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Ducting characteristics of Pc 1 waves at high latitudes on the ground and in space

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[1] Well-defined ULF Pc 1 geomagnetic pulsations have been observed simultaneously from a ground array of five search-coil magnetometers in the morning sector of Antarctica on Mar. 23, 2007. Distributed over a very extensive range of geomagnetic latitudes $(-62^{\circ} \text{ to } -87^{\circ}, \text{ spanning } \sim 2920 \text{ km geographically})$ approximately along a magnetic meridian, the array showed poleward propagation of the Pc 1 waves in the ionospheric waveguide. It is observed that attenuation factors are between ~ 8 and 20 dB/1000 km and the polarization sense changes from left-hand to right-hand as the waves are ducted poleward. However, a complex polarization pattern (i.e., change in ellipticity and major axis angle) was seen on the ground, which might be attributed to the array being close to the wave injection region where the superposed effect of incident waves and ducted waves is dominant. A CHAMP satellite conjunction showed a transverse and nearly linearly polarized Pc 1 ULF wave at the altitude of the ducting layer (~350 km) over a limited latitudinal extent (-53° to -61° ILAT). The polarization analysis performed using the ground data supports the idea that CHAMP detected the wave activity near the wave injection region. The observations are unique in that the ducted waves, seen over an array with unprecedented geomagnetic latitudinal range and positioning along a magnetic meridian (a condition that provides the most efficient ducting), have rarely been measured before.

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1. Introduction

[2] ULF Pc 1 (0.2–5 Hz) geomagnetic pulsations include electromagnetic ion cyclotron (EMIC) waves generated by the cyclotron instability of hot, anisotropic protons in the equatorial region of the magnetosphere in the energy range of ~1-100 keV [Brice, 1965; Cornwall, 1965; Anderson et al., 1996; Kangas et al., 1998]. The theoretical studies [e.g., Horne and Thorne, 1993] and the observations [e.g., Anderson et al., 1996] suggest that Pc 1 waves are generated close to the magnetic equator. It is generally accepted that left-hand polarized (LHP) Alfvén Pc 1 pulsations propagate along the geomagnetic field lines from the magnetosphere to the ionosphere and couple to right-hand polarized (RHP) compressional (fast), isotropic waves in the ionosphere (called the "ionospheric source region" or the "wave injection region") [Fraser, 1975a, 1975b; Altman and Fijalkow, 1980; Fujita and Tamao, 1988]. It has also been shown in

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theory and observations that the compressional waves are trapped in the ionospheric waveguide (or duct), centered around the Alfvén speed minimum (electron density maximum, at an altitude of ~400 km) near the F2 region bounded by the E region (~100 km) and a region where the Alfvén speed increases sharply (~1000 km), after mode conversion from the incident Alfvén waves to the horizontally propagating compressional waves by the anisotropic ionospheric Hall currents [*Tepley and Landshoff*, 1966; *Manchester*, 1966; *Greifinger and Greifinger*, 1968; *Fujita and Tamao*, 1988].

[3] Tepley and Landshoff [1966] discussed a waveguide theory for ionospheric propagation of MHD waves and mode conversion through collisional processes in the ionosphere. Manchester [1966] suggested that as the walls of the duct are not perfect reflectors, the wave is attenuated as it propagates down the duct. A model result given by Greifinger and Greifinger [1973] showed that duct propagation is most efficient along the magnetic meridian. The model suggested by Fujita and Tamao [1988] showed an attenuation rate of 8 dB/100 km near the injection region. They also predicted higher attenuation with increasing dip angle at high latitudes. Ground observations by Hayashi et al. [1981] at high latitudes using a search-coil magnetometer array found that ULF Pc 1 waves propagated from an injection region in a concentric pattern of equicontour lines of its intensity and observed an attenuation of 10 dB/

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Station	Station Code	Geographic Latitude	Geographic Longitude	Geomagnetic Latitude	Geomagnetic Longitude	L	MLT MN (UT)	Distance From HBA (km)
Halley	HBA	-75.50	333.40	-61.56	29.01	4.4	0243	0
AGO P2	P2	-85.67	313.62	-69.84	19.33	8.4	0329	1170
South Pole	SPA	-90.00	0.0	-74.02	18.35	13.2	0335	1610
AGO P1 Ago P5	P1 P5	-83.86 -77.24	129.61 123.52	$-80.14 \\ -86.74$	16.87 29.46	34.1 309.2	0344 0252	2252 2920

Table 1. Geographic and Geomagnetic Locations of the Antarctic Stations Used in This Study^a

^aGeomagnetic coordinates, dipole *L*-values, and MLT MN in UT are obtained from NASA GSFC Modelweb Website, http://modelweb.gsfc.nasa.gov/models/cgm/cgm.html, for epoch 2007, assuming an altitude of 100 km.

100 km in the injection center and 2.5 dB/100 km in the region beyond 500 km from the center. Multipoint observations by *Neudegg et al.* [2000] estimated the average attenuation of 41 dB/1000 km and suggested that the attenuation of waves did not always occur in a consistent and linear fashion, probably due to a leaky waveguide as described by *Manchester* [1968].

[4] Greifinger and Greifinger [1968] estimated that the ionospheric Alfvén speed varies approximately between 200 and 700 km/s depending on local time and sunspot conditions. Neudegg et al. [1995] found a Pc 1–2 propagation speed of 300–800 km/s from a ground-based magnetometer array located at high latitudes over a range of a few hundred km. A model by Lysak [2004] concludes that the wave front propagates on the order of 1000 km/s in the ionospheric waveguide across magnetic field lines and the fast mode wave speed in the ionosphere is close to the Alfvén speed.

[5] The polarization characteristics of geomagnetic pulsations can provide information about the source region and about the wave propagation from the source to the ground. Theoretical approaches by Baranskiy [1970], Greifinger [1972], Altman and Fijalkow [1980], and Fujita and Tamao [1988] showed transmitted LHP Alfvén waves vertically incident on the ionosphere gradually change to RHP as distance from the injection region increases as observed on the ground. Many observations using ground arrays also found the polarization sense changes from predominantly LHP around the injection region to RHP away from the injection region and the ellipticity becomes linearly polarized (LP) with the major axis aligned with the injection location [Summers and Fraser, 1972; Fraser and Summers, 1972; Fraser, 1975a; Hayashi et al., 1981; Webster and Fraser, 1985].

[6] *Fraser* [1975a] estimated the general location of the injection region near the dawn terminator in the range 58° – 66° ILAT (L = 3.5 - 6) using the polarization ellipse major axis azimuthal directions and direction of arrival triangulation method. Simultaneous multipoint ground and satellite observations by *Erlandson et al.* [1996] estimated the latitudinal extent of the Pc 1 source at Viking's altitude at L = 5.1 - 5.5 ($63.7^{\circ}-64.7^{\circ}$ ILAT), which corresponds to a latitudinal width of 120 km at ionospheric altitude. The Magsat satellite observations by *Iyemori and Hayashi* [1989] also showed a source region of <100 km in the ionosphere F region at 58° to 60° ILAT. The latitudinal width of the source of ~ 0.5° in ILAT has been obtained by *Mursula et al.* [1994]. The ST5 satellite observations of Pc 1–2 waves by *Engebretson et al.* [2008] and satellite-borne proton pre-

cipitation measurements by *Yahnin and Yahnina* [2007] also show very narrow regions of wave activity, with a latitudinal extent of $\sim 0.5^{\circ}-1^{\circ}$ ($\sim 50-100$ km).

[7] This study describes ULF Pc 1 geomagnetic pulsations observed from a ground array of search-coil magnetometers predominantly in the morning sector of Antarctica. With extensive latitudinal coverage along the magnetic meridian, the five search-coil magnetometers show very well-defined poleward spectral power attenuation and polarization change of the waves suggesting wave propagation in the ionospheric waveguide (ducting). Halley Station, located at the lowest latitude among the stations in the array, observes the highest spectral wave power and well-defined band-limited signatures. The same wave event, showing less wave power, is found at the other four remote stations at higher latitudes. The conjunction of an overflight of the CHAMP satellite for the event provides a measure of the incident wave power in the ducting layer. Data from CHAMP reveal that Pc 1 waves enter the ionosphere across a limited latitudinal range and that the waves are LP.

2. Instrumentation and Data

[8] The ground data presented in this study were obtained from the five ULF search-coil magnetometers deployed at Halley Station (HBA), South Pole Station (SPA), and three automated geophysical observatories (AGOs) in Antarctica on Mar. 23, 2007. They provide three-axis vector samples of *dB/dt* in local geomagnetic coordinates with X northward, Y eastward, and Z upward parallel to geomagnetic field at a rate of 10 samples/sec [*Engebretson et al.*, 1997]. Table 1 shows the geographic and corrected geomagnetic locations of the ground stations used in this study. This Antarctic ground-based magnetometer array provides observations over a large extent covering geomagnetic latitudes of -62° to -87° (over the distance of 2920 km) as shown in Figure 1 and has been showing very well-defined ULF wave ducting events over the entire extent of the array.

[9] Observations of the ULF waves were also made in the ducting layer by the CHAMP satellite, which was in almost circular, near polar (inclination = 87°) orbit with an altitude of approximately 350 km during the time of this study. The CHAMP satellite is equipped with a fluxgate magnetometer, which provides three-axis vector background magnetic field data at a maximum rate of 50 Hz over the bandwidth (-3 dB) of 13 Hz. During the events in this study, the CHAMP satellite flew over the ground stations with a very good MLT conjunction. The satellite footprint from 0835 to 0845 UT with a ground conjunction is also shown in Figure 1.



Figure 1. Map of Antarctica showing the ULF search-coil magnetometer array used for this study. The geomagnetically most poleward station, P5, and the other four stations, P1, P2, SPA and HBA are aligned well with the magnetic meridian. This map also shows the southern hemisphere ground track of the magnetic field lines traversed by the CHAMP satellite from 0835 to 0845 UT on Mar. 23, 2007, based on data from the Satellite Situation Center Web utility, available at http://sscweb.gsfc.nasa.gov.

[10] CHAMP data are originally acquired in a satellite coordinate system in which the X axis is approximately along the direction of the satellite track, the Z axis points downward, and the Y axis completes a right-handed set. A coordinate transformation is carried out for this study in order to examine the wave mode in the ionospheric ducting layer after the data are detrended to obtain time-varying magnetic fields (b) by subtracting background magnetic fields (\mathbf{B}_0). In this study, a smoothing of the original data from the satellite has been used as background field. One of the three components in the new coordinate system represents a compressional wave component (b_{\parallel}) , which is denoted by "B par" in Figures 8 and 9. Compressional perturbations can be obtained by projecting the detrended data onto the background magnetic fields. The other two components in the new coordinate system contain wave power perpendicular to the background magnetic fields, which is, for this study, decomposed into perpendicular perturbations in the azimuthal $(b_{\perp\varphi})$ and in the meridional direction $(b_{\perp \theta})$, which conforms to the right-hand rule. They are denoted by "B perp phi" and "B perp theta" respectively in Figures 8 and 9. The perpendicular azimuthal perturbation $(b_{\perp \omega})$ is calculated by projecting the detrended data (b) onto the azimuthal vector ($\hat{\varphi}$, normal of the magnetic meridian). The azimuthal vector ($\hat{\varphi}$) can be obtained by crossing the background magnetic field unit vector (\mathbf{B}_0/B_0) and the vertical field component from the original CHAMP data (\mathbf{B}_z/B_z) (i.e., $\hat{\varphi} = \mathbf{B}_0/B_0 \times \mathbf{B}_z/B_z$). The perpendicular meridional perturbation $(b_{\perp\theta})$, which completes the triad $(\hat{\theta} = \hat{\varphi} \times \mathbf{B}_0/B_0)$, is then calculated by projecting the detrended data (**b**) onto the meridional vector $(\hat{\theta})$. The new set of the three components is thus summarized as follows.

$$b_{\parallel} = \mathbf{b} \cdot \mathbf{B}_0 / B_0$$
$$b_{\perp \theta} = \mathbf{b} \cdot \hat{\boldsymbol{\theta}}$$
$$b_{\perp \varphi} = \mathbf{b} \cdot \hat{\boldsymbol{\varphi}}$$

3. Observations and Interpretations

[11] Well-defined, band-limited ULF Pc 1 waves were measured by the five ULF search-coil magnetometer systems deployed in Antarctica as shown in the stacked 0–1 Hz, 2048-point FFT spectrograms (with Hanning window) in Figure 2. Wave power as a function of frequency (0–1 Hz) in the X (north-south) and Y (east-west) components and time is plotted for a 5 hour interval (from 0800 to 1300 UT) on Mar. 23, 2007. The data from the X component at AGO P5 was unavailable during the observation. As shown in Figure 2, identical spectral patterns albeit attenuated across the network suggest that the waves were generated in a localized region within the ionosphere. Otherwise, such identical spectral signatures may not be detected over the wide range.

[12] The distance between the station at lowest magnetic latitude (HBA) and the one at highest magnetic latitude (P5) is 2920 km. The three stations P2, SPA and P1 are aligned approximately along a magnetic meridian within 15 min MLT while HBA is somewhat off-meridian (600 km from the meridional line of the three stations). The MLT difference at P5 is not very significant as it is close to the magnetic pole. The spectral structures over the frequency ranges between 0.3 and 0.6 Hz are most clearly registered at the station located at lowest magnetic latitude, Halley Station (HBA, L = 4.4) from 0830 to 1230 UT. There are some periods during which multiple band structures are observed.

[13] As shown in Table 1, the MLT is approximately 3 hours behind UT, which indicates that the events occurred in the morning sector. Based on the fact that the event was most clearly shown at HBA (L = 4.4), in this lower *L*-shell, EMIC waves in the Pc 1 frequency range are likely to be generated by protons and heavy ions in the ring current (near the equator) and propagate along the field lines. The wave spectral power attenuation is displayed in Figure 2 as the latitude increases, suggesting that the waves propagated poleward in the ionospheric waveguide.

[14] Figure 3 shows the temporal and spectral structures of the Pc 1 waves in a shorter time scale in order for the detailed structures to be displayed (the event during this period is indicated in Figure 2). Wave modulations are observed at HBA during almost the entire event while the other stations at higher latitudes also detected the same signatures but with less spectral power and shorter duration. Such spectral features fall into a ULF subclass, called "pearls" or "structured Pc 1", which are characterized by periodic variations of the wave amplitude, thus appearing as

that the time intervals of Figures 3, 5, and 8 are indicated







Figure 3. Temporal and spectral structures of the ULF Pc 1 waves (called "pearls") measured from HBA in a shorter time scale (from 1020 to 1050 UT). Wave modulation with approximately 3 min period is clearly shown. Note that the event during this period is indicated in Figure 2.

pearls on a string when plotted as a time series. The repetition period is approximately 3 min. The structured Pc 1 is one of the most frequently observed Pc 1 waves and is suggested to propagate in the ducting layer [*Mursula et al.*, 2001].

[15] The CHAMP fluxgate magnetometer measured very similar Pc 1 waves over the frequency band (~0.3 to 0.5 Hz) approximately from 0840 to 0843 UT. The signature measured by CHAMP is shown over a limited extent (-53° to -61° ILAT) while the ground array detected the wave at higher latitudes over a wider range (-62° to -87° ILAT). This study focuses on the ULF waves observed in space and on the ground and their propagation characteristics in the ionospheric waveguide. The pearl structure is not within the scope of this study and will be left for future work.

[16] Sections 3.1–3.4 describe the Pc 1 events and their ducting characteristics in the ionosphere in more detail. Wave power attenuation, wave propagation speed, and polarization are discussed in sections 3.1–3.3, respectively. Section 3.4 presents the spatial extent of the Pc 1 wave injection region observed by the CHAMP satellite.

3.1. Spectral Power Attenuation

[17] Spectral power attenuation is one of the features typically observed in a ducted wave event. Figure 4 shows the absolute power spectra (\log_{10} power versus frequency) of the ULF Pc 1 events observed by the Antarctic search-coil array and the wave power attenuation (in dB) over the distance from HBA (in km) at four selected frequencies (0.3, 0.4, 0.5, and 0.6 Hz). Two different time periods are examined for this analysis in an attempt to separate wider band structure (from 0915 to 0945 UT in Figure 4a) and

narrower band structure (from 0945 to 1015 UT in Figure 4b). Each graph displays the results from both X and Y components. In the power spectra depicted in Figure 4a, three spectral peaks are observed (predominantly in the X component), which are also seen in Figure 2.

[18] The attenuation (in dB) is obtained by multiplying the \log_{10} power in the power spectra by 10. The wave power values at each selected frequency ± 0.01 Hz (this bandwidth corresponds to 5 bins in the 2048-point spectrogram) during the event period are averaged and line-fitted to estimate attenuation over distance. From the results in Figure 4, the attenuation factors appear to be approximately between 8 dB/1000 km and 20 dB/1000 km. More specifically, there seems to be a tendency for the attenuation factor to increase with increasing frequency, which is in agreement with Greifinger and Greifinger [1968], although the stations located far from HBA (P1 and P5, in particular) show no clear tendency of spectral power attenuation, probably due to the poor signal-to-noise ratio. It should also be noted that in general, attenuation in the waveguide may not occur in a linear fashion due to its inhomogeneous conductivity and the leaky ionospheric layer [Manchester, 1968; Neudegg et al., 2000; Fraser and Nguyen, 2001].

[19] The average attenuation factor observed in this study appears to be much lower than that of many other previous studies. The model study by Fujita and Tamao [1988] reported ~8 dB/100 km and the ground observations by Hayashi et al. [1981] showed 10 dB/100 km near the injection center and 2.5 dB/100 km in the region beyond 500 km from the center using a network of 13 stations at high latitudes spanning 30° in longitude and 15° in latitude (from 53.7°N, 290.9°E to 75.1°N, 328.0°E, CGM). Note that these studies used "per 100 km" instead of "per 1000 km". The comparison between model and observation by Manchester [1970] reported ~1-8 dB/1000 km at low/ mid-latitudes. Neudegg et al. [2000] obtained ~41 dB/1000 km using a closely-spaced (~150 km) triangular network near Davis, Antarctica (74.6°S, 102.3°E, CGM) and suggested that the high attenuation might be due to higher dip angle at high latitudes as predicted by Fujita and Tamao [1988]. Hayashi et al. [1981] observed both poleward and equatorward attenuation and concluded that poleward propagation shows slightly less attenuation.

[20] In general, the wide range of attenuation factors obtained from the model/observation studies seem to be related to the fact that wave propagation in the ionospheric waveguide is susceptible to the variation of ionospheric conditions. In addition, since the configurations of the arrays in these studies are different both in latitudinal and longitudinal extent and the distances between the possible injection regions and the arrays are not necessarily the same, attenuation factors can be obtained with quite a large uncertainty if the attenuation is not linear. Moreover, the more efficient poleward than equatorward ducting might be attributed to incident Poynting flux being initially poleward based on the fact that the incident waves are field-aligned Alfvén waves (field lines are angled pointing toward the Poles).

[21] The observations in this study, showing much less attenuation compared to the other previous observations, are unique in that the ducted waves, seen over an array with



Figure 4. Power spectra (\log_{10} power versus frequency) of the ULF Pc 1 events observed by the Antarctic search-coil array and wave power attenuations (in dB) over the distance from HBA (in km) at four selected frequencies (0.3, 0.4, 0.5, and 0.6 Hz) during the two time periods, (a) 0915–0945 UT and (b) 0945–1015 UT. The graphs for each time period display the results from both X and Y components.

unprecedented geomagnetic latitudinal range and positioning along a magnetic meridian (a condition that provides the most efficient ducting as suggested by *Greifinger and Greifinger* [1973]), have rarely been measured before.

3.2. Propagation Speed

[22] Propagation in the ducting layer occurs in the form of compressional waves with a speed of the order of the Alfvén speed in the region. As described earlier, similar patterns of the spectral signatures of the Pc 1 waves are observed at different ground stations. Although wave power was found to attenuate as the waves propagated poleward, the presence of the pearl structure remains clear. By taking the consistent spectral patterns over the large extent in latitude and their attenuations into account, the idea that waves are ducted in the ionospheric waveguide is suggested. In temporally extended time-series plots and spectrograms as shown in Figure 5, propagation time delays among the stations during the event are observed by comparing the onset time of the temporal and spectral signatures (indicated by vertical lines in Figure 5). Note that the event during this period is indicated in Figure 2. The propagation time delay between HBA and SPA, which are separated by ~1600 km, appears to be ~18 sec, indicating that the propagation speed is ~89 km/s. In this study, the data from P1, P2, and P5 are not used since slight timing errors due to the issues of the data acquisition modules at those stations were known to occur.

[23] The propagation speeds obtained by the previous theoretical estimations and observations range from \sim 360 to 720 km/s (day-night, sunspot minimum) and \sim 190 to



Figure 5. Propagation time delay in the temporal and spectral structures observed from HBA and SPA. This event period is band-pass filtered over 0.3-0.5 Hz for the structures to be seen more clearly. The wave arrival time is delayed by ~18 sec between the stations, which are separated by ~1600 km. The wave packets and the spectral patterns that are compared for the timing delay are indicated by vertical lines. Note that the event during this period is indicated in Figure 2.

400 km/s (day-night, sunspot maximum) [*Greifinger and Greifinger*, 1968]; ~500 to 800 km/s [*Manchester*, 1970]; ~540 to 2500 km/s at mid latitudes [*Fraser*, 1975a]; and ~1000 km/s [*Lysak*, 2004]. *Neudegg et al.* [1995] using a triangular network in Antarctica measured speeds of ~150 to 750 km/s. The propagation speed estimated for the event in this study (~89 km/s) is lower than most of the results from the previous studies. *Greifinger and Greifinger* [1968] discussed that variation in propagation speed is largely dependent on ionospheric conditions. We do not, however, exclude a possibility of misinterpretation of the data, which can be caused by relatively big systematic error due to the difficulties in analyzing the data acquired from the stations which are separated beyond the range where autocorrelation and phase correlation analyses are reliably performed.

3.3. Polarization

[24] Two polarization properties – ellipticity and polarization major axis angle are discussed in this study. Ellipticity (ε) is defined as the ratio of the minor axis to the major axis of the ellipse of magnetic field perturbation in the plane

perpendicular to the background magnetic field. Ellipticity is represented in three ranges: $\varepsilon \ge 0.2$ RHP; $\varepsilon \le -0.2$ LHP; and $|\varepsilon| < 0.2$ LP as specified by Anderson et al. [1992]. Polarization major axis angle (θ , polarization angle in short) is the angle between the major axis of the polarization ellipse and the magnetic meridian in the north-south direction. Changes of the polarization properties of the waves during the propagation are shown in Figures 6 and 7, in which a polarization analysis technique as described by Fowler et al. [1967] and Rankin and Kurtz [1970] is used to display ellipticities and polarization angles in a plot of frequency versus time. The ellipticity as shown in Figure 6 is represented in a color scale with -1 being LH circular polarization (negative ellipticity) and +1 being RH circular polarization (positive ellipticity). LP is defined as having $|\varepsilon| < 0.2$ as mentioned earlier. Ellipticities are displayed only for frequencies which exceed a certain power threshold appropriate to the signal-to-noise ratio. Figure 7 shows the polarization angle change during the wave propagation. In this type of analysis, polarization angle ranges between -90° and +90°. The sign represents the direction of angle with



Figure 6. Polarization ellipticity (ε) of the ULF Pc 1 waves observed by the ground array from 0800 to 1300 UT on Mar. 23, 2007 in a plot of frequency versus time. The ellipticity is shown in a color scale with -1 being LH circular polarization (negative ellipticity) and +1 being RH circular polarization (positive ellipticity). LP is defined as having $|\varepsilon| < 0.2$. Note that the time intervals of Figures 3, 5, and 8 are indicated.

respect to the magnetic meridian in the north-south direction (X component in the magnetometer data) with positive angle being counterclockwise and negative angle being clockwise.

[25] The waves observed at lower latitudes are predominantly LHP while RHP signals are more dominant at higher latitudes. The intermediate stations such as P2 and SPA detect intermediate features, i.e., LP. This overall tendency of the wave polarization sense change from LHP to RHP during propagation appears to be in good agreement with many other observations [e.g., *Hayashi et al.*, 1981; *Inhester et al.*, 1984] and models [e.g., *Greifinger and Greifinger*, 1968; *Fujita and Tamao*, 1988]. To summarize, it is com-

monly suggested in the literature that this result implies that 1) LHP Alfvén waves, originating in low latitude regions, are transmitted into the ionosphere; 2) the waves propagate in the ionospheric waveguide; 3) the LHP waves, observed in the vicinity of the injection region, gradually change to RHP (with LP observed between LHP and RHP) as distance from the injection region increases.

[26] It should be noted, however, that there are other spectral components in which the polarization changes in a different way. For example, Figure 6 shows that the spectral signatures observed from 0820 to 0900 UT at HBA contain two dominant polarization senses - LP signals over the



Figure 7. Polarization angle (θ) of the ULF Pc 1 waves observed by the ground array from 0800 to 1300 UT on Mar. 23, 2007 in a plot of frequency versus time. The angle change ranges between -90° and $+90^{\circ}$. The sign represents the direction of the angle with respect to the magnetic meridian in the north-south direction (X component in the magnetometer data) with positive angle being counterclockwise and negative angle being clockwise. Note that the time intervals of Figures 3, 5, and 8 are indicated.

frequency range between 0.3 and 0.35 Hz ($\varepsilon = \sim -0.1$) and LHP between 0.35 and 0.5 Hz ($\varepsilon = \sim -0.25$ to -0.45). It is clearly shown that at AGO P1, the polarization sense appears to be opposite to those at HBA between the two frequency ranges (0.3 and 0.35 Hz; 0.35 and 0.5 Hz). This tendency is seen at other frequencies in other times.

[27] The complexity of the polarization patterns as seen in Figure 6 might be due to the horizontal inhomogeneity of the conductivity in the ionosphere. Waves with multiple frequency components from different injection regions can also affect the pattern. Superposition effects through refraction, reflection, and transmission in the waveguide can also be considered. A model study by *Belova et al.* [1997] showed how the polarization pattern on the ground can change in a complicated fashion as the inhomogeneity of the ionospheric conductivity varies. *Hayashi et al.* [1981] reported greater variation of polarization properties at high latitudes and suggested that the lack of uniformity in the polarization pattern appeared to be related to the fact that the array is located close to the wave injection region where the combination of incident waves and ducted waves is more dominant.



Figure 8

[28] Wave polarization is one of the properties that show the spatial characteristics of the wave propagation and media. EMIC waves are LHP and, within the extent of the incident wave into the ionosphere, the ground data also show LHP. It has also been suggested in theory and observations that the polarization of Pc 1 waves on the ground shows concentric patterns of polarization sense changing from LHP within the extent of the wave injection region to RHP outside the lateral extent of the injection region with LP shown in transition of the sense change [Greifinger, 1972; Hayashi et al., 1981; Fujita and Tamao, 1988]. Since incident waves are attenuated rapidly with distance [Hayashi et al., 1981] and mode conversion from the incident Alfvén mode waves to the ducted compressional mode waves occurs within the extent of the injection region [Fujita and Tamao, 1988], the ground signature of the ducted waves is dominant at larger horizontal distances compared to the extent of the injection region. Greifinger [1972] demonstrated that a ducted wave is nearly LP.

3.4. Spatial Extent of Wave Injection Region

[29] Figure 1 shows the southern hemisphere ground track of the magnetic field lines traversed by the CHAMP satellite from 0835 to 0845 UT on Mar. 23, 2007 at an altitude of approximately 350 km. The orbit was lined up well with the SPA-P2-HBA line during the event. Figure 8 shows the spectrograms of the three components $(b_{\parallel}, b_{\perp \theta}, \text{ and } b_{\perp \varphi})$ of the magnetic field data from the fluxgate magnetometer onboard the CHAMP satellite and the polarization ellipticities during the event in this study. The ground data from HBA (Y-component) is also shown in Figure 8 for comparison. Band-limited ULF waves over the frequency band (~0.4–0.5 Hz) are observed approximately from 0840 to 0843 UT, which have very similar spectral structures to the ULF Pc 1 waves measured on the ground array, suggesting a common localized source and ducting effect. Note that the event during the CHAMP overflight is indicated in Figure 2.

[30] The time of CHAMP observation corresponds to the ILAT between -53° and -61° at L = 2.9 - 4.4. CHAMP passed HBA approximately at 0839:30 UT, the time when rather higher frequency waves (~0.6–0.7 Hz) are observed. Although the signatures are detected in both the perpendicular meridional $(b_{\perp\theta})$ and azimuthal components $(b_{\perp\varphi})$, the signals in the azimuthal component $(b_{\perp\varphi})$ are more dominant. On the other hand, no compressional power (the parallel component, b_{\parallel}) is detected, which indicates the waves are transverse.

[31] The sudden disappearance of the broadband structure from the CHAMP data at 0839 UT (L = 5.6) is a clear indication that CHAMP passed from the plasmatrough region to the plasmasphere. The transition from broadband to narrowband signature is typically observed by CHAMP when it enters the plasmasphere. This is confirmed by using a model developed by *O'Brien and Moldwin* [2003] to estimate the plasmapause location at L = 5.8 during this event, which is close to what was seen from the CHAMP observation.

[32] *Fujita and Tamao* [1988] concluded that the Alfvén wave is dominant near the wave injection region and Hall current associated with the Alfvén wave generates the ground magnetic field variations. Observations using low altitude DE-2 satellite data by *Iyemori et al.* [1994] showed wave injection was confined in latitude (<100 km) and longitude and concluded that a localized region of electron temperature enhancement is caused by the direct acceleration of thermal electrons by the Alfvén ion cyclotron waves.

[33] The ground observations by *Havashi et al.* [1981] estimated the size of the injection region to be in the range 100-300 km in radius. Fraser et al. [1989] determined the injection region of structured Pc 1 at L = 4.9 just inside the plasmapause using satellite-ground observations, which is consistent with the observation results in this study. The satellite observations in the topside ionosphere by Freja [Mursula et al., 1994] showed Pc 1 activity measured in a small latitude range (60° to 63° MLAT) but a wide longitude range (03-14 MLT). The latitudinal extent of Pc 1-2 waves was found to be 0.3° to 1° in ILAT using ST5 satellite data [Engebretson et al., 2008]. Satellite observations at high altitude by the Polar satellite showed that the EMIC wave source region at high altitudes can extend over a very large latitude range of more than 5° in ILAT although the source region of coherent EMIC waves with a constant frequency is much more limited in latitude [Mursula et al., 2001]. Engebretson et al. [2008] stated that the latitudinal localization in the magnetosphere might be attributed to the fact that EMIC waves trapped within a magnetospheric waveguide are guided along narrowly defined density gradients.

[34] Time-series plots of the two perpendicular components, meridional $(b_{\perp\theta})$ and azimuthal $(b_{\perp\varphi})$ perturbations from the CHAMP magnetic field data, and the three components, B_x , B_y , and B_z , of the search coil magnetometer at HBA, during the Pc 1 event from 0840 to 0844 UT are shown in Figure 9. Both satellite and ground data are bandpass filtered over 0.3 to 0.5 Hz so the ULF pulsations are shown more clearly. It appears that the time-series data from CHAMP in Figure 9 also display a pearl structure, which is a good comparison with the ground data. The average peakto-peak amplitudes of the total wave activity between 0841:20 and 0842:00 UT, when the most distinct signals were detected simultaneously, are estimated at the center frequency of 0.4 Hz over the pass-band of the filter (0.3 to 0.5 Hz). CHAMP measured $b_{\perp\theta} = 0.2 \text{ nT}$ and $b_{\perp\varphi} = 0.4 \text{ nT}$ ($b_{\parallel} \approx 0 \text{ nT}$), which leads to 0.45 nT in total (= $\sqrt{b_{\perp\theta}^2 + b_{\perp\varphi}^2}$), while a total of 0.08 nT in the wave activity $(=\sqrt{B_x^2 + B_y^2 + B_z^2})$ was observed from HBA. The ratio of the peak-to-peak wave amplitude at CHAMP to that at HBA is thus approximately 6. It should be noted that the ground search-coil magnetometer measures dB/dt, so the search-coil

Figure 8. Stacked spectrograms of the Y-component of the HBA search-coil data, the three components $(b_{\parallel}, b_{\perp\theta}, \text{ and } b_{\perp\varphi})$ of the magnetic field data and the polarization ellipticities (in three ranges: LP, LHP, and RHP) from the fluxgate magnetometer of the CHAMP satellite during the event in this study. Band-limited ULF waves over the frequency band (~0.4–0.5 Hz) are observed approximately from 0840 to 0843 UT on Mar. 23, 2007. The satellite crossings over SPA, P2, and HBA are shown with the arrows. Note that the event during this period is indicated in Figure 2.



Figure 9. Time-series plot of the two perpendicular components, meridional $(b_{\perp\theta})$ and azimuthal $(b_{\perp\varphi})$ perturbations from the CHAMP satellite magnetic field data (first and second panels, respectively) and the three components, B_x , B_y , and B_z , of the search coil magnetometer at Halley Station, Antarctica (third, fourth, and fifth panels, respectively) during the Pc 1 wave event from 0840 to 0844 UT on Mar. 23, 2007.

data are first converted to corresponding amplitudes of *B*. To be more specific, one can assume that a fluxgate magnetometer measures $B = B_0 \sin \omega t$ while a search-coil magnetometer measures $dB/dt = \omega B_0 \cos \omega t$. Therefore, the amplitude measured by the search-coil instrument is divided by ω to obtain B_0 .

[35] *Iyemori and Hayashi* [1989] showed that the amplitude of the Pc 1 on the ground was more than 2 orders of magnitude smaller than that observed by Magsat. *Engebretson et al.* [2008] found, similarly, that the amplitudes of the Pc 1 waves from the ST5 satellite observations (\sim 5–100 nT) were from 1–2 orders of magnitude larger than corresponding amplitudes observed on the ground. They pointed out that large variations in the ratio of satellite to ground amplitude may be caused by 1) variations in the spatial extent of the wave source region; 2) wave absorption and/or partial reflection by heavy ions in the magnetosphere or 3) ionospheric ducting effect of waves originating in a distant source region.

[36] Polarization analysis of the CHAMP data as shown in Figure 8 indicates that the wave events are nearly LP. The wave is transverse as mentioned earlier, which is one of the characteristics of the incident wave near the wave injection region. Engebretson et al. [2008] also reported transverse Pc 1 wave activity from the ST5 satellite observation. However, whether the signal is Alfvénic cannot be determined since CHAMP has no E-field measurement. Satellite observations in the ionosphere using Magsat [Iyemori and Hayashi, 1989] and ST5 [Engebretson et al., 2008] showed reversals between RHP and LHP and between elliptical and LP. *Ivemori and Hayashi* [1989] attributed the reversal to the coupling of the transverse and fast mode waves in the ionosphere. In theory, magnetoacoustic waves carrying the energy of Pc 1 in the ionospheric duct are LP whereas the observations have shown the waves are elliptically polarized. Baranskiy [1970] suggested the discrepancy might be due to superposition of polarized waves and thus observed signals tend to be elliptic in general and bandlimited waves will show smaller ellipticity (close to LP).

[37] Given certain assumptions, the polarization ellipse observed on the ground becomes increasingly LP with the major axis pointing toward (or away from) the wave injection region as Pc 1 emissions propagate away from the injection region in the ionospheric waveguide [Greifinger, 1972; Summers and Fraser, 1972; Fraser and Summers, 1972; Fujita and Tamao, 1988]. In addition, Fujita and Tamao [1988] predicted that near the injection center the major axis of polarization is perpendicular to the radial direction from the injection region. In the surrounding region, however, the major axis points to the center. Although the polarization angle change shown in Figure 7 appears to be somewhat irregular, it shows a general tendency that the angle changes consistently at a certain time period and a certain frequency range during the propagation. This might imply that the waves were injected near HBA, perhaps near the CHAMP trace between 0840 and 0843 UT (between L = 2.5 and 4.4), and propagated in a poleward direction in the waveguide since strongest spectral power was seen at HBA as mentioned earlier and the higher polarization angles (nearly perpendicular to the magnetic meridian) were observed at HBA as suggested by Fujita and *Tamao* [1988]. For example, the polarization angle during the CHAMP overflight is ~+75° at HBA over the frequency range and becomes less at higher latitudes (particularly at AGO P1) as shown in Figure 7. However, it is not clearly known whether the LP waves observed from CHAMP were due to either that the incident Pc 1 waves were originally in the LP mode as they propagate toward the ionosphere [*Horne and Thorne*, 1994; *Hu and Denton*, 2009] or that CHAMP also detected ducting effect of the Pc 1 waves at lower latitudes.

[38] Although it is quite challenging to determine the extent of the injection region with the meridional configuration of the array, the plasmapause location estimation at L = 5.8 in association with the CHAMP observation as discussed earlier supports the idea of the wave injection near or poleward of HBA since possible regions of EMIC wave generation and propagation are near or higher L-shells of the plasmapause locations (possibly including detached plasma regions) [e.g., Fraser and Nguyen, 2001; Fraser et al., 2005]. Even though the wave injection occurred poleward of HBA, the poleward wave attenuation from HBA to AGO P5 with the signals at HBA being strongest still explains the idea as long as the injection was not far beyond the location of HBA because HBA is located off the meridional line of P2-SPA-P1-P5 and therefore, the wave power attenuates more quickly between HBA and P2 than between the other stations as shown in Figure 4.

4. Summary

[39] Well-defined ULF Pc 1 pulsations were observed from the Antarctic magnetometer array and the CHAMP satellite, providing a very systematic coverage from the satellite orbit at lower latitude to the ground at higher latitudes. The observation is unique in that they were acquired at stations distributed over an unprecedented range in geomagnetic latitude (-62° to -87°, spanning ~2920 km geographically), while positioned approximately along a magnetic meridian and that Antarctica is the only place where such a configuration is possible. The array deployed in the Antarctic terrain also has very significant advantage of minimal geoelectric inhomogeneity. As described by Fraser [1975b], polarization observed on the ground may not reflect the true wave properties due to the inhomogeneous ground conductivity. In addition, clearly distinguishable ionospheric sunlight conditions in Antarctica can provide more systematic change of polarization pattern on the ground.

[40] The extent of the ducting is substantial. The spaced magnetometer array with the latitudinally extensive range along a magnetic meridian revealed very efficient wave propagation in the ionospheric waveguide (~8–20 dB/1000 km), which has rarely been reported before. Propagation speed (~89 km/s), and polarization sense and angle change during the propagation were also shown. LHP was dominant at lower latitude and changed to RHP (or LP) at higher latitudes during propagation. These features clearly suggest poleward wave propagation in the ionospheric waveguide.

[41] The Pc 1 pulsations measured by the CHAMP satellite appear to be transverse and nearly LP, which might imply that the wave activity was observed in the wave injection region in the ionosphere. The injection region is also found to have a limited latitudinal extent (-53° to -61° ILAT). The polarization angle pattern change observed from the ground array (e.g., \sim +75° at HBA, being less at higher latitudes) during the CHAMP overflight and the plasmapause location estimation using a model and the CHAMP observations of the wave activity might imply that the waves were injected near HBA, perhaps near the CHAMP trace (between L = 2.5 and 4.4), and propagated in a poleward direction in the waveguide. However, a complex polarization pattern (i.e., change in ellipticity and polarization angle) was found on the ground during propagation, which might be attributed to the array being close to the wave injection region where the superposed effect of incident waves and ducted waves is dominant.

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