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Pseudo-field line resonances in ground Pc5 pulsation events

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Abstract. In this work we study four representative cases of Pc5 ground pulsation events with discrete and remarkably stable frequencies extended at least in a high-latitude range of ∼20°; a feature that erroneously gives the impression for an oscillation mode with "one resonant field line". Additionally, the presented events show characteristic changes in polarization sense, for a meridian chain of stations from the IMAGE array, and maximize their amplitude at or close to the supposed resonant magnetic field shell, much like the typical FLR. Nevertheless, they are not authentic FLRs, but pseudo-FLRs, as they are called. These structures are produced by repetitive and tilted twin-vortex structures caused by magnetopause surface waves, which are probably imposed by solar wind pressure waves. The latter is confirmed with in-situ measurements obtained by the Cluster satellites, as well as the Geotail, Wind, ACE, and LANL 1994-084 satellites. This research effort is largely based on two recent works: first, Sarafopoulos (2004a) has observationally established that a solar wind pressure pulse (stepwise pressure variation) produces a twin-vortex (single vortex) current system over the ionosphere; second, Sarafopoulos (2004b) has studied ground events with characteristic dispersive latitude-dependent structures and showed that these are associated with twin-vortex ionosphere current systems. In this work, we show that each pseudo-FLR event is associated with successive and tilted large-scale twin-vortex current systems corresponding to a magnetopause surface wave with wavelength 10–20 R_E. We infer that between an authentic FLR, which is a spatially localized structure with an extent 0.5 R_E in the magnetospheric equatorial plane, and the magnetopause surface wavelength, there is a scale factor of 20–40. A chief observational finding, in this work, is that there are Pc5 ground pulsation events showing two gradual and latitude dependent phase-shifts of 180°, at the same time.

Key words. Ionosphere (Electric fields and currents) – Magnetospheric physics (Magnetosphere-ionosphere interactions, Electric fields)

1 Introduction

The "field line resonance (FLR) phenomenon" is of fundamental importance if we are going to study ULF pulsations within the Earth's magnetosphere or in other planetary systems as well. The purpose of this work is to focus our attention on ground recorded events that seemingly appear as representative FLR phenomena, but actually they are not.

The FLR theory has been developed by Tamao (1965), Southwood (1974), and Chen and Hasegawa (1974): a fast mode type surface wave at the magnetopause couples resonantly with Alfvén modes in the magnetosphere due to nonuniformity of the background plasma. The resonant field line is characterized by maximum perturbation amplitude, as well as an 180° phase shift of the toroidal magnetic field perturbation. On the ground and across the resonant field line the polarization sense changes for the horizontal magnetic field perturbation. For the case studies of this work, the solar wind pressure is investigated and probably it changes quasi-periodically and modulates the magnetopause surface throughout the events under study. Therefore, the imposed compression oscillations may actually couple to toroidal-mode standing Alfvén waves at the locations where the driver frequency matches the local toroidal-mode Alfvén frequency (look also at the review papers of Hughes, 1994; Glassmeier, 1995a; Takahashi, 1998). The same notion is treated by numerical simulations (Lee and Lysak, 1991).

Although the FLR theory is able to explain many features of high-latitude ULF pulsation observations, many open questions remain. One of them is that "ground-based observations suggest the presence of just one resonant field line", as it is expressed by Glassmeier (1995b). This requires either a monochromatic source mechanism or another process which allows preparing a broad-band signal in such a way that it appears as a monochromatic signal. Kivelson and Southwood (1985, 1986) suggested the excitation of a discrete cavity mode spectrum by a broad-band source and subsequent coupling of these discrete modes to single field line resonances. Though the latter scenario is rather appealing it has its difficulties. Cavity modes and field line resonances have been observed in simulated ULF pulsation fields, but the existence of cavity modes has not yet directly been proved by spacecraft observations.

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We study cases of ground-based observations with "one resonant field line", and we eventually infer that the supposed resonances do not exist at all. For instance, the observed characteristic phase shifts of 180° are not caused by the FLR mechanism. In these cases there is no any oscillating magnetic field structure, but only a passive magnetosphere response to a solar wind pressure wave. We understand these events as completely disassociated by any scheme of toroidal oscillations. The toroidal oscillations, which frequently have been observed by satellites in a wide range of L (Anderson et al., 1990; Nosé et al., 1995; Potemra and Blomberg, 1996), are probably excited in our cases, but they are screened off from the Earth's observations. We suggest that the toroidal oscillation effects, at least for the case studies included in this work, are covered up by the much stronger effects produced by the direct action of a solar wind pressure wave. A basic tool in this research effort is Tsyganenko's T96 model of magnetosphere magnetic field (Tsyganenko, 1995, 1996) that maps the ground station positions to conjugate points over the equatorial plane. We know the geographic coordinates for each ground station, that is the footpoint for a field line at the Earth's surface, and the trace that line for a specified moment of universal time (UT) using Tsyganenko's T96_01 model (the 22 April 2003 version is used). We apply this model in the dawnside magnetosphere and the conjugate points of IMAGE stations are traced over the magnetotail current sheet. These $(X, Y)_{GSM}$ points are determined as those along the field line with $Z_{GSM}=0$. We use the new T96 model, which was developed with continuous dependence on the solar wind pressure, interplanetary magnetic field (IMF) and D_{st}-index, replacing earlier binning into several K_p-index intervals.

We study four selected events, and we certainly do not perform any statistics. Additionally, any arbitrary generalization or simplification is beyond our intention and out of the scope of this work. However, the suggested discrimination between pseudo- and genuine-FLR events is of great importance and may lead us to resolve the existing discrepancy between ground and in-situ observations within the magnetosphere concerning the FLR phenomenon.

Takahashi (1998) in his review many times stressed that "it is of great importance to examine the state of the solar wind at times when magnetic pulsations are observed on the ground". This suggestion is seriously taken into account in this work, although the solar wind data, for the majority of the cases, are of low resolution and available from only one satellite, which was often positioned distant from the x-axis. The same methodology of approach, although the emphasis was to monitor the solar wind conditions by multi-satellite instruments, was applied in a recent work by Sarafopoulos (2004a).

This article further supports and expands the results of a previous work performed by Sarafopoulos (2004b). Among other findings he presented geographic latitude-dependent delays in signature arrival times at dawnside ground magnetograms. He stressed the great importance for these dispersive structures and demonstrated that these are directly dictated by successive exo-magnetosphere pressure pulses applied along the magnetopause. Another work very frequently mentioned here is that by Sarafopoulos (2004a), in which, observationally, it has been established that a solar wind pressure pulse (stepwise pressure variation) produces a twin-vortex (single vortex) current system over the ionosphere. In this work, and specifically within the discussion section, we conclude that the pseudo-FLR events are associated to repetitive tilted twin-vortex structures over the ionosphere. Key observations and possible source mechanisms concerning the ionosphere twin vortex structure can be found in the works by Glassmeier (1992), and Lanzerotti et al. (1986).

By itself, the idea that frequencies of some of the ULF pulsations are defined not by the internal structure/size of the magnetosphere (cavity modes, FLRs), but rather by the frequency of some external driver (e.g. solar wind) interacting with the magnetopause or plasmapause, is well known since the paper by Lanzerotti et al. (1973). Earlier references suggesting Pc5 pulsations within the magnetosphere directly driven by a solar wind pressure wave can be found in Sarafopoulos and Sarris (1994), and Sarafopoulos (1995).

2 Observations

2.1 Two ground-based examples with "just one resonant field line"

As we have stressed in the Introduction there are examples of ground-based observations suggesting the presence of "just one resonant field line". These events could have been erroneously categorized as FLRs, in the past. Bellow, in a first approach to our subject, we present two such events in Figs. 1 (day 179, 2001) and 2 (day 341, 1994), whereby only a few aspects of great importance are emphasized. The traces from only two successive in latitude ground stations (i.e. Bear Island-BJN and Tromsø-TRO or Hornsund-HOR, see Table 1) are shown, in between the supposed resonant L-shell is located. These Pc5 pulsations show waves characterized by a phase-shift of 180° between the X-component traces (top two panels), whereas for the Y-component traces show waves almost in-phase (next two panels). The dashed line along each trace is a sixth degree polynomial fitting for the shown measurements. Given that across a typical FLR the change in polarization is equivalent to a change in the phase of one of the horizontal magnetic field perturbation components by 180° (Glassmeier et al., 1999), then both of these events may be FLRs. An indicative picture concerning the polarization sense is given through the hodograms of the Hopen Island-HOP and Kilpisjärvi-KIL stations in Fig. 1, for one or two variation cycles. These stations are located at latitudes higher and lower, respectively, from the supposed L-resonant shell. Relatively to the resonant shell the HOP station corresponds to an outer magnetic field shell,

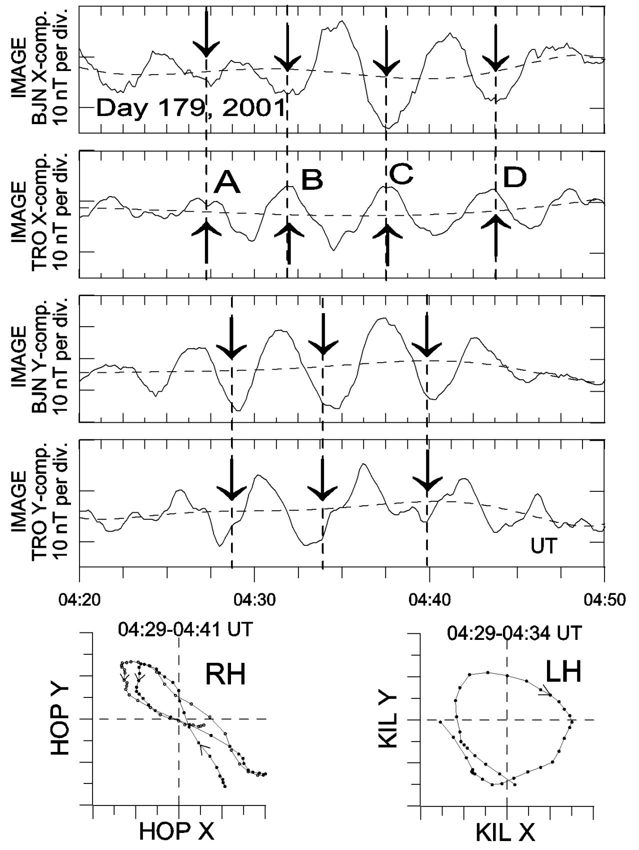

Fig. 1. X and Y component magnetograms, from two successive in latitude (i.e. BJN and TRO) ground stations of the IMAGE array, for the event of day 179, 2001. Between the two stations the X component traces show waves in anti-phase, whereas the Y components vary in-phase. The HOP (KIL) station, which has a latitude higher (lower) than that of the BJN (TRO) station, shows right-hand (left-hand) polarized waves.

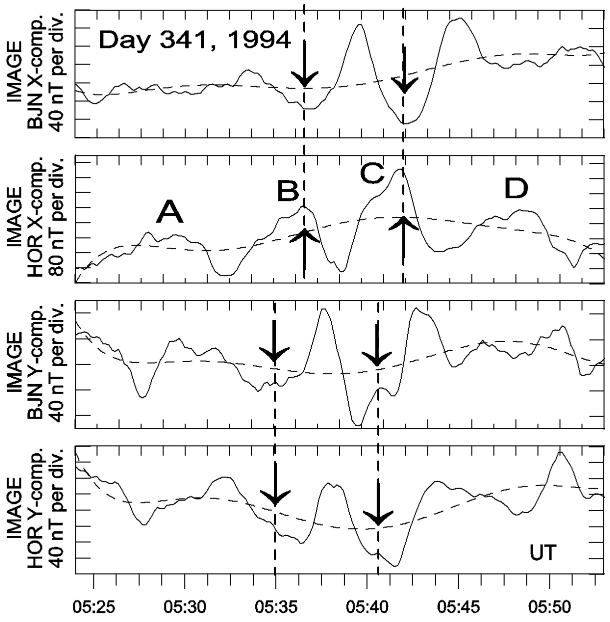

Fig. 2. Same format as in Fig. 1, for the event of day 341, 1994. The X-component wave at HOR changed its phase by 180° as compared to that at BJN. The Y-component traces show pulsations in-phase.

whereas KIL corresponds to an inner shell, while the polarization changes from right-hand (RH) to left-hand (LH), as one would anticipate in agreement in the current FLR model. It must be underlined (and it is shown later on) that the pulsations, in both events, are extended from the lowest up to the highest latitudes of IMAGE stations (i.e. a range of ∼20° in latitude); and in this way the monochromatic character of oscillation is apparent. In a first glance, one may consider that the maximum pulsation amplitude occurs just at the supposed FLR shell. The latter is not true because, as we shall see later on, there are characteristic latitude displacements in observed maximum amplitudes in disagreement with the FLR mechanism.

Below we scrutinize in detail the two already exhibited introductory examples and we question that they are actually FLRs. We are interested in all the available data sets, and especially in those carrying information about the exomagnetospere conditions. Two more events are included and analyzed in this subsection aiming to establish the discrimination effort, undertaken in this work, between local FLRs and other large-scale structures like the twin-vortex ionosphere current systems. Nevertheless, open questions will remain, and a statistical work, for instance, will be of great importance.

2.2 First event on 28 June (day 179) 2001

A representative stack of eight X-component magnetograms from the IMAGE array concerning this event of day 179, 2001, is shown in Fig. 3. Apparently, this is an event of Pc5 ground pulsations whereby the dispersive character of almost each peak is emphatically shown through the slant-dashed lines. Similar dispersive structures, as well as a model producing them, are exhibited by Sarafopoulos (2004b). From bottom to top the station latitudes gradually increase, although the increment is not constant. At 04:37:30 UT a phase shift of ∼180° is seen between the BJN and TRO waveforms (look at the shaded parts of traces). The question is whether this transition in phase is caused locally by the field line resonance mechanism. If we look closer at Fig. 3, then we shall discern that at the same moment between the Ny Ålesund-NAL and BJN station traces there is an ∼180° phase-shift, too. If this is actually a second FLR, then it seems that two distinct L-shells resonate at the same frequency, which is unacceptable. It must be noted that the Pello-PEL and Lovozero-LOZ station traces clearly display the presence of higher harmonics, but the major variations that occurred at ∼04:30 and 04:38 UT demonstrate an oscillation frequency equal to that of the higher latitude stations. Moreover, if a FLR actually takes place between BJN and TRO, showing ΔX variations up to 20 and 10 nT, respectively, then it is unexpected that the HOP station, which is located distant from the resonant shell, displays the maximum

Table 1. Geographical and CGM coordinates of IMAGE stations.

Abbrev.	Name	Geogr. lat	Geogr. long	CGM lat.	CGM long
NAL	Ny Ålesund	78.92	11.95	75.25	112.08
LYR	Longyearbyen	78.20	15.82	75.12	113.00
HOR	Hornsund	77.00	15.60	74.13	109.59
HOP	Hopen Island	76.51	25.01	73.06	115.10
BJN	Bear Island	74.50	19.20	71.45	108.07
SOR	Sørøya	70.54	22.22	67.34	106.17
KEV	Kevo	69.76	27.01	66.32	109.24
TRO	Tromsø	69.66	18.94	66.64	102.90
MAS	Masi	69.46	23.70	66.18	106.42
AND	Andenes	69.30	16.03	66.45	100.37
KIL	Kilpisjärvi	69.02	20.79	65.88	103.79
LEK	Leknes	68.13	13.54	65.40	97.50
LOZ	Lovozero	67.97	35.08	64.23	114.49
PEL	Pello	66.90	24.08	63.55	104.92

ΔX variation of ∼30 nT. In Fig. 4 we have placed over the equatorial plane XY, the conjugate points for several IMAGE stations using the Tsyganenko T96 model; a process similar to that performed by Sarafopoulos (2004b). The solar wind parameters are determined by the ACE spacecraft located at (X, Y, Z)$_{GSE}$=(247.5, 23.5, 12.8) R_E, at 03:30 UT. The solar wind velocity is V_x=400 km·s^{-1} and the needed travel time is ∼65 min. Therefore, we input to the model B_y=−0.2 nT, B_z=0.3 nT, P=1.2 nPa and D_{st}=7 nT for the time 04:30 UT. The geomagnetic activity is extremely low for a prolonged interval preceded this event. The ground station conjugate points, as they are shown in Fig. 4, are associated with different magnetopause surface displacements, given that the magnetopause surface is wavy modulated. According to this scenario, the phase information of the surface wave is probably transmitted directly to the ionosphere via the magnetic field lines, as it is suggested by Sarafopoulos (2004b). A close look at the just proposed mechanism will be given in the discussion section. This time, using in-situ satellite measurements, it is of prime importance to provide convincing evidence that a surface wave actually exists. The observational evidence is based on Cluster satellites, as well as on the Geotail, LANL 1994-084 and ACE satellites, and is exhibited below:

(a) Cluster 3 (CL3), at 04:30 UT, was located at (X, Y, Z)$_{GSE}$=(−5.57, −16.26, 5.57) R_E, and its position is shown in Fig. 4. The magnetic field amplitudes (FGM experiment; Balogh et al., 1997) for all four spacecraft are shown in the four upper panels of Fig. 5. It is clear that the six major decreases marked with the A-F capital letters along the BJN Y-component trace (seventh panel) are seen at the CL1 and CL4 magnetic field magnitude variations. The Cluster spacecraft remains at the plasma sheet boundary layer region (PSBL), and the whole boundary structure seems to oscillate with the same frequency observed in ground stations. We note that Pc5-type standing waves over the PSBL region are commonly observed, and a representative work is that by Sarafopoulos and Sarris (1991). The CL1 and CL4 magnetic field magnitudes are probably affected by the same magnetopause surface wave travelling tailward. The very good anti-correlation between the B_x and B_z traces at CL1 (not shown here) confirms that CL1 enters periodically into the plasma sheet, where the diamagnetic effect of plasma particles reduces the magnetic field magnitude, whereas the B_z increases. Additionally, all four Cluster spacecraft at ∼04:31 UT exit abruptly toward the lobe domain. In a close look at this transition, each satellite reaches a peak value in a slightly different moment, and this delay is probably due to the surface wave that propagates tailward. Actually, the detected order of peaks in Fig. 6 corresponds to what one would anticipate for tailward wave propagation. The spacecraft ΔX distances from the reference satellite CL3 are: ΔX_{13}=1124, ΔX_{23}=−919 and ΔX_{43}=−238 km. A rough estimate of velocity using CL1 and CL3 (or CL1 and CL4) is inferred at 187 km·s^{-1} (151 km·s^{-1}). Again, we stress the fact that this estimate is not based on boundary crossings, but on variations observed well within the plasma sheet.

(b) The geostationary satellite LANL 1994-084 is characterized by the longitude 103.42°, and consequently at 04:30 UT it was positioned at 169.92°, that is close to the noon meridian plane (see Fig. 4). From the LANL energetic particle experiment we select the 50–75 keV energetic electron channel and these flux measurements are shown at the bottom panel of Fig. 5. Indeed, this time profile of fluxes shows six major decreases, one-to-one corresponding to the ground BJN Y-component minima. Consequently, the electron fluxes are probably modulated by the same magnetopause surface wave that affects the ground magnetograms.

(c) Geotail at 04:30 UT was located at (X, Y, Z)$_{GSE}$ = (−8.58, −5.4, 0.5) R_E, (see Fig. 4). The Geotail vector magnetic field is slightly affected during the interval under study and such a variation is better traced through the B$_y$ magnetic field component, which is shown in the fifth panel of Fig. 5. At least the first five major deviations seem to show the same periodicity with the supposed magnetopause surface wave, the BJN pulsations, the Cluster 1 and 4 magnetic field variations and the 1994-084 flux wave.

(d) The low resolution time (64 s) of the ACE/SWEPAM proton density instrument prevents us from monitoring fast variations in the solar wind conditions. Only a major density decrease (Fig. 7, first panel) seems to occur with an abrupt ACE/MAG magnetic field magnitude increase at ∼04:32. However, the ACE magnetic field magnitude in Fig. 7 (second panel) shows indicative variations marked with arrows that may correlate to the BJN station variations (third panel). We have to note that the ACE time series are time-shifted 67 min to match the ground data. The latter is dictated by the ACE position and the solar wind velocity being ∼400 km·s^{-1}. Therefore, in this case we do not have a direct convincing observational evidence for a solar wind pressure wave, although we are much more certain of the development of a magnetopause surface wave. We also note that for a much more extended time interval, than that shown in Fig. 7, the solar wind proton density is generally anticorrelated to the magnetic field magnitude.

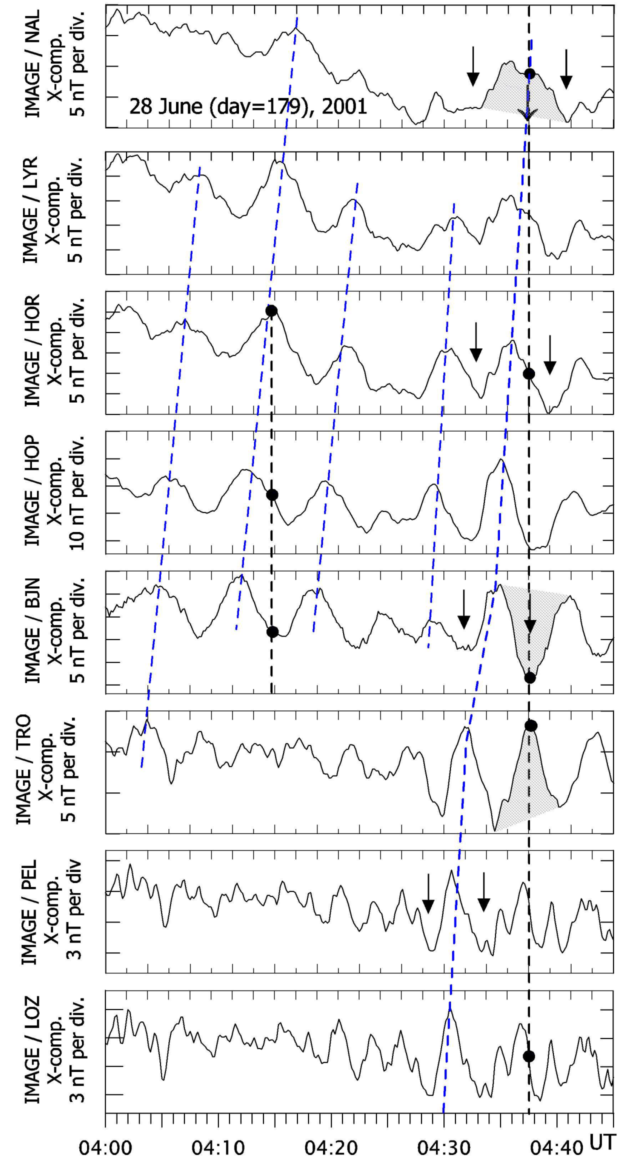

Fig. 3. A stack of eight X component magnetograms from the IMAGE array concerning the event of day 179, 2001. The slant-dashed lines emphasize the dispersive character in signature arrival times. In particular, we pay attention to the double phase change of 180° which occurred at ∼04:37 UT.

2.3 Second event on 7 December (day 341) 1994

A stack of seven X-component ground magnetograms during the interval 05:20–06:00 UT, of day 341, 1994, are shown in Fig. 8. A first and foremost observational feature, which is emphasized by the five slant-dashed lines, is that there is a systematic phase shift in magnetometer waveforms or a delay time in arrival of each of the five distinct ground signatures, marked with the letters a–e. The delay time increases from bottom to top, as we move to higher latitudes. The phase-shift is gradual, and consequently, we fail to determine an L-shell at which the phase changes abruptly 180°, as it would be anticipated in a typical FLR. It seems that the station latitude is directly associated with the signature arrival time. In particular, we pay attention to changes in phase observed at the moment 05:42 UT. If we consider that an abrupt phase change of ∼180° occurs between the stations BJN and Sørøya-SOR or Masi-MAS, with maximum ΔX variations ∼100 and 80 nT, respectively, then the largest amplitude oscillation (ΔX≈250 nT) will be observed at HOR, which is not adjacent to the supposed resonant L-shell. If we consider that a phase change of ∼180° occurs between the stations NAL and BJN, then we shall infer that two FLRs are simultaneously excited with the same frequency at different L-shells; an unacceptable hypothesis. As we shall discuss later on, the presented ground signatures are not associated with FLRs, but with successive twin-vortex ionosphere current systems.

Usually below the BJN station latitude the amplitude of the waves significantly decreases, higher harmonics appear

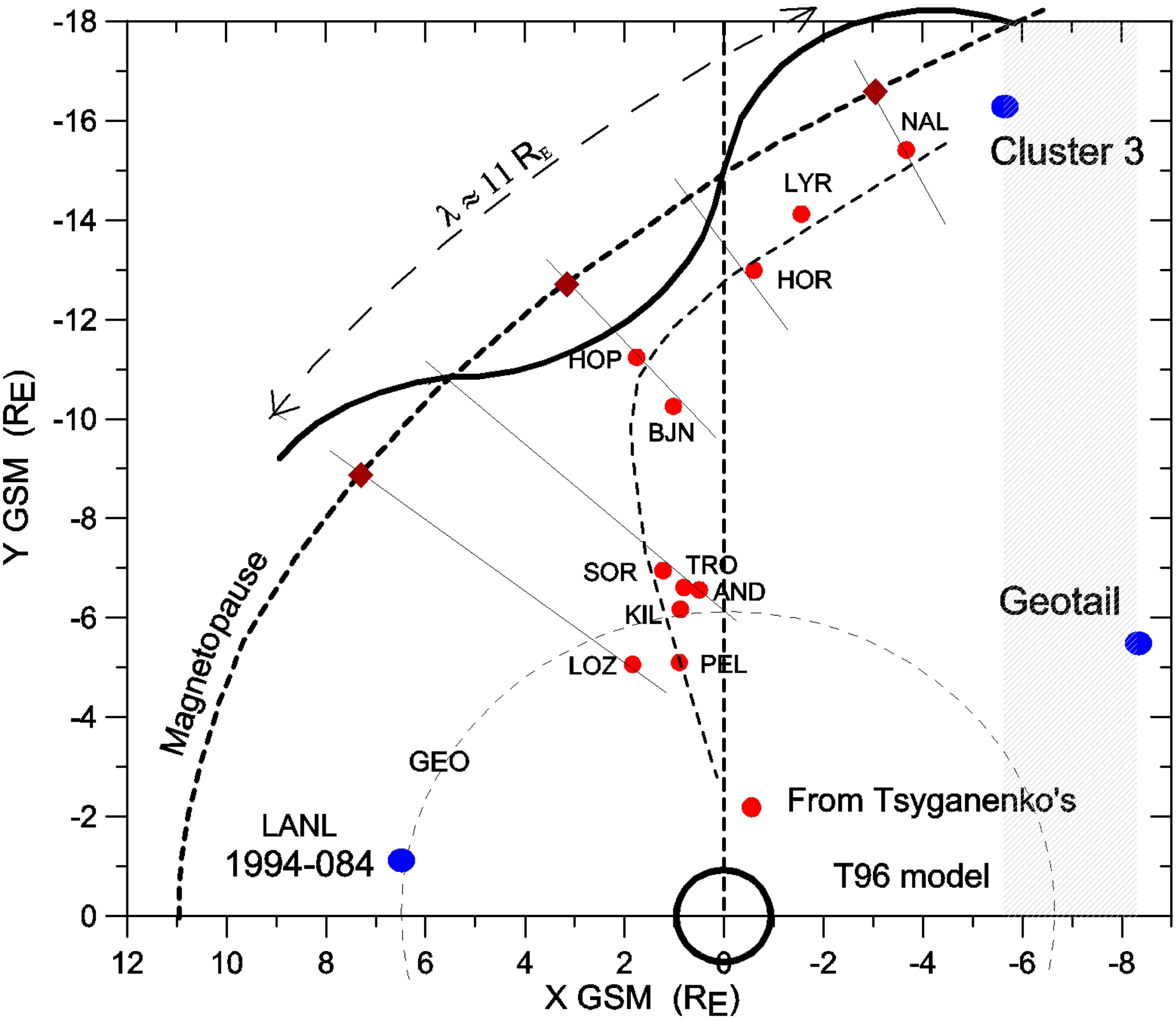

Fig. 4. Cluster 3, Geotail and LANL 1994-084 satellite positions, projected over the XY plane, are shown for the event of day 179, 2001, at 04:30 UT. The points NAL, LYR, HOR, HOP, BJN, SOR, TRO, AND, KIL, LOZ and PEL are determined via the T96 model as the conjugate points of these ground stations over the XY$_{GSM}$ plane. For this event, the magnetopause surface wavelength is ~11 R_E, and therefore different stations are associated with different amounts of magnetopause surface displacements.

and, in general, the recorded waveforms are disturbed, as is the case for the SOR and MAS station traces in Fig. 8. In this case it is interesting to present, with the same format, the stack of the Y-component variations (Fig. 9) which shows the first three variation cycles better (marked with the letters a, b and c) and extended from NAL to MAS. Although the lower latitude Y traces are modulated by higher frequencies, nevertheless, the major decreases (and especially the c) are similar to those at higher latitudes. Moreover, this Y-component stack provides the opportunity for the reader to look at the Y-component variations associated with this event.

Given that the knowledge of interplanetary conditions is of prime importance, we inspect carefully the exo-magnetosphere parameters. Figure 10 shows, from top to bottom, the Wind/3DP proton density, the Wind/MFI magnetic field amplitude, the Wind/3DP ion velocity V$_x$ of solar wind, the Geotail/LEP ion density in dawnside magnetosheath, the Geotail/CPI ion pressure, and the X-component from the IMAGE/NAL station. At 05:30 UT Wind and Geotail were positioned at (X, Y, Z)$_{GSE}$=(53.5, −38.8, −1.8) and (−26.7, −20, 5) R_E, respectively. The dashed lines at the top and bottom panels are sixth degree polynomial fitting lines demonstrating that the major minimum of solar wind density (and the minimum of pressure as well, because the solar wind velocity V$_x$ remains essentially unchanged during the interval under study) produces the positive X-component excursion observed along the NAL station trace after ~7 min. This time is the anticipated travel time for the solar wind

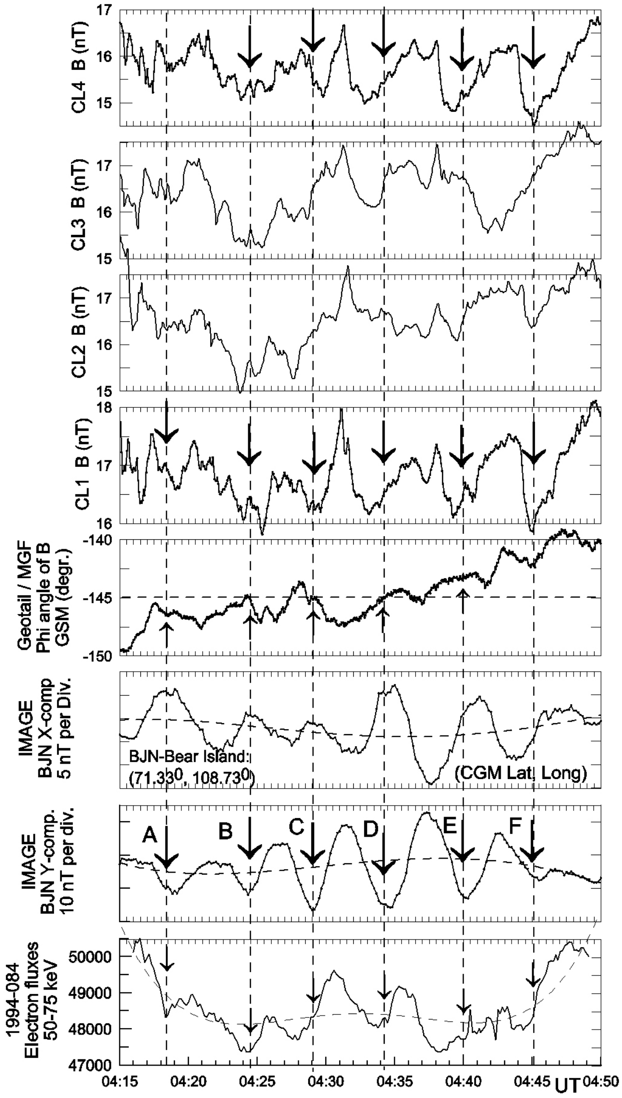

Fig. 5. From top to bottom, magnetic field amplitudes (in nTs) from Cluster 4, 3, 2 and 1, magnetic field azimuthal angle ϕ (in degrees) from Geotail, X and Y components from the BJN station magnetogram (in nTs), and 50-75 keV energetic electron differential fluxes from the 1994-084 satellite. The vertical dashed lines define the distinct decreases marked with the capital letters A-F along the Y component trace of the BJN station.

pressure variations to travel from Wind to Earth with the solar wind velocity of ~720 km·s^{-1}. The same Wind density variations are seen ~9 min later within the dawnside magnetosheath by Geotail. The Geotail/LEP ion density and the Geotail/CPI ion pressure measurements (Fig. 10, fourth and fifth panels) support, in general, our conclusion although the magnetosheath plasma regime is, as usual, very disturbed. We have to note that the editor-B LEP instrument measurements are very useful here, because we are interested in density variations and not in absolute values. There is probably a cause and effect relationship between the two sets of five peaks marked with capital letters in the top and bottom

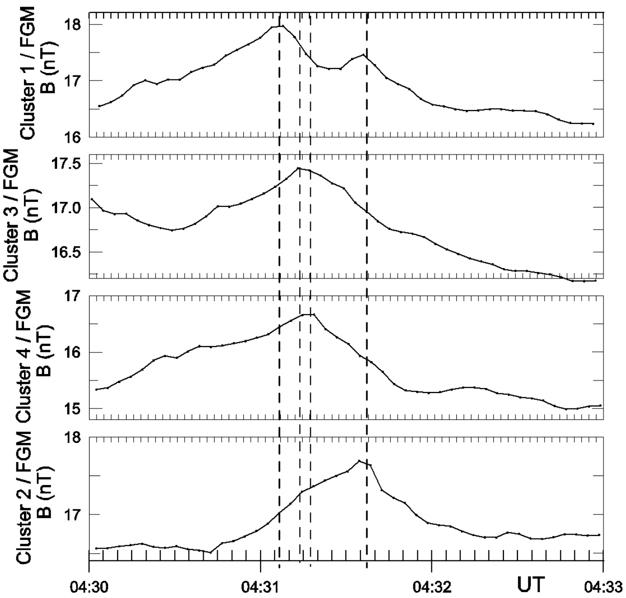

Fig. 6. Magnetic field amplitude variations (in nTs) for all four Cluster satellites, as they approach the lobe structure characterized with increased strength.

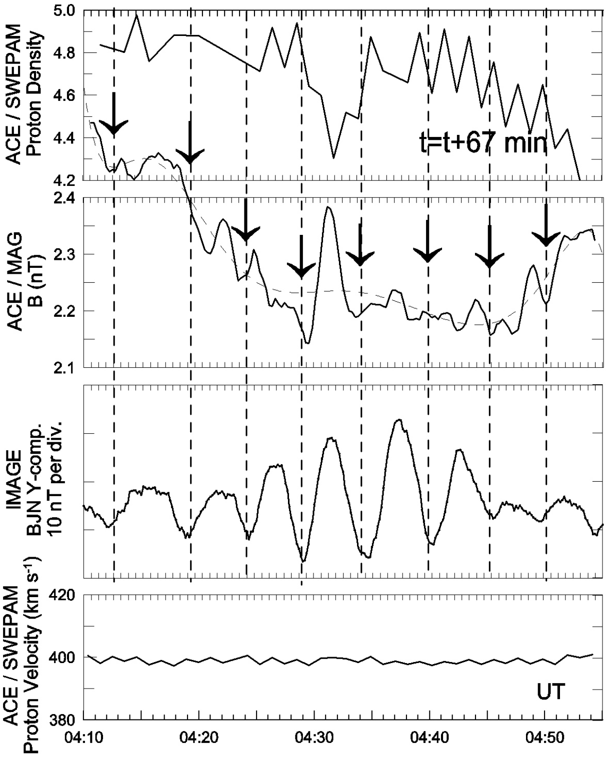

Fig. 7. The solar wind proton density (cm^{-3}) and velocity (km·s^{-1}), as well as the magnetic field amplitude (nT), as measured by ACE, along with the Y component pulsations at BJN.

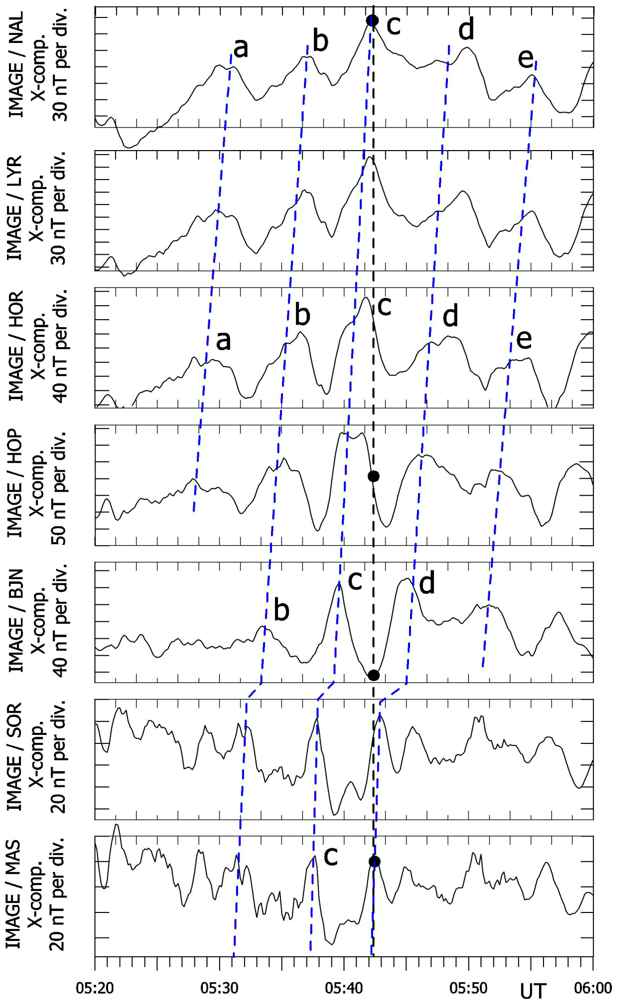

Fig. 8. Same format as in Fig. 3, for the event of day 341, 1994. In particulary, we pay attention to the dispersive peaks marked with the letters (a), (b) and (c), as well as to the double phase change of 180° which occurred at ∼05:42 UT.

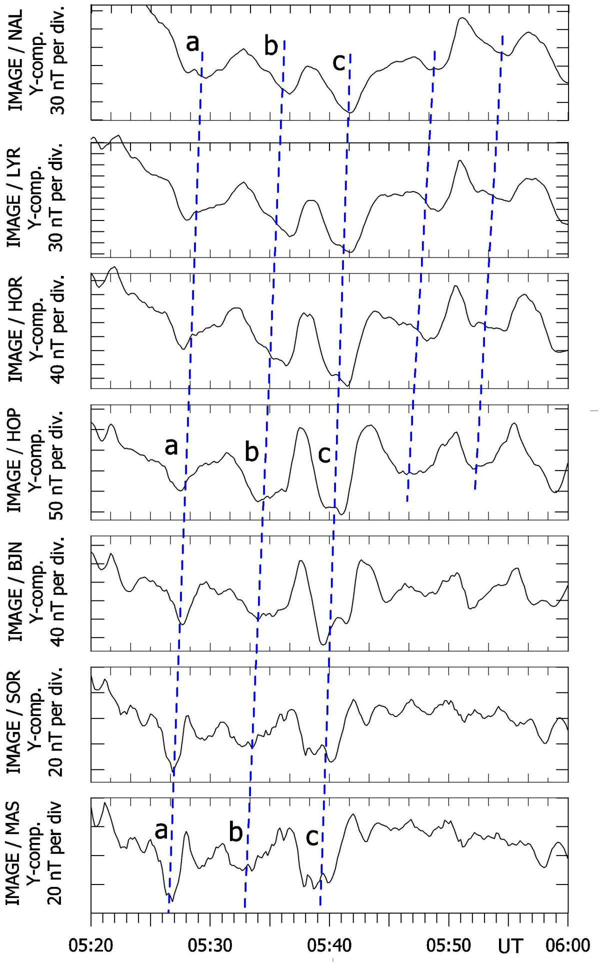

Fig. 9. Same format as in Fig. 3, concerning the Y component magnetograms for the event of day 341, 1994. The dispersive character for the decreases marked as (a), (b) and (c), is apparent for all the stations in a latitude range extended from NAL to MAS.

panels: each individual increase/decrease along the density trace produces a distinct signature on the ground.

Therefore, for this event, it seems that the ground Pc5 pulsations, marked with the letters A–E, are forced oscillations imposed by upstream pressure variations.

2.4 Third event on 2 August (day 214) 2001

During the interval 05:00–05:25 UT of day 214, 2001, the IMAGE ground stations show large amplitude pulsations with peak-to-peak amplitudes up to ∼60 nT, and a periodicity of ∼5 min (Fig. 11). Apparently, there is a gradual phase shift between the neighbour station waveforms, given that the station latitudes decrease from top to bottom; the dashed-slant lines emphasize this observational feature. Between the NAL and BJN traces the phase changes by 180° (look at the solid circle symbols). It is worth noticing that the pulsation amplitudes from NAL to BJN (i.e. a latitude range of ∼4.4°) remain almost constant. The latter is not consistent with the typical FLR phenomenon, which is principally excited in a narrow latitudinal region. According to our understanding, if we place the ground stations over the equatorial plane via the T96 model, then we will have a picture much like that given in Fig. 4. In this framework, we can assume that the NAL, Longyearbyen-LYR, HOR, HOP and BJN stations of this event have conjugate points, over the equatorial plane, which are iso-distant from the magnetopause boundary. At 05:00 UT the Geotail satellite was located at (X, Y, Z)$_{GSE}$=(7.2, 25.2, 4.9) R_E, within the magnetosheath proper. Figure 12 is composed from Geotail valuable data showing the CPI instrument ion density (top panel), the CPI ion dynamic pressure (bottom panel), and the Geotail/MGF vector magnetic field measurements. It seems that the repetitive exo-magnetosphere density and pressure variations, which are marked with arrows along the top panel trace, probably excite the ground pulsations exhibited in Fig. 11.

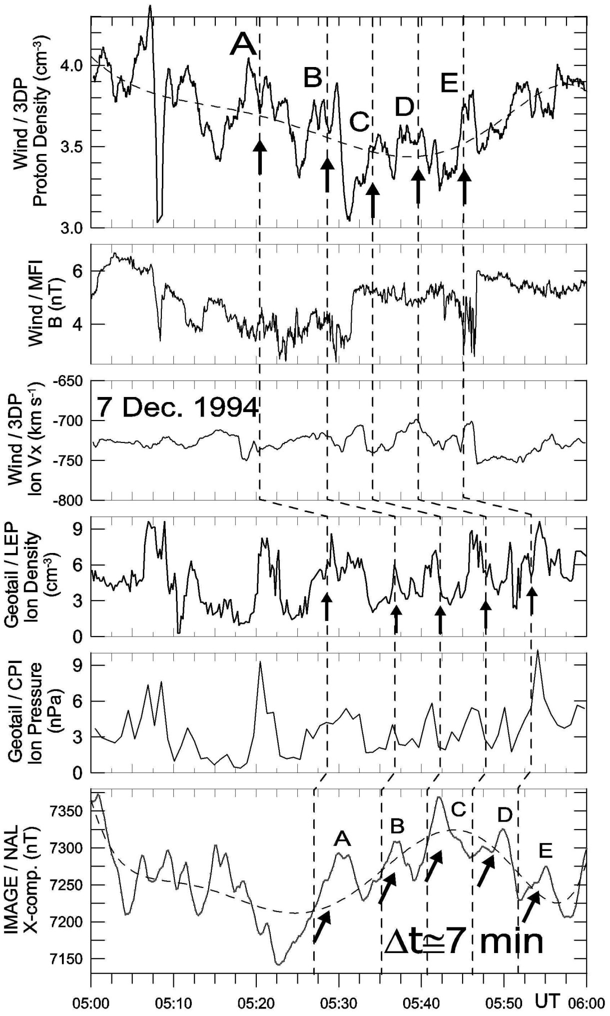

Fig. 10. From top to bottom, proton density (cm^{-3}), magnetic field amplitude (nT) and ion velocity V$_x$ (km·s^{-1}) measured by Wind, ion density and pressure (nPa) measured by Geotail, and X component variations recorded by NAL. The variations marked with the capital letters A–E along the NAL trace are probably dictated by distinct solar wind density increases.

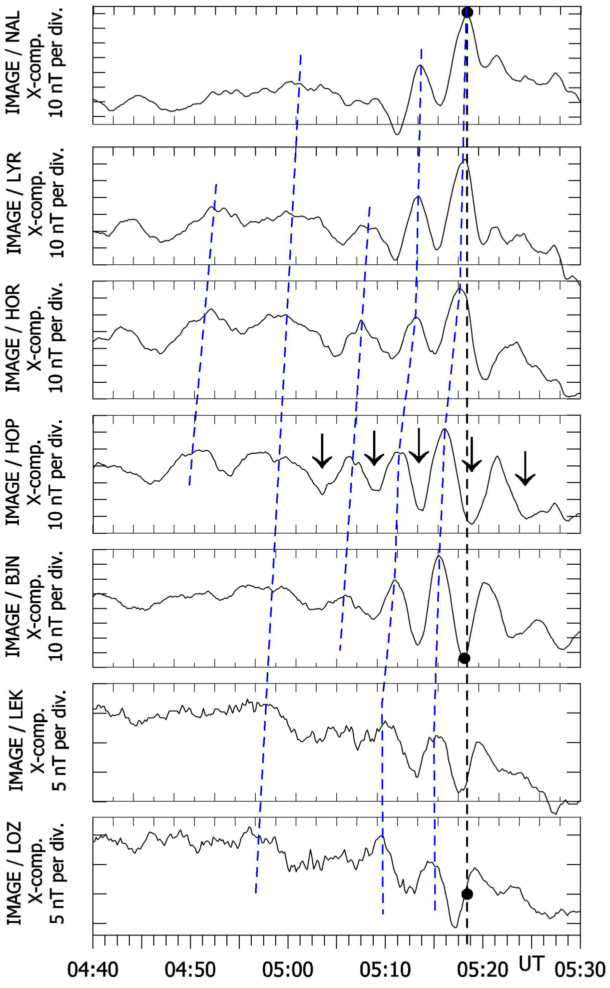

Fig. 11. Same format as in Fig. 3 for the event of day 214, 2001. In particular, we pay attention to the phase changes observed at ∼05:17 UT.

2.5 Fourth event on 19 July (day 200) 2001

Eight X-component magnetograms from the IMAGE stations, with decreasing latitudes, are shown in Fig. 13, for the interval 04:00–05:00 UT of day 200, 2001. The three slant-dashed lines facilitate discerning the systematic delays in arrival time of distinct ground signatures. The vertical-dashed line at 04:38 UT provides a reference time in order to discern the phase shifts among adjacent stations, while the two simultaneous phase changes of ∼180° are underlined with the three solid circle symbols. In the context of this work, these phase changes are not caused by FLRs, but most probably they are the genuine result of a magnetopause surface wave affecting the ionosphere currents. It seems that a surface wave, with one wavelength in extent, maps over the ionosphere and along a meridian chain of stations, and in this way produces the two ∼180° phase-shifts. As it is explained in detail in the Discussion section, we consider that the two phase changes are associated with a tilted twin-vortex current system. Such a scenario would be largely supported by a solar wind pressure wave with the same frequency. Searching for this possibility, for this event, we study the Wind/3DP instrument measurements of solar wind proton density, in parallel to the IMAGE/HOR station X-component pulsations, in Fig. 14. The Wind data are shifted in time by 39 min to match the ground data. Wind was positioned at (X, Y, Z)$_{GSE}$=(251.5, −5, 24.1) R_E, at 04:00 UT, while the proton speed was ∼670 km·s^{-1}. In Fig. 14 a much more extended interval, as compared to that presented in Fig. 13, is shown, with a duration of about three hours. Throughout such a long-lasting interval we observe an anticorrelation between the solar wind density and the magnetic field ground response. The arrows mark the peaks where a cause and effect relationship seems to be clearer. In particular, during the interval 05:17 to 05:45 UT the anticorrelation is prominent.

Wind was located close to the x-axis and probably monitored the appropriate conditions applied later over the magnetosphere. Certainly, the one-to-one correspondence is a risky undertaking mainly because Wind was located far upstream, but we think that it is beyond any doubt that the solar wind density shows an intense quasi-periodic variability which is the ultimate source for the ground wave activity. In any case, the solar wind density wave validates our hypothesis of assuming a magnetopause surface wave.

3 Discussion

3.1 A tilted twin-vortex system of Hall currents over the ionosphere

Sarafopoulos (2004a), using multi-satellite (Wind, Geotail, Interball, IMP 8 and GOES 8) and multi-instrument observations of plasma and magnetic field, confirmed, with in-situ measurements, that every individual solar wind inherent pressure pulse (stepwise variation) that strikes the Earth's magnetosphere produces a twin-vortex (single vortex) system of ionosphere currents at the high-latitude ground magnetograms. He scrutinized, in detail, the ground signatures, while the twin- or single-vortex current systems are studied using the IMAGE array. The differentiation in this study is that many successive solar wind pressure variations are involved that logically create a magnetopause surface wave, which, in turn, probably develops successive twin-vortex current structures over the ionosphere. The new observational feature incorporated in this work is that the presented ground signatures show characteristic latitude-dependent dispersive structures probably originated by tilted twin-vortex current systems. Similar ground dispersive structures caused by a solar wind pressure wave are extensively studied by Sarafopoulos (2004b) and therefore, we are based on his results. In particular, his proposed mapping mechanism of magnetosphere compressions to the ionosphere level is completely adopted in this work. Nevertheless, we have to stress the fact that the dispersive structures exhibited in this study add a new dimension to the previous work by Sarafopoulos. The systematic shift in phase leads here to twofold successive phase-changes of 180°; a precious detail as far as the FLR phenomenon is discussed.

Below we assume a tilted twin-vortex ionosphere current system, which although naturally travels antisunward, in the sketch of Fig. 15 it is considered stationary, whereas the Earth stations A, B and C are thought to move sunward below the supposed structure of Hall currents. The A (C) station corresponds to the highest (lowest) latitudes of the IMAGE array magnetometers. The tilted vortices will produce different ground responses along the three tracks (horizontal-dashed lines) marked as A, B and C, and these responses are drawn underneath the vortices in Fig. 15. For each track the X and Y magnetometer components are sketched, while the horizontal axis always shows the universal time. More specifically, according to Fig. 15, the X-component signatures (look at the shaded areas) along the tracks A, B, and C will be negative/positive (i.e. a NP-bipolar signature), positive/negative/positive (PNP), and positive/negative (PN), respectively. The latitude-dependent double phase-change of 180° at the moment characterized as t_1 is similar to the observations shown in Fig. 3 (at ∼04:37 UT), Fig. 8 (at ∼04:42 UT), and Fig. 13 (at ∼04:38). All three stations for the Y component will show a NPN signature, which should be slightly shifted in time for the station B and even more for the station C, although the latter observational element is not incorporated in Fig. 15. Actually, the Y component does not show abrupt phase changes, like the X-component, and this is what we have observed in Figs. 1 and 2 corresponding to the events studied later in Figs. 3 and 8. Therefore, it is inferred that the large-scale structure of a tilted twin-vortex current system suffices to reproduce all the observational features of studied events; it is not necessary to invoke any resonant magnetic field shell.

A rough estimate of the tilt angle is possible under an assumption concerning the longitudinal extent of the twin vortex structure. Thus, if we assume that the longitudinal extent is equal to the latitudinal one, then the east-west velocities for the second and fourth case studies will be 3 and $2.2\,\mathrm{km{\cdot}s^{-1}}$, and the computed tilt angle will be 50° and 65°, respectively. In the fourth case study, if we assume the velocity of $4.4\,\mathrm{km{\cdot}s^{-1}}$, then the tilt angle will be 50°, too. Certainly, the introduced velocities are close to those estimated by Glassmeier (1992). A more realistic estimate for the tilt angle, in a future effort, must be based on two different ground arrays, for instance, the Greenland and IMAGE arrays.

3.2 Discrepancies between the presented events and an authentic FLR

Many ground events with Pc5 pulsations appear seemingly as FLRs, but actually they are pseudo-field line resonance events. They show phase changes of 180° in the X-component magnetograms, and a large or even maximum wave amplitude response close to the supposed resonant L-shell. Below we summarize the diagnosed discrepancies between the presented events and an authentic FLR event:

(a) The dispersive ground structures that accompany the studied pseudo-FLR events demonstrate an observational feature that the typical FLR mode could not normally produce. We anticipate a FLR to produce symmetric current structures on the ionosphere level and along a magnetic meridian plane.

(b) According to the one-fluid MHD model of the FLR the major oscillation amplitude should occur exactly at the resonant L-shell. Conversely, we do not always observe at the supposed resonant-shell station, or adjacent to it, the maximum amplitude response. For instance, in Fig. 3 the HOP station clearly shows the maximum X-component response, although the supposed FLR seems to occur between BJN and TRO, where a phase-change of 180° is unambiguous. According to

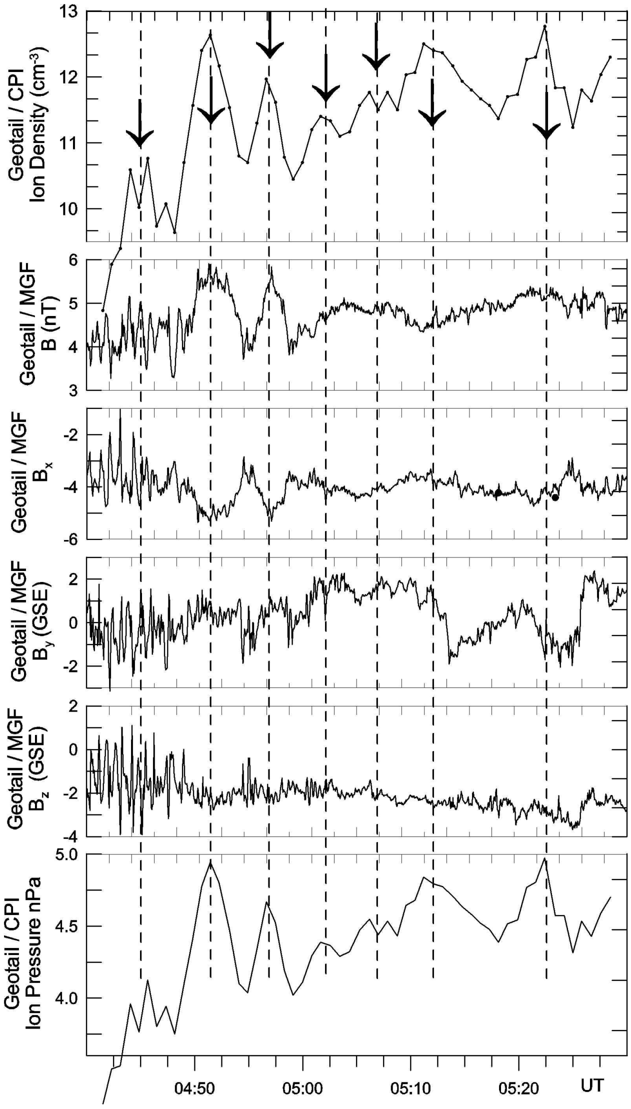

Fig. 12. Ion density, vector magnetic field data, and ion pressure measured by the Geotail satellite within the magnetosheath proper. These measurements correspond to the pulsation event presented in Fig. 11.

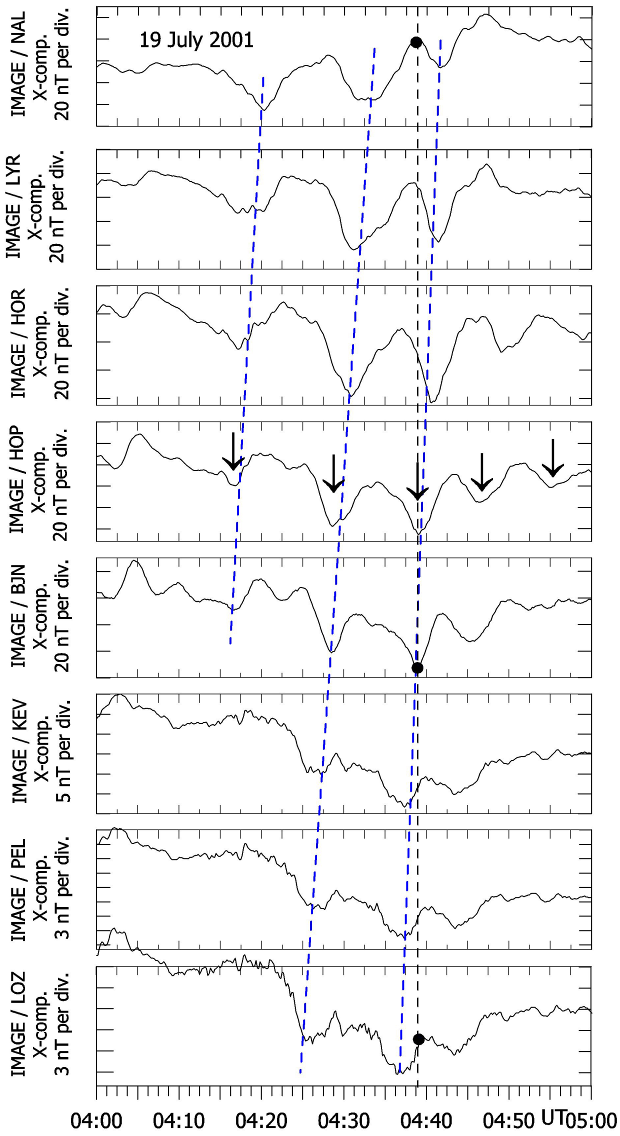

Fig. 13. Same format as in Fig. 3 for the event of day 200, 2001. In particular, we pay attention to the changes of phase observed at ~04:38 UT.

our understanding this happens because the HOP station, over the equatorial plane, maps closer to the magnetopause surface (see Fig. 4), which is wavy modulated. Additionally, the decrease in amplitudes, as one moves away from a supposed L-resonant shell, is not abrupt (for instance, look at the Sect. 2.4), as the FLR theory dictates.

(c) A basic element in this research effort is the fundamental notion according to which there is a systematic tailward displacement for the magnetosphere magnetic field flux tubes located close to the magnetopause: The closer to the magnetopause the tube is placed, the stronger the tailward displacement must be. We have also to note that the latter in not merely a qualitative assumption, but it is quantitatively supported by the T96 magnetosphere magnetic field model. In this type of approach, a meridian chain of ground stations does not produce a radial placement for the station conjugate points over the equatorial plane. Conversely, in particular, the higher latitude stations are projected, over the XY plane, to positions along the magnetopause, and therefore are associated with different phases of the magnetopause wave.

(d) The mechanism that creates on the ground the observational features that mimic those of "one resonant field line" is not the toroidal oscillations of field lines, but successive tilted twin-vortex ionosphere current

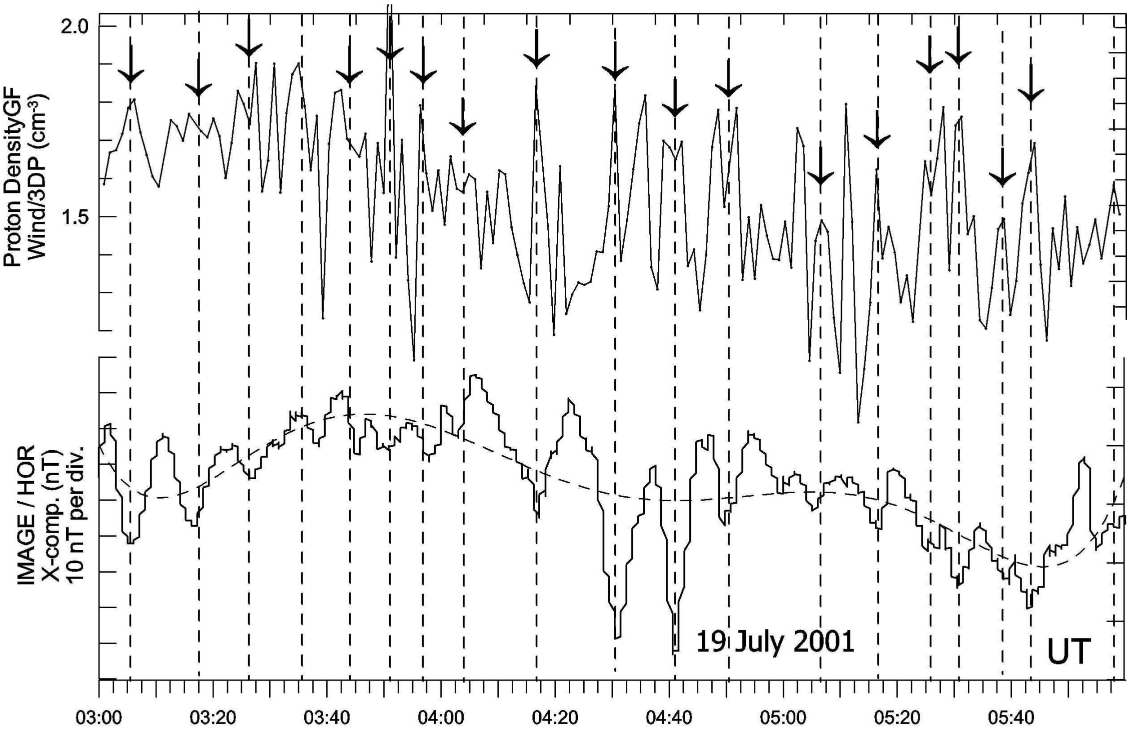

Fig. 14. Solar wind proton density (cm^{-3}) measured by Wind, along with X component variations from the HOR station magnetogram, for a three-hour interval of day 200, 2001. The Wind data are shifted in time 39 min to match the ground data.

systems, as it is suggested in the first Discussion subsection. These travelling convection vortices are magnetic field and current structures organized in large scales, as opposed to localized FLR structures estimated to be ~0.5 R_E in extent over the equatorial plane and about 100 km over the ionosphere plane (Singer et al., 1982; Mitchell et al., 1990; Glassmeier et al., 1999). Our Fig. 4 demonstrates that a twin-vortex ionosphere structure corresponds to a surface span of $\approx 11\ R_E$ (i.e. the magnetopause surface wavelength that is $\lambda \approx 11\,\mathrm{R}_E$). The typical FLR phenomenon, as determined by ground radar, is extended in latitude ~2° (Walker et al., 1979), whereas our events extend in a range of at least ~20° in latitude.

(e) The already presented ground events with Pc5 pulsations are probably originated by magnetopause surface waves due to solar wind pressure waves. Toroidal resonances commonly have been observed by AMPTE/CCE (Anderson et al., 1990; Nosé et al., 1995; Engebretson et al., 1986), and ISEE 1 and 2 (Mitchell et al., 1990) in a wide range of L. Anderson et al. (1989) pointed out that the AMPTE/CCE did not observe large amplitude resonances on discrete L shells such as are commonly seen on the ground. Our second studied event shows Pc5 waves with a peak-to-peak value ~250 nT. Therefore, the FLR effects on the ground may are completely covered up by the much larger amplitude waves due to the magnetopause surface waves. Certainly the ionosphere "spatial integration" is another possibility for screening out the FLR effects from the ground observations.

3.3 The cavity-waveguide mode

The following arguments do not encourage us to adopt the excitation of a cavity mode as the ultimate mechanism able to produce the observed pulsation events:

(a) In the three out of four presented case studies, it is clear that the X-component traces of IMAGE stations, with decreasing latitude, show two phase-shifts of ~180°at the same time. The latter means that the polarization sense changes twice. If both phase shifts are attributed to FLRs, then it would be inferred that two different L-shells resonate with the same frequency simultaneously, which is apparently unacceptable. Therefore, these phase-shifts are not associated with FLRs.

(b) We have suggested that a tilted twin-vortex ionosphere current system reproduces very well all the observed ground features. Consequently, there is no reason to introduce resonant L-shell oscillations. Each twin-vortex structure corresponds to one solar wind pressure pulse (Sarafopoulos, 2004a). More accurately, a tilted twin-vortex current structure over the ionosphere is directly reproduced by a magnetopause surface wave with just one wavelength, while the ionosphere-magnetosphere mapping is quantitatively determined by the T96 model.

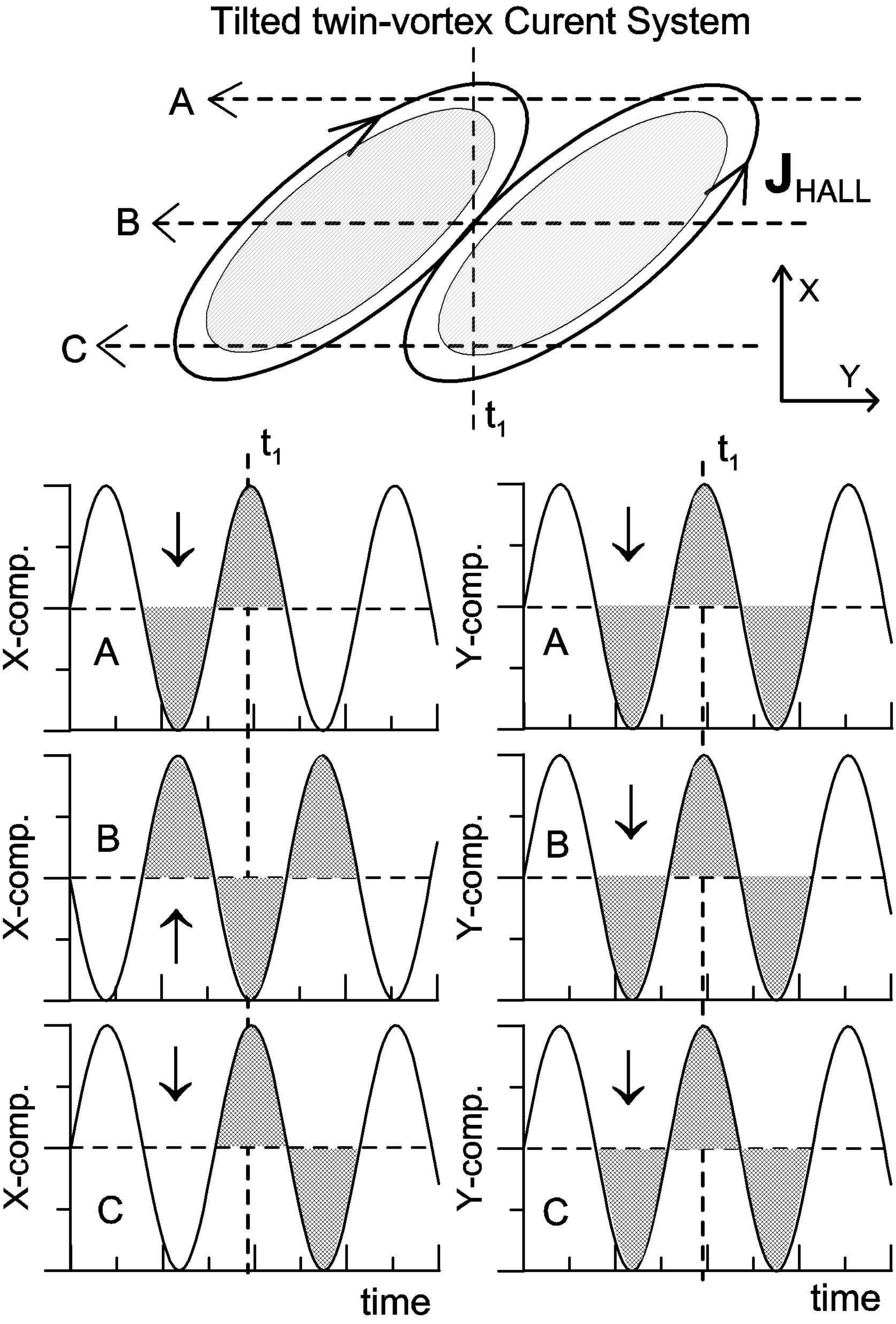

Fig. 15. Tilted twin-vortex current system with opposite polarities of Hall currents, which although naturally moves antisunward above the IMAGE stations, here is considered stationary. Current flow is denoted with an arrow on each vortex structure, while the Sun is located to the left side of this page. The representative ground stations A, B and C are considered to move sunward below the Hall currents. The ground responses, along the three tracks (horizontal-dashed lines) for the three stations, are drawn underneath the vortices. For each track the X and Y magnetometer components are sketched, while it is apparent that at the moment t_1 (vertical-dashed lines) a double phase change of 180° takes place within the latitude range extended from A to C.

(c) Samson et al. (1992) and Walker et al. (1992) reported that the cavity mode frequencies vary little and do not depend on the geomagnetic conditions. Our events of ground pulsations show the periodicities of T≅6.5 min (Fig. 8), 5 min (Figs. 5 and 11) and ∼10 min (Fig. 13), which most probably correspond to the solar wind similar pressure wave periodicities. Therefore, the detected ground frequencies probably do not reflect any eso-magnetosphere process independent of outside conditions, as should be the situation for an excited cavity mode.

(d) Samson et al. (1991; see also Walker et al., 1992) argued that "there is a definite preference for ground high latitude FLRs to be excited at certain frequencies". They claimed that these frequencies are the eigenfrequencies for the magnetosphere cavity (Hughes, 1994). In our cases the high latitude field lines are actually excited in the Pc5 frequency band, but the quasi-periodic Pc5 pulsations are directly forced by a solar wind pressure wave affecting first and foremost the near magnetopause magnetic shells. The magnetosphere seems to respond in a passive way, and the identified periodicity along the ground magnetograms is merely the final synthesis of unique and individual events of solar wind pulses. Each pulse produces a twin-vortex current system (Sarafopoulos, 2004a), and successive pulses produce repetitive twin-vortex structures. In a large degree, the cavity mode model was introduced to play the same role as a monochromatic solar wind energy source. It seemed that the cavity mode would resolve the problem of the "one resonant line" that frequently is observed in ground data. In our case studies, the identified "one resonant line" in ground events is closely and always associated with a solar wind pressure wave, or a magnetopause wave, which naturally produces the large-scale twin-vortex current systems (the so-called pseudo-FLRs) and no authentic local FLRs.

3.4 About the discrepancy between ground phase velocities and those of magnetopause surface waves

It was stressed by Hughes (1994) that if the azimuthal phase velocity measured by Hughes et al. (1978) and Olson and Rostoker (1978) on Earth was mapped out to the magnetopause, speeds of 500–1000 km·s^{-1} should be obtained. These speeds are well in excess of typical magnetosheath velocities, whereas the phase speed of Kelvin-Helmholtz (KH) surface waves should be slower than the magnetosheath velocities. This inconsistency between the pulsation and KH surface wave velocities is characterized by Hughes (1994) as "an enigma". In the context of this work, we have to pay attention to the inference that at high latitudes the ionosphere east-west velocity does not correspond to the magnetopause boundary velocity. Instead, from the dispersive structures presented in this work and corresponding to the dawnside magnetosphere, we can estimate the north-south component of velocity which actually maps to the surface velocity, given that the T96 model is taken into account. For the first case study we compute the ionosphere north-south velocity ∼3.5 km·s^{-1}, which corresponds to the surface wavelength $\lambda \cong 11\ R_E$ and the surface phase velocity of ∼230 km·s^{-1}.

3.5 Twin-vortex systems mapping well-inside the magnetopause

In his Fig. 12 Sarafopoulos (2004b) has proposed a possible generation mechanism for single, as well as multiple, twin-vortex current systems. According to his model, a magnetopause surface wave dictated by a solar wind pressure wave, having an extent of one wavelength, will produce a distinct twin-vortex structure. This structure is apparently a pair of two travelling convection vortices (TCVs) originated well-inside the magnetopause boundary. This is further supported in this work with dispersive structures displaying two phase-shifts of 180°, at the same time, and producing pairs of tilted TCVs. This work (Fig. 4) shows emphatically that the twin-vortex systems map to the region well-inside the magnetopause boundary. Our work lines up with the result of Moretto and Yahnin (1998), who found that the TCV centres map to deep inside the magnetosphere and not to the magnetopause. Therefore, it naturally follows that the field-aligned currents associated with our studied TCVs must be produced within the magnetosphere.

4 Conclusion

In this work we study Pc5 ground pulsation events with discrete and remarkably stable frequencies and discriminate between FLRs and tilted twin-vortex repetitive structures. The latter are called in this work pseudo-FLRs, because these events appear seemingly as field line resonances: They show impressive changes in polarization sense, while they maximize their amplitude at or close to the supposed resonant magnetic field shell. For all the studied cases, with in-situ measurements, we have confirmed the existence of a magnetopause surface wave, which most probably seems to be dictated by a solar wind pressure wave. Therefore, in our case studies, the identified "one resonant line", in ground events, is closely and always associated with a magnetopause wave, which naturally produces the twin-vortex current systems and no local FLRs. Our events are associated with tilted large-scale twin-vortex ionosphere structures corresponding to magnetopause surface waves with a wavelength 10–20 R_E. Between an authentic FLR event observed within the magnetosphere and a twin-vortex structure there is a scale factor 20–40, over the equatorial plane. The pseudo-FLR events often display two latitude-dependent phase-shifts of 180°, and are associated with field-aligned currents that are produced within the magnetosphere. This work shows events of ground pulsations with discrete and stable frequencies which are completely disassociated from any cavity mode excitation scenario.

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