosheath and magnetosphere conditions is 270–280 km/s. The value of the magnetosheath plasma flow is 290–310 km/s.

[17] In the time interval the magnetopause was observed to be unstable and oscillating, two ULF events were detected by the Th E spacecraft located deeper in the magnetosphere (Figure 4). The spacecraft (s/c) distance to the magnetopause changed from 7 R_E to 5 R_E during the interval 1240–1410 UT; the L shell changed from 6.5 to

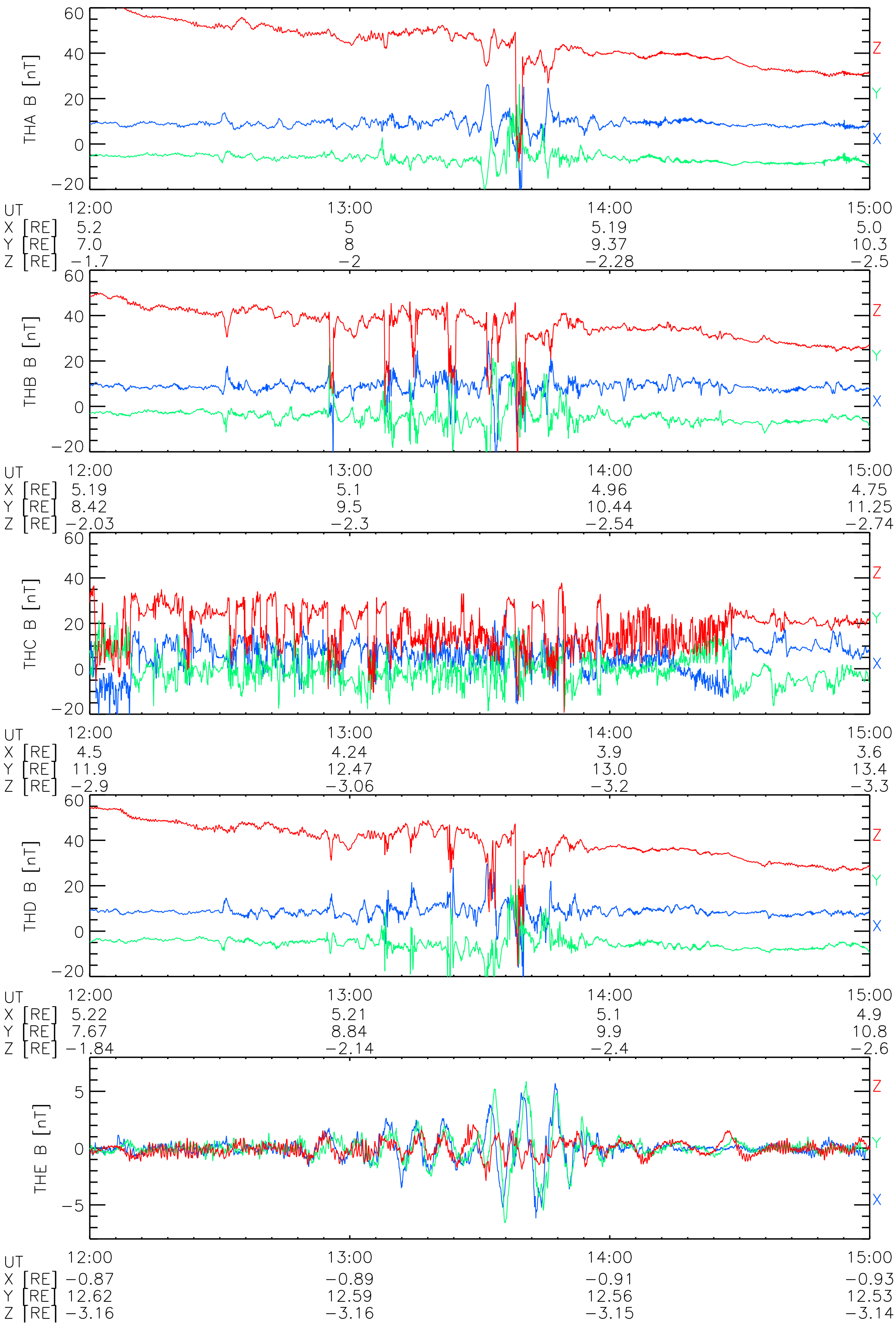

Figure 2. Magnetic field measurements GSE components made on board the THEMIS spacecraft Th A, Th B, Th C, Th D, and Th E during the time interval on 25 April 2007 from 1200 to 1500 UT. The Th E magnetic field measurements are shown in the field-aligned coordinate system.

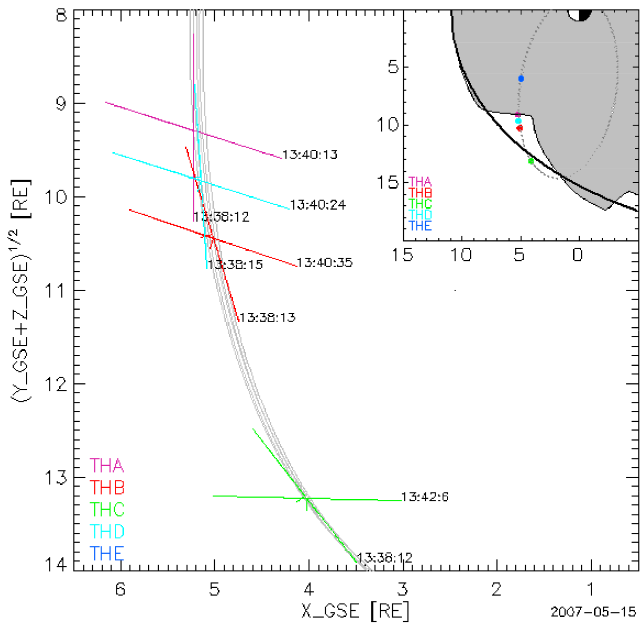

Figure 3. THEMIS system 25 April 2007, 1300–1400 UT. Spacecraft trajectories during the observed time interval are shown with grey lines. Magnetopause local boundary plane observed during spacecraft crossings is shown. The magnetopause crossing time moments are listed. The schematic reconstruction of the MP surface perturbation is shown at the top.

8.6, that is the s/c moved outward and approached the magnetopause. The magnetic field perturbations captured by Th E are analyzed in a mean field-aligned (MFA) coordinate system in Figure 2 (fifth panel). The z direction is defined as the direction of the background magnetic field. The y direction of the MFA system is obtained by cross product of spacecraft's position vector and z_{MFA} and points azimuthally eastward. The x direction completes the orthogonal right-hand system. To emphasize the field perturbations, the background magnetic field B_0 was subtracted. Thus, only the fluctuating component $b = B - B_0$ is shown. Figure 2 clearly indicates that the pulsation events are predominantly transverse polarized with the toroidal component dominating.

[18] The $\vec{k}$ wave vector of observed ULF event is shown in Figure 4. Its magnetic field-aligned direction supports our assumption of the FLR nature of observed magnetic field oscillations.

[19] The real part of the Morlet wavelet analysis of the magnetic field variation transverse to the background magnetic field as observed by Th E (Figure 5) wave process with frequency near 1.9 mHz. Theoretically estimated resonance frequencies for corresponding L shells are in range of 2.1–2.3 mHz, respectively [e.g., *Nishida*, 1978]. A corresponding analysis of the frequency of the magnetopause oscillations as seen in the $B_{Z,GSE}$ of Th B indicates a continuously decreasing frequency from 2.2 to 1.9 mHz, which corresponds well with the frequency of the wave event. The dotted line indicates the temporal variation of the frequency components with maximal amplitude. We interpret this as evidence for a resonant coupling between boundary motion and magnetospheric oscillations. The situation is schematically shown in Figure 6.

[20] To obtain further information about the spatiotemporal structure of the ULF perturbations, we use the method of the analytical signal or Carson-Gabor representation [*Carson*, 1937; *Gabor*, 1946; *Glassmeier*, 1980; *Cramm et al.*, 2000] which allows us to determine the instantaneous amplitude, phase, and frequency of a signal. For any given monochromatic signal x(t) the complex or analytic signal z(t) is given by

$$z(t) = x(t) - i\,\frac{1}{\pi}\int_{-\infty}^{\infty}\frac{x(\tau)}{1-\tau}\,d\tau, \qquad (2)$$

where the imaginary part is the Hilbert transformation of x(t). Using instantaneous amplitudes and phases of two transverse magnetic field components, the ellipticity and orientation of the transverse polarization ellipse can also be determined. Results of such an analytical signal analysis, applied to Morlet wavelet filtered magnetic field variation transversal to the background magnetic field in the frequency ranges of interest 1.8–2.2 mHz, are displayed in Figure 7. The amplitude exhibits a clear maximum at 1342 UT, much as one would expect for a radially localized field line resonance. The half width of the resonance is about 1 R_E. The phase difference remains approximately stable until 1324 UT, when the phase decreases until 1409 UT. At this time a phase change of π is detected which is not atypical for analytical signal results as minor amplitude changes can cause such rapid phase variations [*Glassmeier*, 1980]. Taking this into account the phase difference decreases by about 180° between 1324 and 1424 UT, that is, across the amplitude maximum. The polarization also changes across the region of maximum amplitude. Change of polarization, localization of the toroidal wave amplitude, and a phase change by 180° are characteristic features of a field line resonance as described by *Tamao* [1965], *Southwood* [1974], and *Chen and Hasegawa* [1974]. One might argue that the observed amplitude localization in the spacecraft frame of reference is the consequence of a finite lifetime of the event. However, in such a case one would expect the observed phase change across the time of maximum amplitude. Thus, a finite lifetime effect is not expected. We thus conclude that the 25 April 2007 wave event is a proper candidate for a classical field line resonance with the s/c Th A, Th B, Th C, and Th D observing magnetopause oscillations and Th E measuring the resulting localized resonant field line oscillation.

3. Conclusions

[21] Observations made during the coast phase of the THEMIS mission between March and October 2007 show an unexpectedly low number of toroidal ULF wave events in space. Most of the pulsations observed on board THEMIS during 2007 exhibit an evidence of the compressional component. This is in accord with earlier problems to identify classical field line resonances in space [*Glassmeier et al.*, 1999].

[22] Only one event could be identified sofar which shows all the characteristics expected for a classical field line resonance generated by the KHI rising on the magne-

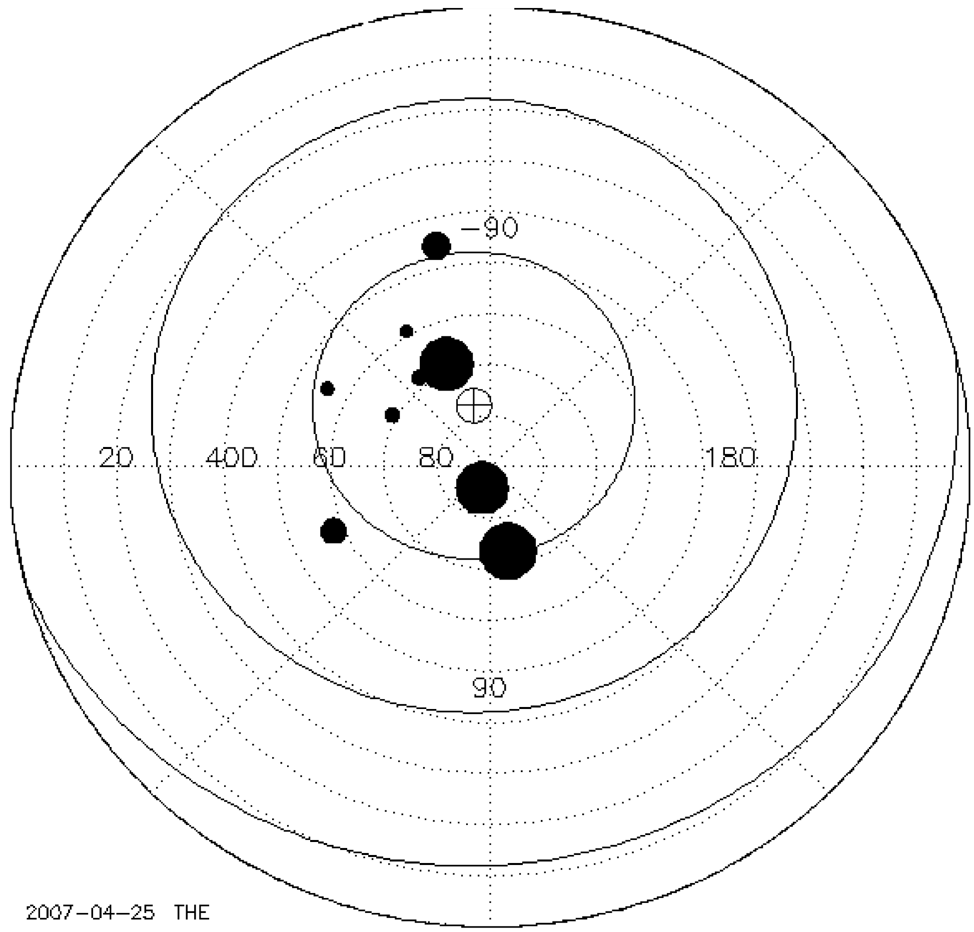

Figure 4. The directions of the $\vec{k}$ vectors of the ULF wave observed during 1300–1400 UT, 25 April 2007. The Sun is to the right; the polar axis is in the Z_{GSE} direction. The background magnetic field direction is shown with the cross in the circle. The 30, 60, and 90 angles from the background magnetic field are shown with the solid lines. The comparative wave power is shown with the circle radius.

topause surface. This event has been analyzed in detail here and, next to a ULF event analyzed by *Rae et al.* [2005], is probably the only observed example of a field line resonance in space most likely generated directly by clearly identified surface wave. The most probable energy transport mechanism from the magnetopause to FLR is the waveguide modes generation and their coupling with FLR modes as it was proposed by *Rae et al.* [2007]. But there is no clear evidence of waveguide mode in presented here event. The oscillation is mainly in the transverse magnetic field component with its amplitude localized in the radial direction and with an oscillation frequency corresponding to the local field line resonance natural frequency. The amplitude maximum was located at about L = 8 and the half width was about 1 R_E. Across the region of maximum amplitude, a phase change by 180° and a change of the sense of polarization is observed. The $\vec{k}$ direction supports the FLR nature of the observed ULF wave event. The wave event is found to be generated by a high-amplitude surface wave observed at the same time by the other THEMIS s/c. The conditions of the KHI growing on the magnetopause were satisfied during the interval of observations.

[23] THEMIS multispacecraft observations made in the time interval April–September 2007 provided for a unique opportunity to reconstruct the magnetopause surface dynamics [see also *Plaschke et al.*, 2009]. During this time interval the THEMIS s/c crossed magnetopause surface more than 300 times. About half of the crossings were multicrossings (several inward and outward boundaries crossing of single spacecraft during short time interval). As the five s/c were also in a string-of-pearls configuration in radial direction ample opportunity for the observation of KHI-driven classical field line resonances did exist.

[24] The sparsity of the clear toroidal ULF pulsations detected in the THEMIS data so far is surprising, as during a comparable time interval many more so-called field line resonance events are usually detectable in ground magnetic or ionospheric electric field observations. Several reasons can be discussed to explain the sparsity of FLR resonance events. First, only a small fraction of the observed multicrossings was found to satisfy the KHI growth criterion. Thus, most of the observed quasiperiodic magnetopause motions are probably quasi-static motions of the magnetopause, not surface wave–driven perturbations. This can be caused by generally low level of the solar activity during

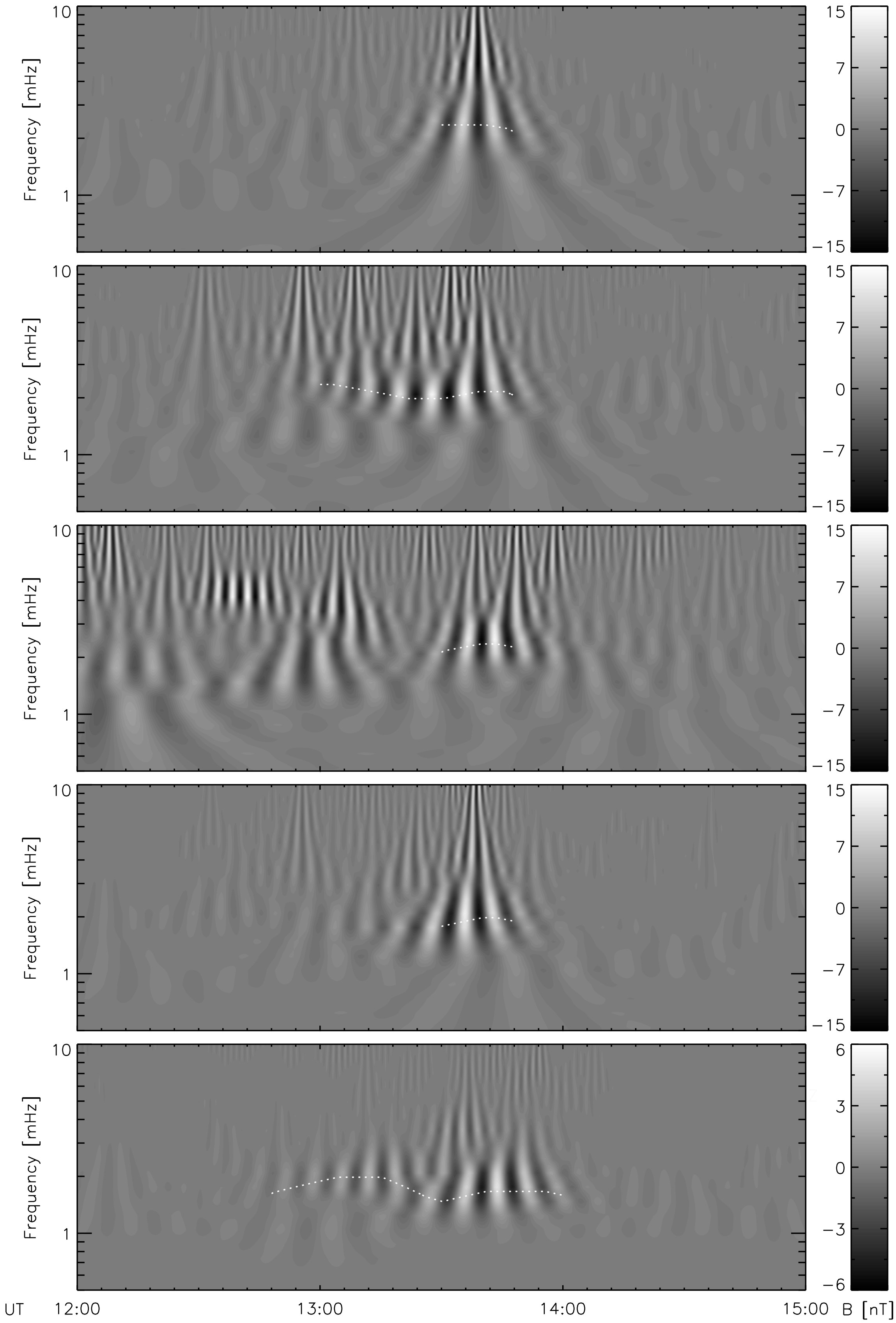

Figure 5. The real part of the Morlet wavelet spectrum of the $B_{Z,GSE}$ component measured at s/c Th A, Th B, Th C, Th D (first through fourth panels) and the transverse magnetic field perturbation component measured at s/c Th E (fifth panel) during the time interval 25 April 2007, 1200–1500 UT. The dotted line indicates the temporal variation of the main frequency components.

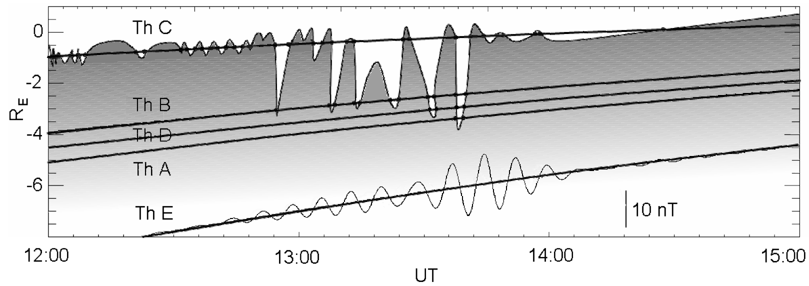

Figure 6. A schematic reconstruction of the magnetopause position using the observed magnetopause crossings and the Fairfield-71 magnetopause model. Radial positions of the different s/c are given with respect to the model magnetopause used. The magnetospheric wave event as seen by Th E is also shown along the Th E track.

observation period and respectively lower averaged values of the solar wind velocity. THEMIS spacecraft system during 2007 more often was close to a magnetic equatorial plane. This can make FLRs harder to find in the THEMIS data set.

[25] Second, if one assumes that the low number of observations of classical field line resonances in the THEMIS data is not surprising, the reason for the large number of FLR wave events usually observed in ground magnetic or ionospheric electric field observations needs to be discussed. A discussion of the spatial character of the ground magnetic field and the ionospheric electric field of an Alfvén mode might be helpful here. Below the ionosphere, any magnetic field is due to the source-free part of the ionospheric current system [e.g., *Glassmeier*, 1984]. Thus, any wavefield localized in NS direction must exhibit a shear structure which is equivalent to a 180° phase variation in NS direction. A similar argument holds for the ionospheric electric field of an Alfvén mode whose electric field must be irrotational [e.g., *Glassmeier*, 1984]. Again, if the wavefield is localized in the NS direction, its Alfvénic nature imposes a directional change of its NS component implying a 180°. Thus, any process generating a localized ULF wavefield detected in the ionosphere or at the ground is associated with the typical 180° phase change. Due to the ionospheric screening effect [*Hughes and Southwood*, 1976] this 180° phase change is smeared out and can be detected as a significant NS phase variation. If no major phase change of a ULF wavefield is detected in NS direction this implies that the wavefield is not localized. Thus, an interpretation as a field line resonance would be inappropriate. A major phase change is merely a necessary condition for the identification of a field line resonance, not a sufficient one.

[26] One mechanism to cause spatial localization is the field line resonance mechanism. Any other localizing process will give rise to the same spatial structure. Possible alternative localization mechanisms could be spatially limited regions in the ring current, for example, where wave-particle interaction-driven instabilities can generate ULF waves and FLR [*Chisham and Mann*, 1999; *Wright et al.*, 1999]. Also, the presently little understood dynamic feedback between the ionosphere and the magnetosphere can be responsible for spatial localization [e.g., *Streltsov and Lotko*, 2005]. Unambiguous identification of FLR is only possible if magnetopause observations are also available, allowing one to identify the generating mechanism of the ULF wave observed. The case study presented here provides such an unambiguous identification, much as did the study by *Rae et al.* [2005].

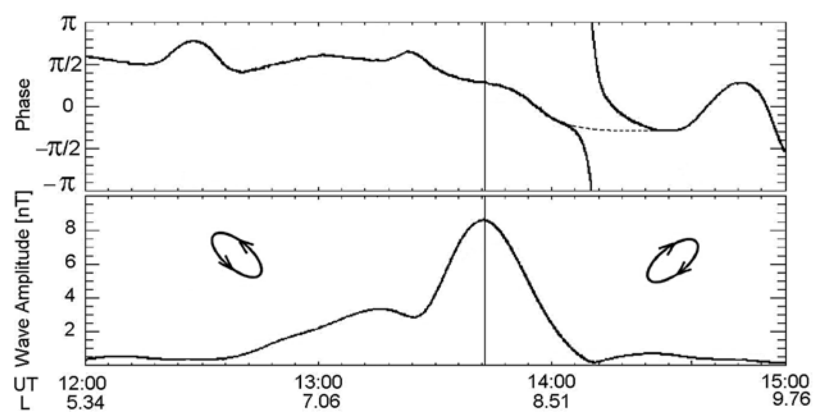

Figure 7. Analytical signal analysis results of Th E magnetic field measurements: (top) phase difference between the B_X and B_Y components in the field-aligned coordinate system and (bottom) amplitude of the transverse magnetic field component for the frequency range 1.8–2.1 mHz in the time interval on 25 April 2007 from 1200 to 1500 UT. The polarization is schematically shown as well.

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