The 8 June 2000 ULF wave activity: A case study

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We examine the characteristics of a train of ULF waves observed in the magnetosphere and at ground after the sudden impulse (SI) onset of 8 June 2000. A highly monochromatic and large-amplitude wave at \( f = 3.3 \) mHz was observed between 9:10 and 9:50 UT at the GOES8 orbit (on the dawn flank of the magnetosphere) and across a wide longitudinal range of ground stations from low to high latitudes. The combination of the long period of these pulsations (5 min), their extended duration (~40 min), the latitude-independent frequency, and the small azimuthal wave number suggests the occurrence of a global magnetospheric mode driven by the sudden enhancements of the solar wind dynamic pressure. The amplitude and cross-phase analysis of the wave activity on the ground and the polarization pattern indicate that the global mode coupled to the field line resonance (FLR) occurs at different latitudes at different local times. Such FLRs occurred at latitudes smaller than usually observed at the same frequency, suggesting a significant reduction of the local field line eigenfrequencies as compared with usual values. A model estimation (time of flight approximation) of such eigenfrequencies suggests a change in the magnetospheric field geometry characterized by more elongated field lines than those for usual conditions. It was probably caused by the compression of the magnetosphere driven by the pressure pulse coupled with the stable northward orientation of the interplanetary magnetic field.


1. Introduction

Sudden impulses (SIs) are sudden variations of the geomagnetic field generated by steep increases in the solar wind dynamic pressure (\( P_{SW} \)). They are occasionally followed by ultra-low-frequency (ULF) waves, typically in the Pc5 range (\( T \sim 150-600 \) s). Pc5 waves, in general, can be excited externally (i.e., by the solar wind (SW)) or within the magnetosphere [Rostoker and Sullivan, 1987; Chisham and Orr, 1997; Mathie et al., 1999a; Mann et al., 1995; Villante, 2007]. External SW drivers include the Kelvin-Helmholtz instability by means of surface waves at the magnetopause [Southwood, 1974; Chen and Hasegawa, 1974], direct SW pressure changes [Southwood and Kivelson, 1990], and SW density and velocity discontinuities [Allan et al., 1982; Wright, 1994; Mathie and Mann, 2000; Lee et al., 2007].

The study of Pc5 waves following SIs has at least two advantages: Their specific source is clear, and the response of the system to an impulsive or steplike function is expected to yield eigenmodes of the system [Mathie and Mann, 2000]. Therefore, these events can be used as a diagnostic tool for the magnetosphere [Allan and Poulter, 1992]. Modeling studies have shown that the magnetosphere can also act like a cavity in response to disturbances at the magnetopause [Radoski, 1974; Kivelson et al., 1984; Kivelson and Southwood, 1985, 1986]. Despite different model geometries, these studies, conducted for impulsive excitation of different magnetosphere configurations [Allan et al., 1982; Chen and Hasegawa, 1974; Lee and Lysak, 1989, 1991], presented a basic picture in which the impulse excites several monochromatic compressional eigenmodes in the magnetospheric cavity. Southwood and Kivelson [1990], examined the response of the magnetospheric cavity to perturbations in the external pressure impinging on the magnetospheric boundary and showed that a time-dependent pressure perturbation can excite internal fast mode and transverse mode eigenscillations. In addition, these modes can transfer energy into the field line resonance (FLR), where the local field line frequency matches the frequency of the cavity mode.

Zhang et al. [2010] performed an analysis of ULF waves driven by positive and negative \( P_{SW} \) sudden variations at geosynchronous orbit in the frequency range of 1.67–6.67 mHz. They showed that the magnitude of ULF waves is larger around 12:00 LT than at dawn and dusk and the magnetospheric response to positive pulses is much stronger compared with that of negative pulses. Moreover, the magnitude of the poloidal component is stronger than that of the toroidal component.

The characteristics of Pc5 pulsations at geosynchronous orbit have also been investigated by Amata et al. [1986],
who showed that oscillations excited by a SW shock have a complicated structure: A magnetosonic wave propagating from the dayside to the nightside sector appears at the storm sudden commencement (SSC) instant, and resonant shear Alfvén waves are generated during the propagation of this magnetosonic wave. Hudson et al. [2004] studied the morphology of Pc5 pulsations related to SIs on the CRRES satellite data. They found that toroidal oscillations are observed in the dawn sector. In the dusk sector, similar oscillations were observed only in 10 out of 21 cases. In the remaining cases, the oscillation energy was distributed between two or all three field components.

Figure 1. The solar wind (WIND) and the magnetospheric observations (GOES) for the SI event occurred on 8 June 2000: (a) the SW density, (b) the SW velocity, (c) the SW dynamic pressure, (d) the IMF |B|, (e) the IMF B\textsubscript{Z} component, (f) the B\textsubscript{X} component of the magnetospheric field measured by GOES8 (solid line) and GOES10 (dashed line), (g) the B\textsubscript{Y} component of the magnetospheric field measured by GOES8 (solid line) and GOES10 (dashed line), (h) the B\textsubscript{Z} component of the magnetospheric field measured by GOES8 (solid line) and GOES10 (dashed line). The vertical dashed lines identify the SW pressure jump and the SI occurrence.

Many studies on the characteristics of Pc5 following SIs detected on the ground have been carried out. In a pioneering investigation, Takao and Matsushita [1967] suggested that the ULF wave activity is likely due to hydromagnetic waves. Ziesolleck and Chamalaun [1993] examined mid-latitude to low-latitude Pc5 and found amplitudes of several nT decreasing with decreasing latitude. Moreover, the frequency was not dependent on either latitude or longitude. Araki and Allen [1982] found that many transient pulsations (Pc5 range) associated with SIs showed polarization reversal between $\lambda \sim 64^\circ$ and $\lambda \sim 72^\circ$. Kleimenova et al. [1999] analyzed pulsations at Dumont
in the frequency range 1–6 mHz.

In this paper, we present simultaneous observations in the magnetosphere and on the ground of Pc5 pulsations following an SI. The event occurred on 8 June 2000 in the time interval 9:10 – 9:50 UT, and its characteristics have been analyzed over a wide latitudinal and longitudinal extension (43 ground stations).

**2. Data Analysis**

The ground-based magnetic field data used in this study were obtained from 43 magnetometers from CARISMA, INTERMAGNETNA (North American sector), IMAGE, and SAMNET arrays. During the event, INTERMAGNETNA and CARISMA were located in the premidnight-morning sector (23:00 – 7:00 LT, LT being the magnetic local time), while IMAGE and SAMNET were located in the noon sector (10:00 – 13:00 LT). The time resolutions of the magnetic measurements are 1 min for CARISMA, IMAGE, and INTERMAGNETNA, and 5 s for SAMNET. SAMNET data were resampled at 1 min after averaging the original 5 s data.

During the period of interest, GOES8 and GOES10 spacecraft were located in the early morning magnetosphere (LT = 04:15) and near the local midnight (LT = 00:15), respectively. GOES magnetic field data are at 1 min resolution and are expressed in geocentric solar ecliptic (GSE) coordinates. For this analysis, the GOES magnetic field data have been also rotated into the mean-field-aligned (MFA) coordinate system to separate the field perturbations into transverse and compressional components. In this system, \( \hat{e}_m \) is along the mean field \( B_0 \) as defined by a 15 min vector average of the magnetic field data; \( \hat{e}_n \), perpendicular to \( \hat{e}_m \) and to the spacecraft vector position \( \hat{r}_{\text{space}} \), is directed eastward; \( \hat{e}_j \) completes the orthogonal system. Waves in the \( \hat{e}_m \), \( \hat{e}_n \), and \( \hat{e}_j \) directions are referred to as compressional, poloidal, and toroidal, respectively [Dungey, 1954]. We also used the plasma particle measurements obtained from the Los Alamos National Laboratory (LANL) geosynchronous spacecraft. The 1 min resolution SW plasma and interplanetary magnetic field (IMF) key parameters from the WIND satellite were obtained from CDAWeb (http://cdaweb.gsfc.nasa.gov/).

The aspects of the polarization pattern have been evaluated using the technique for partially polarized waves as described by Fowler et al. [1967]. In particular, we evaluated over each 10 min interval the ellipticity \( \varepsilon \), i.e., the ratio between the minor and the major axes of the polarization ellipse in the horizontal plane) and the polarization azimuth \( \Psi \), the angle between the major axis of the polarization ellipse and the H (or \( \hat{e}_j \)) direction, counted positively from north through east). The sense of polarization is given by the sign of \( \varepsilon \). A positive (negative) \( \varepsilon \) corresponds to the
3. Observations

3.1. Solar Wind and Magnetospheric Observations

[11] Figure 1 shows the SW density (Figure 1a), velocity (Figure 1b), dynamic pressure (Figure 1c), interplanetary magnetic field (IMF) magnitude $|B|$ (Figure 1d) and $B_Z$ components (Figure 1e) observed by WIND ($X_{GSE} = 40.8 R_E$, $Y_{GSE} = -26.4 R_E$, $Z_{GSE} = -4.3 R_E$) on 8 June 2000, 8:45–9:45 UT. A sharp pressure increase can be easily seen at ∼09:04 UT (dotted lines). In fact, the SW velocity, in less than 3 min, varied from ∼490 to ∼742 km/s, the density increased from ∼4 to ∼14.5 cm$^{-3}$, and the dynamic pressure increased from ∼1.5 to ∼14 nPa. The IMF magnitude increased from ∼6.5 to ∼20 nT, and its orientation was northward ($B_{Z,IMF} ∼ 10$ nT) up to ∼25 min after the shock front passage.

[12] The GSE magnetospheric field components from GOES8 (solid line) and GOES10 (dashed line) are plotted in Figures 1f, 1g, and 1h. Both spacecraft observed at ∼09:10 UT (LT = 04:10 at GOES8, LT = 00:10 at GOES10) a large increase of the $B_X$ component, while the $B_Y$ and the $B_Z$ components experienced smaller amplitude changes. This SI event was analyzed by Villante and Piersanti.
[2008, 2010]. They compared the observed profiles with those predicted for the observed changes of the SW parameters [Tsyganenko, 2002a, 2002b] and speculated that the variations of the magnetospheric field components could be interpreted in terms of a significant stretching of the field lines into the magnetotail as possibly determined by a closer hinging point (i.e., the separation point between closed and open field lines) and a thinner current sheet thickness with respect to usual conditions.

[13] For the present analysis, the most important feature is the occurrence of sharp quasi-monochromatic oscillations in the Pc5 range ($T = 5$ min.) at GOES8. Figure 2a shows that these oscillations appeared on both the toroidal and poloidal components.

[14] The power spectra (Figure 2b) showed a clear peak at 3.3 mHz in both components with the toroidal power ≈10 times greater than the poloidal one. At GOES10 such waves have negligible amplitude, if any (Figure 1): Indeed, the power spectra (not shown) revealed enhancements on the poloidal and compressional components with amplitudes 10 times and 2 times smaller than those at GOES8, respectively. No evidence for oscillations at the same frequencies was detected by WIND.

3.2. Ground-Based Measurements

[15] The ground-based data have been organized into two LT sectors: the midnight-morning sector (~23:00–07:00 LT, hereafter sector 1) and the noon sector (10:00–13:00 LT,
hereafter sector 2). The PBQ station (Poste-de-la Baleine, \(\lambda = 65.1^\circ\), where \(\lambda\) is the geomagnetic latitude; LT = 4:06), located close to the GOES8 footprint, was used as a reference station for comparison between magnetospheric and ground observations for sector 1.

Apart from three stations located near midnight (RES: \(\lambda = 83.3^\circ\), LT = 00:48; GDH: \(\lambda = 75.7^\circ\), LT = 00:37; CMO: \(\lambda = 65.1^\circ\), LT = 23:48), the power spectra (not shown) revealed a peak centered at \(f \approx 3.3\) mHz in both sectors. This latitude-independent frequency was used for coherence, amplitude, and cross-phase analyses for the ground measurements.

Sector 1: Figure 3 shows the filtered data at \(f = 3.3\) mHz for the \(H\) (solid line) and \(D\) (dotted line) components in the interval 09:10–09:40 UT with \(\lambda\) decreasing from the top. The vertical dashed line indicates the SI occurrence (UT = 09:12) at PBQ. Above \(\lambda > 65^\circ\), the \(D\) component shows oscillations with an amplitude comparable with that of the \(H\) component, while for \(\lambda < 65^\circ\) it shows negligible amplitude. Exceptions occur at stations located around local dawn (OTT: LT = 4:15; PBQ: LT = 4:06; NAQ: LT = 7:01) where the \(H\) and \(D\) components show comparable amplitudes. Both \(H\) and \(D\) attain their maximum amplitude at NAQ (\(\lambda = 66.1^\circ\), LT = 07:01). Figure 4a shows the coherence between PBQ and other stations. A coherence of >0.75 occurred in general from high (\(\lambda \approx 83^\circ\)) to low (\(\lambda \approx 38^\circ\)) latitudes for both \(H\) (open circles) and \(D\) (solid circles). The latitudinal profiles of the amplitude ratio, i.e., the ratio normalized to the \(H\) and \(D\) amplitudes at PBQ (Figure 4b), show peak values at \(\lambda \approx 66^\circ\) (NAQ). At such latitudes, the cross phase (Figure 4c) attains its maximum value (~145°).

Figure 5. The \(H\) (solid) and \(D\) (dotted) components of the geomagnetic field at ground station locations in the noon sector (10:00 < LT < 13:00) on 8 June 2000 (09:10–09:40 UT). The data are filtered at \(f = 3.3\) mHz. The vertical dashed line indicates the SI occurrence (UT = 09:12) at BJN (\(\lambda = 71.45^\circ\), LT = 12:07).
Sector 2: Figure 5 shows the filtered data at $f = 3.3$ mHz for the $H$ (solid line) and $D$ (dotted line) components in the interval 09:10–09:40 UT at the SAMNET-IMAGE stations. The vertical dashed line indicates the SI time occurrence (UT = 09:12) observed at BJN ($\lambda = 71.45^\circ$, LT = 12:07), where the amplitudes of both $H$ and $D$ oscillations reach maximum values.

Figure 6a shows the coherence between BJN and other stations. Values $>0.70$ occurred in general from high ($\lambda \approx 75^\circ$) to low ($\lambda \approx 51^\circ$) latitudes for both $H$ (open circles) and $D$ (solid circles). The peak value of the normalized amplitude (Figure 6b) at $\lambda \approx 71.5^\circ$ (BJN) was accompanied by the peak value of the cross phase (Figure 6c). Phase reversals at the maximum-amplitude location in both sectors have been reported in previous studies [Samson and Rostoker, 1972; Walker et al., 1979; Mathie et al., 1999a, 1999b; Sung et al., 2006] and are currently interpreted as FLR signatures.

Figure 7 shows the LT and the latitudinal dependence of the polarization pattern. Open circles identify counterclockwise (CCW) polarization, black circles identify clockwise (CW) polarization, and diamonds identify linear polarization ($|\varepsilon| < 0.1$). The pattern clearly reveals the polarization reversal at $\lambda \approx 72^\circ$ in sector 2 and some evidence for a similar feature at $\lambda \approx 66^\circ$ in sector 1. The dotted curve tentatively identifies the line of the maximum wave amplitude and corresponds to the region of linear polarization. According to theoretical models, such a polarization pattern can be interpreted as an effect of the resonant coupling between compressional and Alfvén modes [Southwood, 1974; Chen and Hasegawa, 1974], which predicts a polarization reversal at the latitude of the resonant field line. The geometry of the inferred profile (dotted line) is consistent with the one proposed by Samson [1972] at high latitudes ($\lambda \approx 63^\circ$, $f = 5$ mHz) as well as with the one proposed by Villante et al. [2009] at Antarctic latitudes ($\lambda \approx -80^\circ$, $f = 4$–5 mHz). They interpreted such behavior in terms of a
resonance line shifting to a lower latitude moving toward the dark hemisphere because of the LT dependence of the length of the local field line [Waters et al., 1996; Mathie et al., 1999b].

3.2.1. Comparison Between GOES Observations and Ground Measurements

Figure 8 shows the comparison between GOES observations and filtered ground measurements. It is worth noting the spectacular correspondence between the toroidal and poloidal components of the unfiltered magnetospheric field components (dashed line in Figures 8a and 8b) with the filtered data at $f = 3.3$ mHz of the $H$ and the $D$ components observed at PBQ (solid line), respectively. Note that the ground amplitudes are $\approx 3$ times greater than in the magnetosphere, a feature that is probably due to the close proximity of PBQ to the resonance region.

The high coherence ($\approx 0.9$, not shown) between the toroidal and poloidal components of GOES8 and the $H$ and $D$ components at PBQ, respectively, allows a comparison of the ground and magnetospheric polarization parameters. In particular, we evaluated the degree of polarization $R$ (defined as the ratio of the polarized intensity to the total intensity of the wave [Fowler et al., 1967]) and the polarization azimuth $\Psi$ over 30 min. Figures 8c and 8d show $R$ as a function of frequency as evaluated at PBQ and GOES8, respectively (the vertical dashed line corresponds to $f = 3.3$ mHz). Both ground and magnetospheric data reveal a highly polarized wave ($R \approx 0.95$). The comparison of the azimuth angle between the magnetosphere ($\Psi \sim 86^\circ$, Figure 8e) and ground ($\Psi \sim -3^\circ$, Figure 8f) reveals the expected $\sim 90^\circ$ rotation of the polarization axes at $f \approx 3.3$ mHz caused by the ionosphere [Hughes and Southwood, 1974].

Figure 8g and 8h show the superposition of the $B_Z$ and $B_X$ components of the magnetospheric field measured at GOES10 (dashed line) with the filtered data at $f = 3.3$ mHz for the $H$ and the $D$ components, observed at the ground stations located near the GOES10 footprint (i.e., close to the midnight meridian). As can be seen, GOES10 (LT = 00:15) observed an irregular, small-amplitude, short-duration variation along both $B_Z$ and $B_X$. Ground observations showed negligible variations along both components. This behavior can be tentatively interpreted in terms of the LT position of the spacecraft and ground stations, close to the midnight meridian where the field lines are open downtail and global oscillation modes would not be observed [Kivelson et al., 1984; Kivelson and Southwood, 1985, 1986; Kepko and Spence, 2003; Claudepierre et al., 2009].

3.2.2. The Azimuthal Wave Number Evaluation

The azimuthal wave number represents a measurement of the number of wave cycles that occur around the Earth in the azimuthal plane and is defined by

$$m = \Delta \varphi / \Delta \Phi.$$
where $\Delta \varphi$ and $\Delta \Phi$ are the phase and the longitude difference between two points on the Earth, respectively [Olson and Rostoker, 1978]. With such a technique, Pilipenko et al. [2010], estimated at high latitudes low-$m$ values (in the range $[1/3, 1/6]$) for a Pc5 wave activity during the recovery phase of a geomagnetic storm.

Figures 9a and 9b show our estimates of the $m$ value as a function of latitude for sector 1 and sector 2, respectively. As can be seen, $m$ typically ranges between 0 and 1, attaining greater values in only two cases ($m \approx 4$ in sector 1 and $m \approx 6$ in sector 2). A different analysis is performed in Figures 9c and 9d, where $m$ has been estimated by the gradient of a linear fit (dotted lines) of the cross phase versus longitude for both sectors [Ziesolleck and McDiarmid, 1995; Howard and Menk, 2001]. Consistently, we obtain $m = 0.21$ in sector 1 (Figure 9c) and $m = 0.34$ in sector 2 (Figure 9d). Following the same procedure, Fenrich et al. [1995] estimated $m$ values associated with ULF wave events using SuperDARN measurements and determined $m$ values in the range $[3, 40]$.

4. Discussion

[26] The long period of the discussed pulsations (5 min), their extended duration (~40 min), and their ubiquitous occurrence suggest a global magnetospheric oscillation driven by the enhanced SW dynamic pressure [Kivelson and Southwood, 1985, 1986; Waters et al., 2002; Lee and Lysak, 1989]. In addition, the characteristics of the ground wave amplitude and phase as well as the behavior of the polarization pattern suggest that such a wave leaked energy to the FLR at $\lambda \sim 66^\circ$ in the early morning sector and at $\lambda \sim 71^\circ$ in the noon sector. Theoretical studies on the global modes coupling to the FLR suggest a strong dependence on the azimuthal wave number [Radoski, 1967; Southwood, 1974; Chen and Hasegawa, 1974; Hughes, 1994]. Namely, while a
pure cavity mode \((m = 0)\) does not couple with the FLR, large-\(m\)-value modes are expected to couple to the FLR where the mode eigenfrequency matches the field line eigenfrequency. However, model studies [Kivelson and Southwood, 1986; Mann and Wright, 1999; Goldstein et al., 1999] suggest that small-\(m\)-number global cavity modes \((0 < m \leq 1)\) can excite transverse oscillations (mostly toroidal) near \(L\) shells whose resonant frequency matches the frequency of the global mode.

On the other hand, statistical analysis of geomagnetic fluctuations [Samson et al., 1992; Ziesolleck and McDiarmid, 1994, 1995; Francia and Villante, 1997; Mathie et al., 1999a, 1999b; Villante et al., 2001, 2007] showed a number of preferential frequencies, approximately at \(f / \nu \approx 2.1, 3.1, 3.9,\) and 4.9 mHz. Chisham and Orr [1997] suggested that those frequencies, observed on a SAMNET magnetometer array after a SSC occurrence, might be the result of global modes driven by solar wind impulses. Moreover, they found evidence that the maximum coupling between global modes and the FLR occurs for low azimuthal wave numbers \((m \sim 1)\). More recently, Hudson et al. [2004], in their statistical analysis on Pc5 oscillations following the SSC at CRRES orbit, showed that, for low-\(m\) values, the toroidal resonances are the dominant modes on the dawnside of the magnetosphere following a SSC.

In substantial agreement with such global scenarios, the event discussed in the present investigation might be interpreted as a small-\(m\)-number compressional cavity mode, with toroidal characteristics in the dawn sector at geosynchronous orbit, coupling to the FLR at \(\lambda \sim 66^\circ\) in the early morning sector and at \(\lambda \sim 71^\circ\) in the noon sector.

Model studies [Waters et al., 1994; Rankin et al., 2005] and experimental observations [Menk et al., 2003] highlighted that the FLR frequency expected at those latitudes is typically higher than 3.3 mHz. To better investigate this aspect, we performed a cross-phase analysis between two ground stations close to the noon FLR latitude in order to estimate the eigenfrequency of a magnetospheric field line at a midway position between observing stations [Waters et al., 1991; Chi and Russell, 1998].

Figure 10 shows the cross-phase dynamic spectra between two high-latitude stations (near the resonance region) in the noon sector approximately along the same meridian (i.e., MUO: \(\lambda = 64.72, LT = 11:58;\) SOR: \(\lambda = 67.34, LT = 12:00\)) for 8 June 2000. The local eigenfrequency is usually identified by a band of positive maxima in the cross phase [Waters et al., 1991; Green et al., 1991]. As can be seen, before the SI the maximum phase difference occurred at \(\sim 6\) mHz (blue horizontal line), while after the SI it slowly decreased to lower values (\(\sim 3-4\) mHz, blue
[31] On the other hand, the resonant frequency of a field line with both ends fixed in the ionosphere depends on its length, on the strength of the magnetic field, and on the plasma mass density along the field line [Singer et al., 1981; Waters et al., 1996; Rankin and Tikhonchuk, 2001; Berube et al., 2006]. Such field line eigenfrequencies can be estimated using the time of flight (TOF) approximation, in which the eigenfrequency $f$ is determined by [Warner and Orr, 1979]:

$$f = \frac{1}{2} \int \frac{dl}{V_A},$$

where $V_A$ is the Alfvén speed along the field line, $B_{T01}$ is the magnetospheric field along the field line, and $\rho(r)$ is the density at the geocentric distance $r$. To estimate $B_{T01}$, we used the $T01$ Tsyganenko model [Tsyganenko, 2002a, 2002b], and the integration is carried out over the entire length of the field line. The plasma density variation along the magnetospheric field line is approximated by the equation in the work by Chappell [1972] as

$$\rho(r) = \rho_0 \left(\frac{r}{r_0}\right)^4,$$

where $\rho_0$ is the equatorial plasma mass density measured by a reference spacecraft at its geocentric distance $r_0$. We adopted LANL$_{04}$ as the reference spacecraft for the close position of its footprint to NAQ. Densities detected by LANL$_{04}$ have been calculated assuming that ions are all H$^+$. [32] Figure 11a shows the total plasma density measurements. During the period under analysis, LANL$_{04}$ was located in the dawn magnetosphere ($X_{GSE} = -2.95 R_E; Y_{GSE} = -5.647 R_E; Z_{GSE} = -1.708 R_E$). After the SI (vertical dashed line), the total plasma density values are almost constant (horizontal arrowed line), with an average value, evaluated over a 20 min interval ([09:10–09:30], horizontal arrowed line), of $\sim 7$ cm$^{-3}$, suggesting that the SI event did not drive any significant variation in the magnetospheric plasma density.

[33] Figures 11b and 11c show the representation of the field line anchored at NAQ in the $X_{GSE}$–$Z_{GSE}$ plane and the $Y_{GSE}$–$X_{GSE}$ plane, respectively, for 8 June 2000 (dashed line) and for a reference quiet day at LT = 7:01 (4 June 2000, dotted line), modeled by $T01$. For quiet time conditions, the field line eigenfrequency at NAQ, using the corresponding LANL$_{04}$ data ($\rho \sim 10$ cm$^{-3}$), is 6.2 mHz. The same calculation for the 8 June 2000 conditions, using the modification proposed by Villante and Piersanti [2008] to interpret the aspects of the SI variations, suggested a more stretched field line (dashed line) in the dawn sector. The eigenfrequency associated with this field line geometry is $\approx 3.35$ mHz, in close agreement with the observed value. Repeating the same procedure at noon using plasma measurements (average value $\rho \sim 0.02$ cm$^{-3}$) from LANL$_{89}$ (located in the morning magnetosphere), we obtained $f = 3.3$ mHz at $\lambda = 72.5^\circ$, very close to BJN ($\lambda = 71.45^\circ$, LT = 12:07), consistent with a field line somewhat more extended into the dayside region than for usual conditions. This suggests that the lower values of the resonance frequency with respect to usual conditions can be interpreted in terms of a
modification of the magnetosphere geometry driven by the pressure pulse coupled with a long-time, stable northward (\(\sim 20\) min) IMF condition (Figure 1).

5. Summary and Conclusions

[34] An SI event occurring on 8 June 2000 was analyzed over a wide spatial extent using ground magnetometer data from 43 stations and geosynchronous satellites. The SI event was followed by a clear wave activity at 3.3 mHz. The combination of the long period of these pulsations (5 min), their extended duration (\(\sim 40\) min), the latitude-independent frequency over a wide longitude, and the low azimuthal wave number might be interpreted tentatively in terms of a small-\(m\)-number global cavity mode driven by the enhancement of the SW dynamic pressure [Kivelson and Southwood, 1986; Mann and Wright, 1999; Goldstein et al., 1999; Waters et al., 2002; Lee and Lysak, 1989].

[35] The coherence, the amplitude, and the cross-phase analyses computed at ground stations as well as the behavior of the polarization pattern suggest that the global mode coupled to the FLR at \(L\) shells corresponding to \(\lambda \sim 66^\circ\) in the dawn sector and to \(\lambda \sim 71^\circ\) in the noon sector. Typically, at those latitudes and longitudes the resonance frequency is greater than 3.3 mHz [Waters et al., 1996; Rankin et al., 2005; Menk et al., 2003]. The cross-phase dynamic spectra computed between two high-latitude stations (near the resonance region) along the same local meridian (in the noon sector) confirmed the shifting of the resonance frequency to lower values after the SI occurrence (Figure 9). Such values of the resonance frequency at these latitudes might likely occur as a consequence of a reconfiguration of the magnetospheric field lines and/or of an increase of the plasma mass density [Singer et al., 1981; Waters et al., 1994; Rankin and Tikhonchuk, 2001; Berube et al., 2006]. Applying the TOF approximation, we estimated the field line eigenfrequencies at NAQ and BJN latitudes, evaluating the magnetospheric configuration by means of the Tsyganenko model [Tsyganenko, 2002a, 2002b] with the modifications introduced by Villante and Piersanti [2008] to interpret the SI characteristics. We obtained results well consistent with the occurrence of FLRs observed at both NAQ and BJN. Since the mass density measurements did not reveal any significant variation driven by the SI occurrence, we speculate that the FLR observed at \(\lambda \sim 66^\circ\) in the dawn sector and at \(\lambda \sim 71^\circ\) in the noon sector was caused by a change in the magnetospheric field geometry characterized by field lines more elongated than for usual conditions, more explicitly in the dawn sector. As remarked by Villante and Piersanti [2008], this condition was probably produced by the compression of

Figure 11. (a) The magnetospheric plasma density measured by LANL_94 during 09:09–10:00 UT on 8 June 2000. The vertical dashed line represents the SI onset at GOES. (b) The trace of the magnetospheric field line anchored at NAQ at 09:15 UT in the \(X-Z\) GSE plane evaluated using the 701 model [Tsyganenko, 2002a, 2002b] for a quiet day (dotted line) and for 8 June 2000 (dashed line). (c) The trace of the magnetospheric field line anchored at NAQ at 09:15 UT in the \(Y-X\) GSE plane evaluated using the 701 model [Tsyganenko, 2002a, 2002b] for a quiet day (dotted line) and for 8 June 2000 (dashed line).
the magnetosphere driven by the pressure pulse coupled with the long-time, stable northward (~20 min) IMF condition.

[36] The comparison between magnetic field variation data recorded by GOES8 and the ground showed the expected 90° rotation of the polarization axes through the ionosphere for shear Alfvén waves [Hughes and Southwood, 1974].

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