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ULF geomagnetic pulsations at different latitudes in Antarctica

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Abstract. We present a study aimed to characterize the ULF (1–100 mHz) geomagnetic pulsation activity in the polar cap at different latitudes. We used magnetic measurements obtained through 2005–2007 in Antarctica, at Dome C (89° S corrected geomagnetic latitude) and at Terra Nova Bay (80° S corrected geomagnetic latitude). The results indicate a solar wind control of the wave activity, more important at larger distances from the cusp, as well as a significant role of the local ionospheric conditions. The different position of the two stations, with respect to the cusp and closed field lines, is responsible for the observed different pulsation characteristics. At Terra Nova Bay, due to the approaching of the station to the cusp and closed field lines in the daytime, the ULF power is characterized by a maximum around noon; daytime pulsation events in the Pc5 frequency band are related to the fundamental field line resonances occurring at lower latitudes, while higher harmonics of the fundamental may account for the characteristics of Pc3–4 pulsations. In the nighttime, at Pc3 frequencies, the results suggest waves propagating sunward, possibly due to the transmission of upstream waves from the magnetosheath via the magnetotail lobes. At Dome C, near the geomagnetic pole and very far from closed field lines, the ULF power in any frequency band only shows an enhancement in the postmidnight sector, more pronounced for Pc3 pulsations. The ULF activity appears to be driven by processes occurring in the magnetotail: in particular, nighttime Pc3 pulsation events may be originated from upstream wave penetration through the magnetotail lobes.

Keywords. Magnetospheric physics (MHD waves and instabilities; Polar cap phenomena; Solar wind-magnetosphere interactions)

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1 Introduction

The availability of magnetic measurements since 2005 at Dome C (DMC, corrected geomagnetic latitude 89° S), at the Antarctic Italian/French base of Concordia, provided us a unique opportunity to study and characterize the pulsation activity very close to geomagnetic pole in comparison with that one observed at Terra Nova Bay (TNB, 80° S), at the Italian "Mario Zucchelli" base, latitudinally separated by few degrees.

Geomagnetic field pulsations are the ground signature of ultra-low-frequency hydromagnetic waves (ULF waves, 1 mHz–1 Hz) in the Earth's magnetosphere. In the low and mid-frequency range (1–100 mHz), pulsations ultimately get their energy from the solar wind (SW), through several processes occurring in the outermost regions of the magnetosphere, where high latitude geomagnetic field lines extend. In this sense, ULF measurements at high latitudes represent a useful tool to study some interesting aspects of the SW-magnetosphere interaction.

At low frequencies ($\sim$1–7 mHz, Pc5) the most important generation processes are: a) the Kelvin-Helmholtz instability, for which waves are generated along the flanks of the magnetopause by the relative motion of the SW with respect to the stationary plasma of the magnetosphere (Atkinson and Watanabe, 1966); b) broad-band pulses, such as SW pressure pulses whose impact on the magnetopause can drive magnetospheric cavity/waveguide modes (Kivelson and Southwood, 1985, 1986; Samson et al., 1992; Francia and Villante, 1997; Villante et al., 2001); c) fluctuations of the SW pressure, directly transmitted into the magnetosphere possibly via the modulation of the magnetopause current (Kepko and Spence, 2003; Villante et al., 2007). At high latitudes, low frequency pulsations can be also related to field line resonances (FLRs), i.e. standing oscillations of the local field line resulting from the resonant coupling between compressional waves and Alfvén modes of the line itself (Southwood, 1974; Chen and Hasegawa, 1974).

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In the mid-frequency range (7–100 mHz, Pc3–4), pulsations are mainly due to the transmission into the magnetosphere of interplanetary upstream waves (Greenstadt et al., 1980) generated through ion-cyclotron instability by protons reflected off the bow shock along the interplanetary magnetic field (IMF) lines; given the spiral orientation of the IMF and the frequency dependence on the IMF strength (f(mHz) ∼6 B (nT); Troitskaya and Bolshakova, 1988), the resulting waves are mostly observed in the morning side at frequencies in the Pc3 range. The Kelvin-Helmholtz instability might play a role in the amplification of these waves, as they are convected and transmitted through the magnetopause (Engebretson et al., 1986). The most accepted mechanisms for the entry of upstream wave energy into the magnetosphere are basically two: a direct propagation through the subsolar region (Russell et al., 1983) and an indirect process involving particle and current modulation at the near-cusp ionosphere (Engebretson et al., 1991). Recently, in order to interpret some aspects of the Pc3 activity in the polar cap, Chugunova et al. (2004, 2006) proposed an additional propagation path of upstream waves to the ground via the magnetotail lobes (see also De Lauretis et al., 2005). In the magnetosphere, due to the latitudinal dependence of the field line length, upstream waves can couple to fundamental FLRs at low and mid latitudes, and to higher harmonics at high latitudes (Howard and Menk, 2005).

Several studies based on our ULF facility in Antarctica at TNB (operating since 1994) showed a significant ULF wave activity in the polar cap, both in the low and mid-frequency range (Villante et al., 2000a, b; Francia et al., 2005). Namely, the Pc3–5 power exhibits a magnetic local time (MLT) dependence, characterized by a broad maximum around noon, when the station approaches the dayside cusp and closed field lines, and a strongly reduced nighttime activity. In addition, the Pc3–4 power appears more strongly controlled by the SW speed than at cusp latitudes (Wolfe et al., 1987), where it is more influenced by local phenomena.

Recently, we compared data obtained during a test campaign at DMC in November 2003 with simultaneous TNB measurements (De Lauretis et al., 2005). During quiet magnetospheric conditions, such analysis evidenced that, while at TNB the Pc3–4 power showed the typical maximum around local noon, at DMC, far from the cusp, it did not show any clear local time dependence. The correlation between the Pc3–4 power and the SW speed at TNB was lower than at DMC, possibly due to the ULF turbulence of the cusp region. The frequency dependence on the IMF amplitude for Pc3 events simultaneously observed at TNB and DMC, appeared consistent with an upstream wave source.

The polarization characteristics of ULF waves are useful for investigating their generation and propagation mechanisms. For example, waves generated by the Kelvin-Helmholtz instability are expected to propagate antisunward, i.e. westward in the local morning and eastward in the afternoon; in the Southern Hemisphere, it would correspond to clockwise (CW, looking downward on the Earth) polarized pulsations in the morning and counterclockwise (CCW) polarized pulsations in the afternoon (Southwood, 1974). However, the polarization pattern can be modified by the resonant coupling between compressional waves and Alfvén modes (Southwood, 1974; Chen and Hasegawa, 1974); in particular, for a given frequency, polarization reversals are predicted at Λ_1, the latitude of the resonant field line, and at Λ_2, the latitude corresponding to the amplitude minimum between the magnetopause and the resonant field line. At high latitudes, due to the diurnal variation of the field line length in the outer magnetosphere (Mathie et al., 1999), both Λ_1 and Λ_2 have a local time dependence, being significantly higher around local noon with respect to dawn and dusk. Such model explains well the results reported, for low frequency (1–5 mHz) pulsations, by Samson et al. (1971) and Samson (1972) at geomagnetic latitudes between 60°–80°, where, depending on latitude, two or more polarization reversals were observed through the day. Statistical studies of the polarized pulsations at TNB (Villante et al., 2009, and references therein) found characteristics consistent with a station always located poleward with respect to Λ_1. In particular, for frequencies below 4 mHz, four sectors with alternate polarization appeared through the day: in the early morning and evening the polarization indicated an antisunward propagation, while the reversed sense in the prenoon and afternoon suggested that, in the dayside, TNB moves into the region between Λ_2 and Λ_1, where resonance effects can be still observed ("resonance region"). On the other hand, in the mid-frequency band, the polarization sense was clear only in the morning and in the evening sector, indicating sunward propagation, consistent with an upstream wave source from the magnetotail lobes.

In this work we report the results of a statistical comparison of the ULF pulsation power observed at DMC and TNB through 2005–2007, during the declining phase of the 23rd solar cycle. It represents a comprehensive analysis aimed to focus similarities and differences in the ULF activity detected at different latitudes in the polar cap.

2 Data analysis

In this analysis we use geomagnetic measurements obtained at DMC and at TNB (Table 1). The instrumentations at the two stations are similar and consist in high resolution triaxial search-coil magnetometers, recording the northward (H), eastward (D), and vertically downward (Z) components of the geomagnetic field variations, with a sampling rate of 1 Hz. The amplitude response linearly increases in the range 1–100 mHz (about 2–5 mV/nT/mHz).

TNB data are available through the entire 2005–2007 interval, with a data gap between March–October 2005. After a test campaign in November 2003, the DMC station has been operating since February 2005: as a matter of fact, due to instrumental problems, simultaneous measurements at TNB

Table 1. Coordinates of the recording stations.

Station	Geographic coordinates	Corrected geomagnetic coordinates	Time of magnetic local midnight (UT)
Concordia (DMC)	75.10 S 123.38 E	88.84 S 55.73 E	0:55
Mario Zucchelli (TNB)	74.69 S 164.12 E	80.01 S 306.94 E	08:11

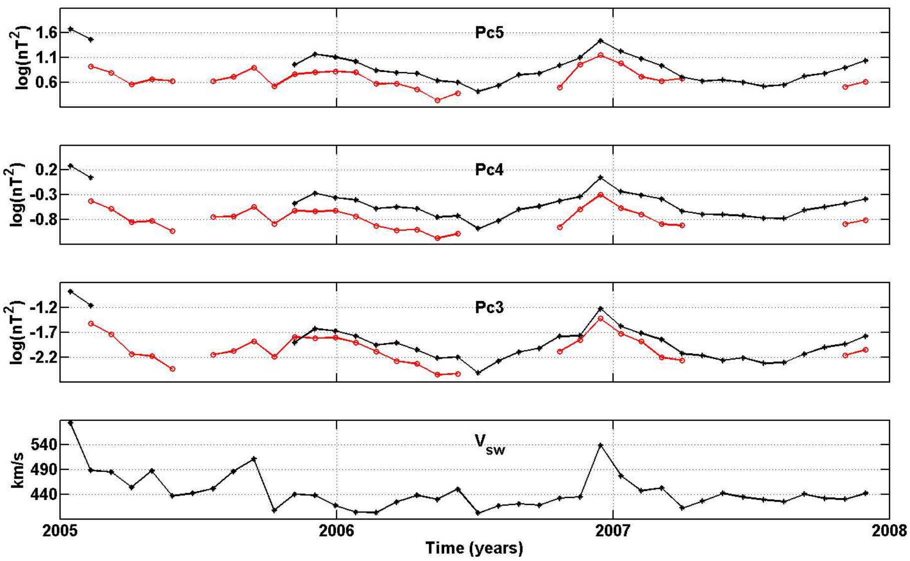

Fig. 1. 27-day averages of ULF power (log scale) at DMC (red line) and TNB (black line) and SW speed through the years 2003–2007. From top to bottom: Pc5 (1–7ṁHz), Pc4 (7–22 mHz), Pc3 (22–100 mHz) power of the horizontal component, SW speed V_{SW}.

and DMC were available mostly during local summer in the years 2005–2007.

The spectral power of the horizontal component ($P_H + P_D$) of the geomagnetic field has been computed by means of the Welch periodogram method over 1-h intervals. The intrinsic pre-whitening effect of the search-coil sensor was compensated in the frequency domain by dividing the power spectra estimates by the square of the amplitude response.

Polarization parameters were computed using the technique for partially polarized waves as proposed by Fowler et al. (1967). In particular, the polarization ratio R (i.e., the ratio between the polarized and total intensity of the horizontal signal) and the ellipticity ε (i.e., the ratio between the minor and the major axis of the polarization ellipse in the horizontal plane) were evaluated over each hour. The wave is linearly polarized when ε=0 and circularly polarized when $\varepsilon=\pm 1$. For $0<|\varepsilon|<1$ the wave is elliptically polarized. The sense of polarization is given by the sign of ε: a positive (negative) ε corresponds to CW (CCW) sense. In order to consider only intervals characterized by a negligible noise contribution and by a well defined polarization sense, our polarization analysis was restricted to intervals with $R>0.8$ and $|\varepsilon|>0.1$.

For a comparison with the interplanetary medium conditions we considered the SW and IMF parameters from ACE spacecraft at the L1 libration point upstream of Earth.

3 Experimental results

We investigated the dependence of the ULF power on the SW speed through 2005–2007, considering at first 27-day averages. Figure 1 shows, from the top, the logarithm of the Pc5 (1–7 mHz), Pc4 (7–22 mHz) and Pc3 (22–100 mHz) pulsation power at TNB (black line) and DMC (red line), and the SW speed (V_{SW}). As can be seen, when simultaneously available, the observations at the two stations follow each other, with the power at DMC always lower than at TNB. Two features clearly emerge in all frequency bands, both at DMC and TNB: a) the power variations well follow the V_{SW} variations, b) the ULF power shows an annual modulation characterized by a minimum (maximum) during local winter (summer). Such seasonal variation might be related to the different ionospheric conditions occurring in winter, when the stations are embedded in the dark sector, and, with regard

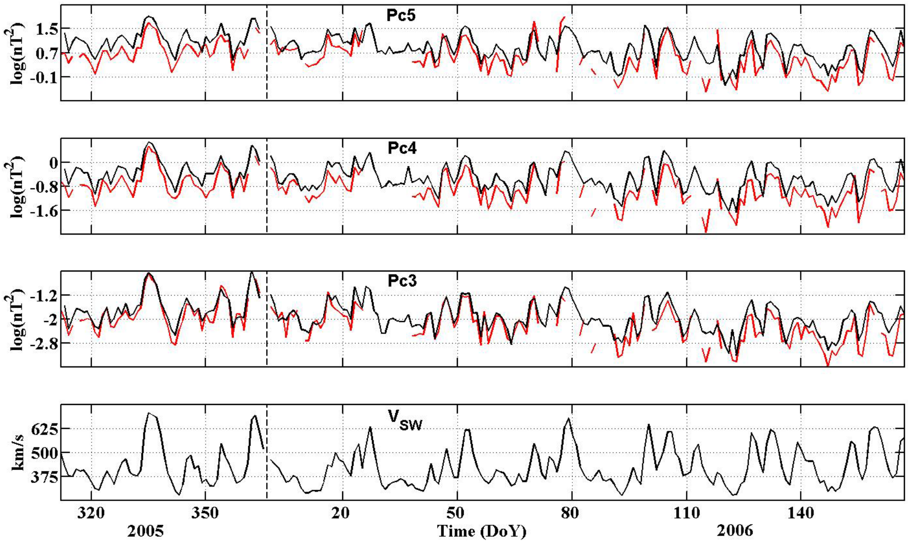

Fig. 2. 1-day averages of ULF power (log scale) at DMC (red line) and TNB (black line) and SW speed in the time interval 8 November 2005–16 June 2006. From top to bottom: Pc5 (1–7 mHz), Pc4 (7–22 mHz), Pc3 (22–100 mHz) power of the horizontal component, SW speed V_{SW}.

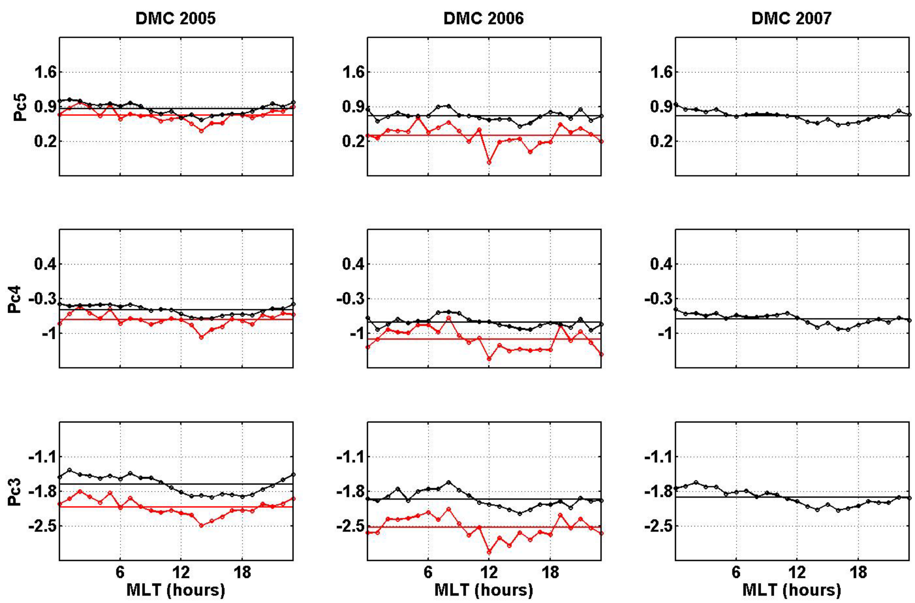

Fig. 3. MLT variation of the hourly power (log scale) of the horizontal component at DMC through the years 2005–2007 in the Pc5 (top panels), Pc4 (middle panels), Pc3 (bottom panels) frequency bands. Black lines correspond to summer while red ones to winter. Horizontal lines indicate the average powers.

to TNB, to the greater distance of the station from the cusp region (Zhou et al., 1999).

The correspondence between the variations of the SW speed and the pulsation power emerges in minute detail when we consider daily averages; in Fig. 2 we show, for example, the time interval 8 November 2005–16 June 2006, when a good data coverage is available from both stations. This correspondence has been further examined by computing the correlation coefficient between the logarithm of the spectral power and V_{SW}. Since, as previously observed, the relationship between the ULF power and V_{SW} may be influenced by seasonal effects, we considered the entire data set and, separately, summer (January, February, November and December) and winter (May, June, July and August) months. Such analysis, restricted to simultaneous data for a direct comparison, has been conducted on different time scales, i.e.

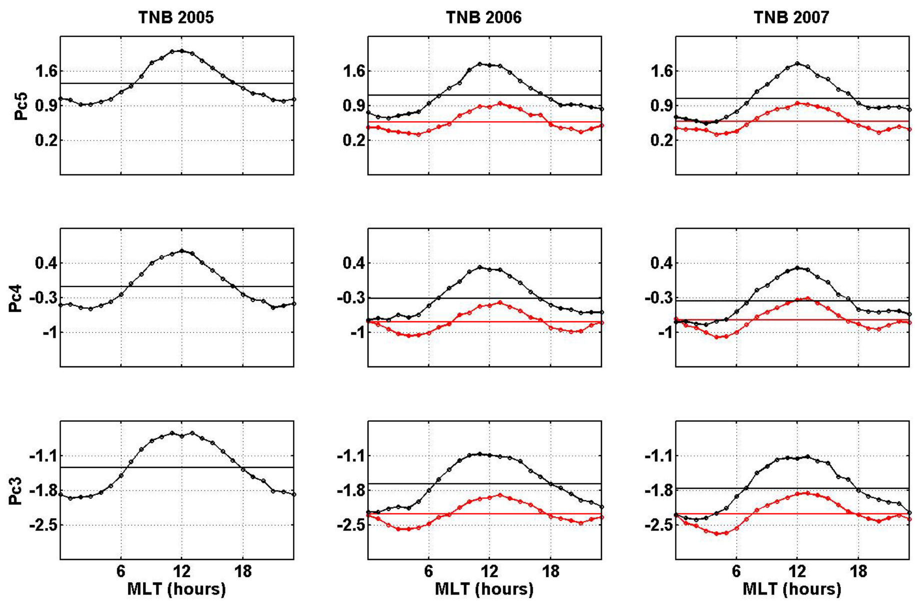

Fig. 4. Same as Fig. 3 at TNB.

Table 2. Correlation coefficient ρ between the logarithm of the Pc3, Pc4 and Pc5 power at DMC and TNB and V_{SW} [a].

		1-day			1-h		
		All	Summer	Winter	All	Summer	Winter
	N	348	219	48	2543	2024	199
DMC	Pc5	0.75	0.83	0.81	0.67	0.70	0.69
	Pc4	0.79	0.85	0.83	0.73	0.76	0.72
	Pc3	0.76	0.84	0.85	0.71	0.74	0.74
TNB	Pc5	0.67	0.73	0.74	0.52	0.53	0.62
	Pc4	0.71	0.74	0.77	0.56	0.57	0.62
	Pc3	0.72	0.76	0.76	0.59	0.61	0.62

[a] N represents the number of averages.

considering 27-day, 1-day and 1-h averages. The propagation time, smaller than 1 h, from ACE to the magnetosphere has not been taken into account, since the SW speed exhibits only negligible variations on such time scales (indeed, the autocorrelation coefficient of the SW speed during this interval was higher than 0.98 at 1 h lag time). In Table 2 we show the correlation coefficients ρ obtained at DMC and TNB only for 1-day and 1-h averages; indeed, such coefficients are highly significant (well above the 99% confidence level) while, due to the low number of data points, the correlation is poorly significant for the 27-day averages. Independently on frequency, time average and data set, ρ appears higher at DMC, where measurements are not affected by cusp phenomena, confirming the results of De Lauretis et al. (2005). At both stations, as expected, higher values of ρ are generally observed when seasons are examined separately; in addition, at TNB ρ tends to be higher in winter than in summer, possibly indicating that the variable distance from the cusp turbulence may influence the V_{SW} dependence. Note also the lower values of ρ for hourly averages: it might be a consequence of the daily modulation of the ULF power.

Concerning this aspect, we show the MLT dependence of the hourly average power in the Pc3–5 frequency bands through the years 2005–2007 at DMC (Fig. 3) and TNB (Fig. 4). Given the observed seasonal variation, we examined separately summer (black line) and winter (red line) months.

At DMC the power does not exhibit a clear diurnal modulation, except for a general tendency for higher values in the postmidnight hours, more evident for Pc3 pulsations. In addition, the power is higher in summer than in winter, according to the seasonal variation observed in Fig. 1.

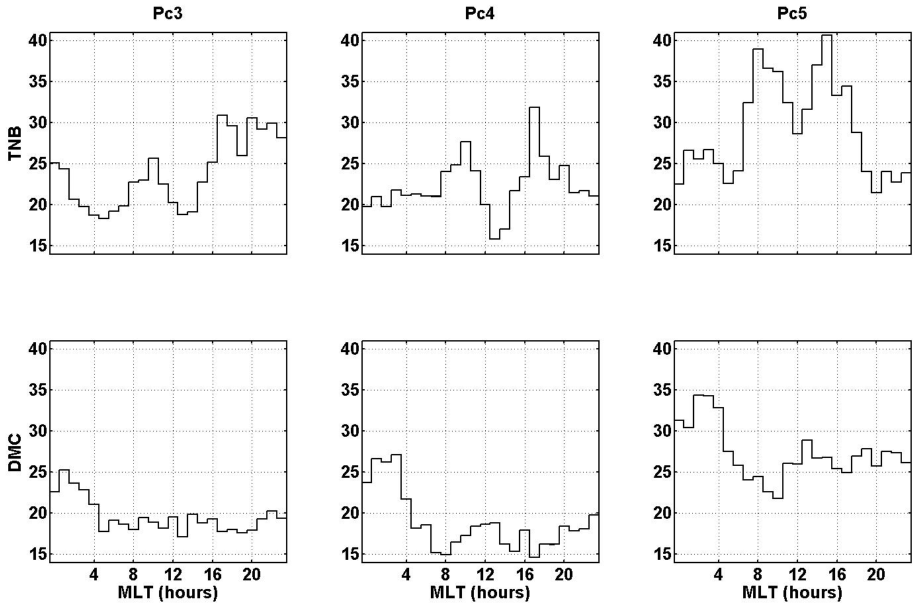

Fig. 5. MLT distribution of the percentage of polarized signals at DMC (bottom panels) and TNB (top panels) in the Pc5, Pc4 and Pc3 frequency band during the 2005–2007 local summer months.

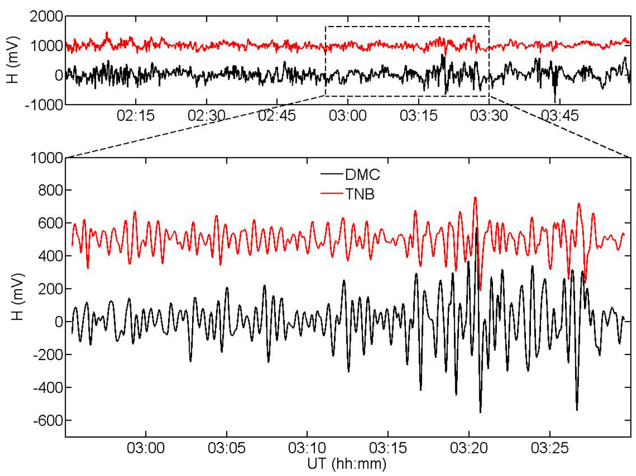

Fig. 6. A pulsation event observed on 10 February 2005, 02:00–04:00 UT, on the H component at DMC and TNB (top panel) and a detail of the 20–60 mHz filtered signal (bottom panel).

At TNB, in each frequency band, year and season, a strong diurnal modulation emerges, with the well known maximum around noon (Villante et al., 2000a; b; Francia et al., 2005). Also the seasonal effect is clearly observed: indeed, as expected from Fig. 1, in summer the power is generally higher and shows a greater excursion between minimum and maximum values; moreover, the minimum values occur some hours later in winter than in summer (i.e. at ∼04–05 MLT with respect to ∼02 MLT), possibly due to the different sunlight effect on the ionosphere; note also that a minor power peak emerges around midnight in winter, when the general level of power is lower, indicating a weak pulsation activity, related to magnetotail processes.

It is interesting to note that, at both stations, the average power (horizontal line) in 2005 is always higher than in 2006, due to the concurring effect of the higher V_{SW} values during 2005.

Figures 3 and 4 also show that the average power at TNB is higher than at DMC in all frequency bands (consistently with the results of Fig. 1), essentially because of the peak around noon while, on the contrary, in the morning and evening the power at TNB reduces to lower values than at DMC.

Lastly, we performed the polarization analysis for simultaneous measurements at DMC and TNB during the 2005–2007 summer months. Considering only intervals having $R>0.8$, the number of selected intervals reduces in average to ∼25–30% and ∼20–25% of the available intervals at TNB and DMC respectively, and shows a MLT and frequency dependence (Fig. 5). At DMC, the percentage of polarized signals is higher in the postmidnight hours with respect to the rest of the day. At TNB, in the Pc5 frequency band, two clear peaks of occurrence are observed around ∼08 and ∼15–16 MLT, approximately symmetric with respect to noon, which might be indicative of a source mechanism such as Kelvin-Helmholtz instability; in the Pc4 frequency band, the percentage of polarized signals shows peaks at ∼10 MLT and at 17:00 MLT while, in the Pc3 band, it shows, in addition to peaks at ∼10 MLT and at 17:00 MLT, a large maximum in the evening-postmidnight hours suggesting a source in the magnetotail. As an example of signal, we present in Fig. 6 the Pc3 event of 10 February 2005, simultaneously

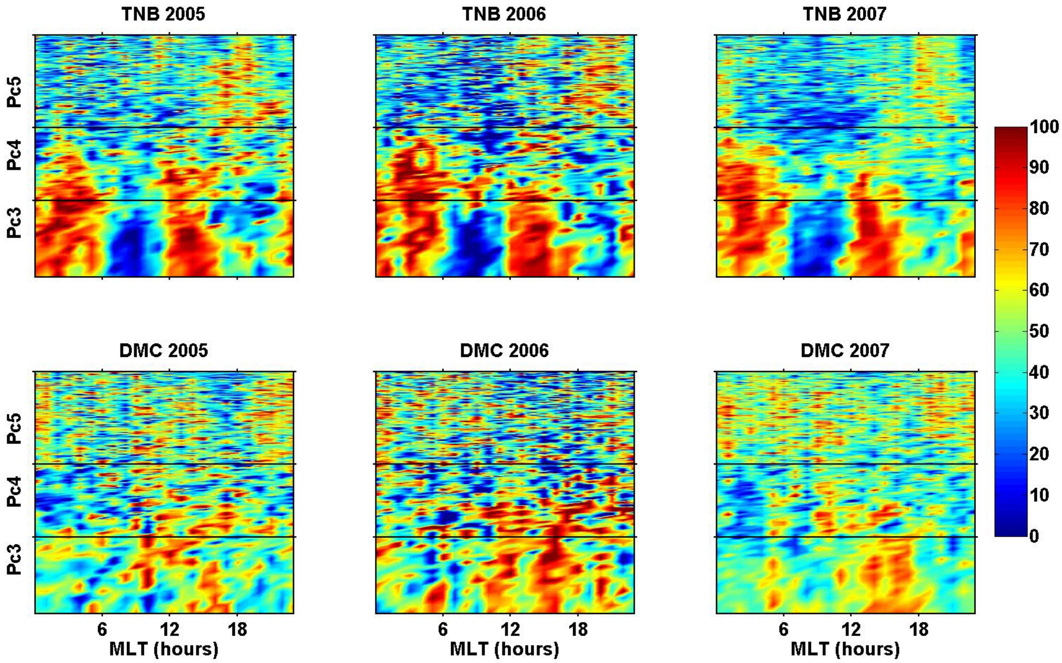

Fig. 7. MLT and frequency distribution of the percentage of CW events at DMC and TNB stations, separately for 2005, 2006 and 2007 summer months. Pc5, Pc4 and Pc3 labels indicate the band of frequency between the black horizontal lines on a log scale, i.e. 1–7 mHz, 7–22 mHz and 22–100 mHz, respectively.

observed at DMC and TNB. The signal, filtered in the 20–60 mHz frequency band, appears with similar waveforms at the two stations from ~03:11 UT, corresponding to ~02:06 at DMC (in the postmidnight sector) and to ~19:00 MLT at TNB (in the evening, when the station is well far from the cusp). The spectral analysis (not shown here) reveals the presence of a common peak at ~25–30 mHz, possibly related to the penetration of upstream waves (the expected frequency is indeed 30 mHz).

The MLT and frequency dependence of the percentage of CW polarized signals at DMC and TNB for the different years is presented in Fig. 7, in a colour scale. At each station the pattern is basically the same through the years but clear differences emerge between DMC and TNB.

At TNB the pattern confirms and extends previous results (Villante et al., 2009, and references therein). In particular, up to $f \sim 20$ mHz, the day is divided into 4 sectors with alternate sense of polarization: CW between ~00–06 MLT, CCW between ~06–12 MLT, newly CW between ~12–17 MLT and lastly CCW up to ~23 MLT. Such polarization sense is consistent with that expected for waves propagating antisunward in the morning and in the evening while in the prenoon and afternoon sectors it appears reversed. This result suggests that, in the daytime, signatures can be detected not only of the fundamental FLRs (with frequencies up to 7 mHz) but also of higher harmonics occurring at somewhat lower latitudes (Howard and Menk, 2005). At higher frequencies, in the Pc3 frequency range, the pattern is less clear; nevertheless, in particular in 2006 and 2007, a slightly prevailing CCW and CW polarization sense can be still observed respectively in the prenoon and afternoon sectors; in the evening, the CW polarization becomes highly predominant while a mixed/CCW polarization appears around and after midnight.

The polarization pattern at DMC appears less defined. Up to ~15 mHz it emerges some evidence for a two sector structure characterized by a predominant CW polarization in the afternoon, and by a slightly prevailing CCW polarization in the morning sector; such features may be indicative of the occurrence of waves propagating sunward, possibly generated by magnetotail processes. At higher frequencies the pattern does not show a well defined polarization sense, and a mixed/patchy structure is observed throughout the day.

4 Summary and conclusions

We report the results of a statistical analysis of ULF pulsations measured in Antarctica at TNB and DMC through 2005–2007, during the declining phase of the solar cycle. The aim is to characterize the pulsation activity at the two sites, both located in the polar cap but at different distances from closed field lines.

A significant correlation between the ULF pulsation power at the two stations and the SW speed is evidenced, in spite of the low SW velocity variability during most of the period of interest; in particular, the correlation is higher at DMC, which is far from the cusp turbulence, confirming previous results obtained from more limited sets of data (De Lauretis et al., 2005). In addition, it is observed that the pulsation power at TNB is better correlated to the SW speed during local winter, when the station is at a larger distance from the cusp (Zhou et al., 1999). The correlation with V_{SW}, observed for low and mid frequency pulsations, is indicative of an important role of the Kelvin-Helmholtz instability both in generating waves and in enhancing the transmission into the magnetosphere of upstream waves.

An interesting result is represented by the annual variation of the ULF power which strongly decreases in the local winter at both stations. It may indicate that ionospheric conditions have an important role in determining the level of the pulsation activity observed on the ground; an additional element, at least at TNB, can be the distance from the cusp, which increases in local winter.

From the analysis of the MLT dependence of ULF power and polarization, different characteristics emerge at TNB and DMC. As regard to TNB, an essential aspect is represented by the approaching of the station to the cusp and closed field lines in the daytime hours; such effect accounts for the strong, broad power maximum observed around noon and for the observation, in the Pc5 frequency band, of signatures of FLRs occurring at somewhat lower latitudes (Mathie et al., 1999), possibly generated by the Kelvin-Helmholtz instability. Indeed, since ionospheric effects smear at ground the magnetospheric field variations, ground magnetometers respond to ionospheric currents over a range of latitudes (Hughes and Southwood, 1976a, b; Samson et al., 1995); for example, Matthews et al. (1996) identified a $f\sim3.3$ mHz pulsation close to the cusp latitude and found that this pulsation persisted coherently up to $\sim5°$ poleward of the cusp.

Obviously, a similar behavior should progressively disappear with increasing latitude and vanish at DMC, in the deep polar cap. Actually, up to $\sim$15 mHz, the polarization pattern at DMC appears to indicate waves propagating sunward, possibly originated from processes in the magnetotail (Pilipenko and Engebretson, 2002) and transmitted along the local field lines, stretched into the magnetotail.

In the Pc3–4 frequency band, the effects of several concurrent phenomena can be detected at TNB. For example, the power peak around noon might be explained as due to the ULF turbulence in the cusp region, related to upstream wave penetration (Engebretson et al., 1991). However, around noon, the polarization pattern of Pc3–4 may be still interpreted in terms of higher harmonics of FLRs occurring at lower latitudes; in this sense, it is worth to note that Fig. 4 shows very similar peaks of occurrence of Pc4 and Pc3 polarized waves in the prenoon and afternoon sectors. Our suggestion is consistent with the results of Howard and Menk (2005) who showed that at high latitudes (between 70°–76° CGM latitudes) about 24–30% of the observed Pc3–4 events were higher harmonics of fundamental Pc5 FLRs; they did not found evidence for localized modulated electron precipitation, they rather suggested that upstream waves, entering near the subsolar region, propagate earthward and couple to field guided Alfvén modes generating FLR harmonics at latitudes where frequencies match standing oscillations. On the other hand, differently from Pc4–5 signals, Pc3 events peak also in the evening and in the postmidnight sector (Fig. 4), showing a polarization sense consistent with waves propagating sunward; such result, which confirms previous findings by Villante et al. (2009), might indicate that Pc3 signals in the nighttime are due to upstream waves propagating to the ground via the magnetotail lobes, as suggested by Chugunova et al. (2004, 2006) and De Lauretis et al. (2005).

At DMC, the polarization pattern in the Pc3 frequency band appears patchy, as for waves propagating in opposite directions; the occurrence of Pc3 polarized pulsations peaks only in the postmidnight sector, as also observed at approximately the same latitude by Chugunova et al. (2004, 2006), who assumed that such pulsations are due to upstream waves which penetrate from the magnetosheath to the magnetotail lobes mainly on the dawn flank. So, the ULF activity at DMC appears, throughout the day, to be driven by phenomena occurring in the magnetotail.

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