

Two-dimensional structure of long-period pulsations at polar latitudes in Antarctica

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[1] Two-dimensional (2-D) statistical distributions of spectral power and coherence of polar geomagnetic variations with quasi-periods about 10 min are analyzed using data from magnetometer arrays in Antarctica. Examination of the 2-D patterns of spectral power and coherence shows the occurrence of significant variations in geomagnetic power levels but with low spatial coherence near the cusp projection and in the auroral region. At the same time, low-amplitude pulsations, which we coin $Pi_{cap}3$ pulsations, are very coherent throughout the polar cap. The region occupied by coherent $Pi_{cap}3$ pulsations is shifted toward local MLT night from the geomagnetic pole and is decoupled from the regions of auroral and cusp ULF activity. The spectral power varies with time at polar latitudes in a manner different from that at auroral latitudes. Diurnal variations of power at different stations at the same geomagnetic latitude exhibit different behavior depending on the station's position relative to geomagnetic and geographic poles. This asymmetry is shown to be partly attributed to the variations of the ionospheric conductance. The primary source of polar pulsations is probably related to intermittent magnetosheath turbulence and tail lobe oscillations, though a particular propagation mechanism has not as yet been identified.

INDEX TERMS: 2776 Magnetospheric Physics: Polar cap phenomena; 2752 Magnetospheric Physics: MHD waves and instabilities; 2744 Magnetospheric Physics: Magnetotail; 2724 Magnetospheric Physics: Magnetopause, cusp, and boundary layers; **KEYWORDS:** ULF waves, polar cap, cusp, magnetotail

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1. Introduction

[2] The presence of flow turbulence in the magnetospheric boundary regions has a profound effect on the large-scale electrodynamic of the near-Earth environment. Geomagnetic disturbances/waves from the boundary regions and magnetotail can be transported along stretched field lines into the polar ionosphere. Variations of the plasma properties of boundary regions and the magnetotail can be monitored with ground-based magnetic observations at polar latitudes in Antarctica and the Arctic. Because of the difficulties in operating permanent bases in these regions, long-term observations are rather rare. The paucity of ULF studies

prior to recent years at very high geomagnetic latitudes was partly due to a dominating view that the polar cap region is a relatively quiet area and thus ULF variations in this region would merely be a combination of residual cusp and auroral activity.

[3] However, even early researchers noticed the occurrence of geomagnetic disturbances at high latitudes, above the auroral oval [Davies, 1935; Stagg, 1935], and studied their diurnal, seasonal and spatial distributions. *Nikolski* [1951] and, later, *Whitham et al.* [1960] and *Bobrov et al.* [1964] used the length of a curve on hourly paper chart magnetograms as an index for the estimation of the level of geomagnetic activity. The disturbances described by this index corresponded to the long-period edge of the ULF band (Pc5 and lower).

[4] Although the structure of the magnetosphere and the physical nature of geomagnetic ULF variations were unknown at this time, some of these early results were later reproduced after the language for the description of the morphological and physical properties of geomagnetic pulsations had been created. Using data from ice-drifting Arctic geomagnetic stations, *Nikolski* [1958, 1963] found a complicated pattern of amplitude variation of irregular disturbances in the region between the geomagnetic and geographic poles. Comparison of data from high latitude Canadian stations at high geomagnetic latitudes ($\Phi \geq 80^\circ$),

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poleward of the auroral oval, but at different longitudes by *Whitham et al.* [1960] revealed the strong azimuthal asymmetry of the zone of additional enhancement of daytime irregular activity.

[5] The main results of the early studies of geomagnetic activity at high latitudes may be summarized as follows: (1) two maxima existed in the diurnal variation of polar geomagnetic disturbances with different seasonal and spatial distributions and associated with different sources, and (2) the first one (a nighttime maximum) at all stations was located near local magnetic midnight, whereas the occurrence time of the second maximum shifted from the local morning at auroral latitudes to the noon MLT sector at the highest latitudes ($\Phi \geq 80^\circ$). The ground level of activity at polar latitudes under very quiet geomagnetic conditions was revealed by *Bobrov et al.* [1964]: the amplitude of the dayside maximum was ≥ 50 nT, whereas the amplitude of polar disturbances varied in a similar way at all stations with $|\Phi| > 77^\circ$. More recently, *Detrick and Lanzerotti* [2001], using magnetometer data from the P5 and P6 automatic geomagnetic observatories, studied the quiet time Sq variations in the polar cap, only a few degrees on either side of the geomagnetic dipole pole, and found that the Sq variations at these two sites were considerably larger than expected from Sq models.

[6] An important aspect of polar studies was the search for an extension of auroral/substorm activity to higher latitudes, deep into the polar cap. *Bolshakova and Khorosheva* [1973] found broadband pulsations at geomagnetic latitudes $|\Phi| \geq 75^\circ$, related to strong auroral activity. *Heacock and Chao* [1980] compared broadband activity in the 5–25 mHz frequency range at a station deep in the polar cap ($\sim 86^\circ$) and a cusp station ($\sim 76^\circ$), and found that together with the substorm related activity there was residual irregular activity at polar cap latitudes that was not correlated with K_p . Polar cap activity preceding a substorm onset by several hours was found at the polar cap station with no effect at lower latitudes. One of the effects of substorm expansion into the polar cap, simultaneous periodic variations in magnetic field and particle precipitation with frequency ~ 2 mHz, was reported by *Weatherwax et al.* [1997].

[7] The occurrence of a near-noon maximum of pulsation power at $\Phi \sim 80^\circ$ stimulated interest in the possibility of finding a signature of the cusp in ground-based pulsation data, so the majority of publications on ULF variations at very high latitudes has been focused on the search for cusp-specific ULF activity. It should be mentioned that here the cusp is to be understood in a wider sense, as dayside boundary regions, because some ULF events in this region were shown to be associated actually to the convection reversal boundary [*Clauer et al.*, 1997] or LLBL [*Pilipenko et al.*, 2003]. *Olson* [1986] showed that the diurnal variation of the spectral power at a cusp latitude station ($\Phi \simeq 74^\circ$) in all frequency bands from Pc5 band to 1 Hz had maxima at nighttime and prenoon. *Ballatore et al.* [1998] found a daytime power increase in local summer of the power distribution in the Pc5 range at four Antarctic stations in a longitudinal profile along $\sim 80^\circ$ MLAT.

[8] However, the analysis of network observations at high latitudes by *Engebretson et al.* [1995] showed that temporal

variations dominated at high dayside latitudes rather than the spatially localized variations traditionally associated with cusp position. This analysis was extended by including data of different seasons and stations in two hemispheres by *Posch et al.* [1999]. Thus inspection of magnetograms or dynamic spectra have not revealed any evident spatial features of long-period pulsations at stations passing beneath the nominal cusp projection.

[9] In some studies, on the contrary, narrow-band Pc5 emissions were considered as an image of the polar boundary of the cusp, in particular the separatrix between open and closed field lines. These pulsations were inferred to be produced by resonances on the outermost closed field lines. *Rostoker et al.* [1972] found that, averaged over quiet days, the position of the dayside maximum of the total Pc5 power approximately lies on the separatrix between open and closed field lines. *McHarg and Olson* [1992] found that the ionospheric projection of the dayside boundary layers was characterized by the combination of broad-band unpolarized noise with the narrow band polarized signal. The typical polar cusp signal was polarized and narrowband (3–5 mHz), and had arch-type dynamic spectra with maximal frequency at noon. *McHarg et al.* [1995], by the comparison of ULF spectral features with optical data, demonstrated convincingly that the maximal frequency of narrow band signal corresponded to the projection of the dayside cusp. *Lanzerotti et al.* [1999] also found band-limited (~ 5 mHz) local day time pulsations at latitudes 70° – 75° with typical arch forms in dynamic spectra, that were well conjugated between hemispheres, and not observed at higher latitudes ($\geq 80^\circ$). Comparison of their ground-based band-limited pulsations with simultaneous overflights of the Akebono spacecraft, whose instrumentation could delineate the magnetopause location, confirmed that the band-limited pulsations occurred close to the magnetosphere boundary. It seems that only the application of advanced statistical polarization techniques may help to reveal some spatial ULF features related to a possible cusp projection [*Szuberla et al.*, 2000].

[10] Thus, although earlier observations indicated the occurrence of long-period disturbances in the polar caps, it is still unclear whether there is a specific polar cap activity or these pulsations are caused by the expansion to the polar caps of disturbances from the cusp and the auroral oval. The study of ULF disturbances at very high latitudes in the nighttime sector in our earlier work [*Yagova et al.*, 2002], using data from a meridional chain of Antarctic stations that extended into the polar cap, indicated the occurrence of pulsations specific to the polar cap. These quasiperiodic short-lived irregular variations have typical periods of about 4–20 min. Because of their frequency range and waveforms they would be classified as Pi3 according to the ULF nomenclature. To distinguish them from the known type of nighttime Pi3 pulsations related to substorm activity [*Saito*, 1978], we will hereafter name them as $Pi_{cap}3$ pulsations. In the nighttime hours, $Pi_{cap}3$ pulsations at $|\Phi| \geq 80^\circ$ were found by *Yagova et al.* [2002] to be coherent, whereas coherence between the cap and auroral stations was lacking. This indicated that the cap pulsations were decoupled from the auroral activity in the same MLT sector.

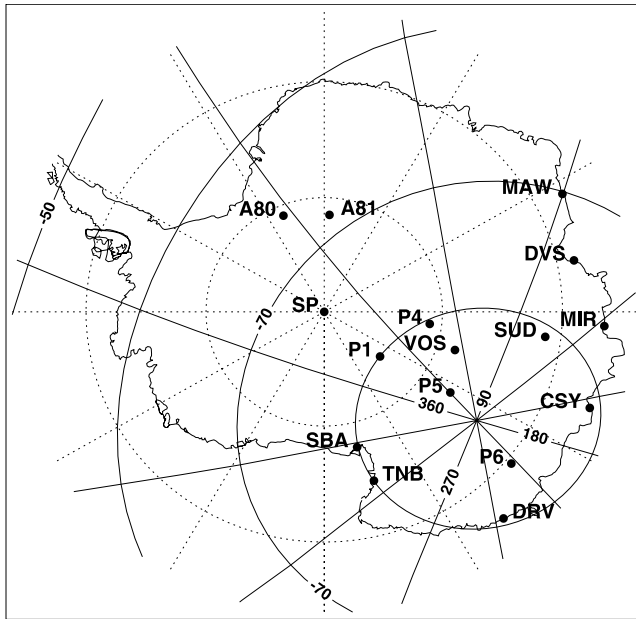


Figure 1. A map illustrating the position of the Antarctic fluxgate magnetometers. Both geographic (dashed lines) and geomagnetic (solid lines) coordinates are indicated.

[11] However, the interpretation of ULF disturbances at high latitudes as specific polar cap pulsations on the basis of observations only along a meridional chain has some ambiguity. The motivation of the present work therefore is to determine a method to identify specific polar cap pulsations by analyzing a 2-D distribution of spectral power and cross-spectral parameters. For this study data from the 2-D array of Antarctic stations located in all MLT sectors at Φ from $\sim -87^\circ$ to $\sim -70^\circ$ are used.

2. Observational Facilities

[12] For the data analysis we have compiled a comprehensive database of magnetic data from an array of 16 available magnetic stations in Antarctica (the map is shown in Figure 1). This array comprises the United States

AGO P1 and P4–P6 stations, South Pole station, British Antarctic Survey (BAS) stations A80–A81, Russian bases Vostok, Mirny and Sude, the Italian station Terra Nova Bay, Australian stations Davis, Casey and Mawson, the New Zealand station Scott Base, and the French observatory Dumont D’Urville. The geographic and corrected geomagnetic coordinates of the stations, universal time of solar (LT) and magnetic (MLT) local midnights, difference between magnetic and solar local times, station codes, sampling periods, and sensor orientation (G for geographic and M for geomagnetic coordinates) are given in Table 1. All the stations are equipped with fluxgate magnetometers with flat frequency response in the band 0–1.0 Hz.

[13] The stations can be classified into 4 latitudinal groups: polar ($|\Phi| > 80^\circ$): P5, VOS, P6; longitudinal profile along geomagnetic latitude $\sim 80^\circ$: P1, P4, SUD, CSY, DRV, TNB, SBA; polar auroral ($|\Phi| \simeq 74^\circ - 77^\circ$): MIR, SP, DVS; and auroral ($|\Phi| \simeq 70^\circ$): A80, A81, MAW. The longitudinal profile along $\sim 80^\circ$ covers all MLT sectors. The polar stations, P5, VOS and P6 are located in nearly opposite MLT sectors. The lower latitude stations cover about one quarter with MLT midnight between 20 and 04 UT.

[14] All the data (with exception of TNB and A80) have been analyzed for the period with best data coverage, February 1998. The results of the analysis are verified on the data of the same month in 1997. The stations available during February 1997 are almost the same as in February 1998, but with A80 substituted for A81 and TNB included.

[15] Data gaps and spikes were automatically excluded, then the data have been low-pass filtered ($f < 8.3$ mHz), decimated to a common 1 min sampling period and rotated into geomagnetic north-south (H) and east-west (D) components using the IGRF-DGRF model.

3. Data Processing Methods

[16] The results of our previous study [Yagova et al., 2002] were based on a standard spectral analysis of a one-dimensional (1-D) observational profile. Analysis of 2-D patterns of multistation, multicomponent observations

Table 1. Antarctic Stations

Station Name	IAGA Code	Geodetic		CGM		LT Midnight	MLT Midnight	MLT-LT	Sensors
		Latitude	Longitude	Latitude	Longitude				
AGO P5	P5	-77.24	123.52	-86.7	029.5	15:45	02:47	12:58	1s, M
Vostok	VOS	-78.46	106.82	-83.3	054.4	16:53	01:01	15:52	10s, M
AGO P6	P6	-69.51	130.03	-84.9	215.4	15:20	14:29	00:51	1s, M
AGO P1	P1	-83.86	129.61	-80.1	016.9	15:22	03:43	-12:21	1s, M
AGO P4	P4	-82.02	096.76	-80.0	041.6	17:33	01:57	-08:24	1s, M
Sude	SUD	-71.30	096.30	-80.8	107.1	17:35	21:28	-03:53	10s, M
Casey	CSY	-66.17	110.32	-80.7	155.2	16:39	18:31	-01:52	1m, G
Dumont D’urville	DRV	-66.66	140.01	-80.6	235.8	14:40	12:55	01:45	1m, G
Terra Nova Bay	TNB	-74.69	164.12	-80.0	307.7	13:04	08:08	04:56	1m, M
Scott Base	SBA	-77.85	166.78	-79.9	327.5	12:53	06:57	05:56	1m, M
Mirny	MIR	-66.55	093.02	-77.2	122.2	17:48	20:34	-02:46	10s, M
South Pole	SP	-90.00	0.0	-74.0	018.3	-	03:35	-	1s, M
Davis	DVS	-68.58	077.97	-74.6	100.1	18:48	21:30	-02:42	1m, G
BAS A80	A80	-80.90	337.70	-66.3	028.1	01:29	02:49	-01:20	1s, M
BAS A81	A81	-81.50	003.00	-68.6	036.5	23:48	02:18	-02:30	1s, M
Mawson	MAW	-67.60	062.90	-70.2	089.8	19:48	22:42	-02:54	1m, G

demands the application of a more specialized and advanced technique, as is described below. The first step in showing the existence of specific polar cap-related wave activity is the identification of a boundary of these pulsations. If this boundary does exist, $Pi_{cap}3$ pulsations then can be identified, isolated, and examined both statistically, as well as through case studies.

3.1. Spectral Power Estimates

[17] Spectral power has been estimated using the Blackman-Tukey method with a Kaiser-Bessel tapering window. For calculation of diurnal variations of ULF wave parameters the moving time window was selected to be 60 min, with a time shift between windows of 30 min.

[18] We analyze the spectral and cross-spectral parameters averaged over the spectral band 1–1.5 mHz. The ULF pulsation intensity will be characterized by the total horizontal spectral power, $T_f^2 = H_f^2 + D_f^2$. No preliminary discrimination of narrow-band and wide-band signals has been made, assuming that polar pulsations are dominated by short-lived and broad-band signals. The only selection criterion for the time intervals is the existence of valid data at all stations.

3.2. Two-Dimensional Distribution of Spectral Coherence of Vector Time Series

[19] The spatial scale of the signal, i.e., $Pi_{cap}3$ pulsations, can be estimated from an analysis of the spatial distribution of spectral coherence between the corresponding horizontal components of the geomagnetic field. However, the orientation of polarization ellipses of the pulsations under study at different locations may vary. In particular, at Antarctic stations more widely separated, a better correspondence may be observed between the orthogonal horizontal components, namely H and D, than between the same components [Lepidi et al., 1996]. Therefore it is necessary to apply a coherence analysis to vector data.

[20] The cross-spectral matrix for \hat{C} two vector time series $\mathbf{b} = (b_1, b_2)$ and $\mathbf{q} = (q_1, q_2)$ is derived via their Fourier transforms as

$$C_{ik}(\omega) = B_i(\omega)Q_k^*(\omega)$$

where i, k refer to the horizontal components of the geomagnetic field. The cross-spectral matrix [Born and Wolf, 1998] can be presented as a sum of two matrixes: a diagonal matrix with equal diagonal elements (non-coherent part) and a zero-determinant matrix with complex conjugate non-diagonal elements (coherent part). The scalar degree of coherence is introduced as the ratio of the intensity of the coherent part to the total intensity as follows

$$\gamma^2 = 1 - \frac{4|\hat{C}|}{[\text{Tr}(\hat{C})]^2}$$

where $|\hat{C}|$ is the determinant and $\text{Tr}(\hat{C})$ is the trace of the cross-spectral matrix. The scalar coherence γ introduced this way is invariant to the choice of axes. Totally coherent vector time series are characterized by a constant amplitude ratio and phase difference, while non-coherent vector time

series correspond to random phase differences for all the component pairs.

[21] The values of γ were calculated for all the station pairs and are presented below as graphs with all the stations connected by lines. The numerical values of γ are indicated by the line widths between the station pairs.

3.3. Regression Technique for Distinguishing Pulsation Sources

[22] Groups of stations with high average coherence correspond to regions with signals of similar spectral content and stable phase difference. Such signals are very likely to be generated by the same source. However, the condition of high spectral coherence is too strong for the problem of discrimination of independent pulsation sources. Signals at two points, (1) and (2), may have a common source, but be strongly modified upon propagation to the observation sites. In this situation, one might expect highly-correlated time variations of spectral power, $T_f^{(1)}(t)$ and $T_f^{(2)}(t)$, but low peak-to-peak correspondence between signals at different observation sites. The extreme (zero or unity) values of correlation coefficient R between $T_f^{(1)}(t)$ and $T_f^{(2)}(t)$ show the statistical independence or identity of the signals, correspondingly. If signals from at least two sources coexist at two stations with different contributions of each source, intermediate values of R will be obtained.

[23] Therefore the power variation $T_f(t)$ at any station can be expanded with a linear regression procedure into two fractions: the fraction of $T_f(t)$ proportional to that at a reference station and the fraction statistically independent of it. During the analysis of power variation across a network of stations, the stations with mutually correlated $T_f(t)$ that are decoupled from those at other stations of the network may be associated with an independent source of regional spatial scale. A fraction, $\tilde{T}(t)$, of the raw time series, $T_0(t)$, “rectified” from the influence of variable $V(t)$ is given as $\tilde{T}(t) = T_0(t) - \hat{R}V(t)$, where \hat{R} is the matrix of regression coefficients. Selecting reference stations, most closely corresponding to the expected sources, it is possible with this regression technique to decompose the power variation at each station of the array into fractions corresponding to these sources and local “noise.”

[24] This technique is applied below to the Antarctic stations listed in Table 1. At the first stage the power variations, $T_f(t)$, are expanded into 2 fractions: that proportional to the power in the auroral region, and the auroral-independent power. Then this procedure is repeated for dayside and nightside polar regions. To exclude the influence of systematic diurnal variations $T_f(t)$ is calculated in relatively narrow UT intervals.

4. Results of Analysis of Data From the Antarctic Array

[25] An example of long-period pulsations in the polar cap is given in Figure 2. This detrended magnetogram of H component data recorded on 16 February 1998 on the trans-Antarctic meridional profile of magnetometers shows quasi-periodic variations with typical periods about 20 min, at about 04–06 UT, deep in the polar cap, at stations P5 and P6. These variations are evidently not related to the night-

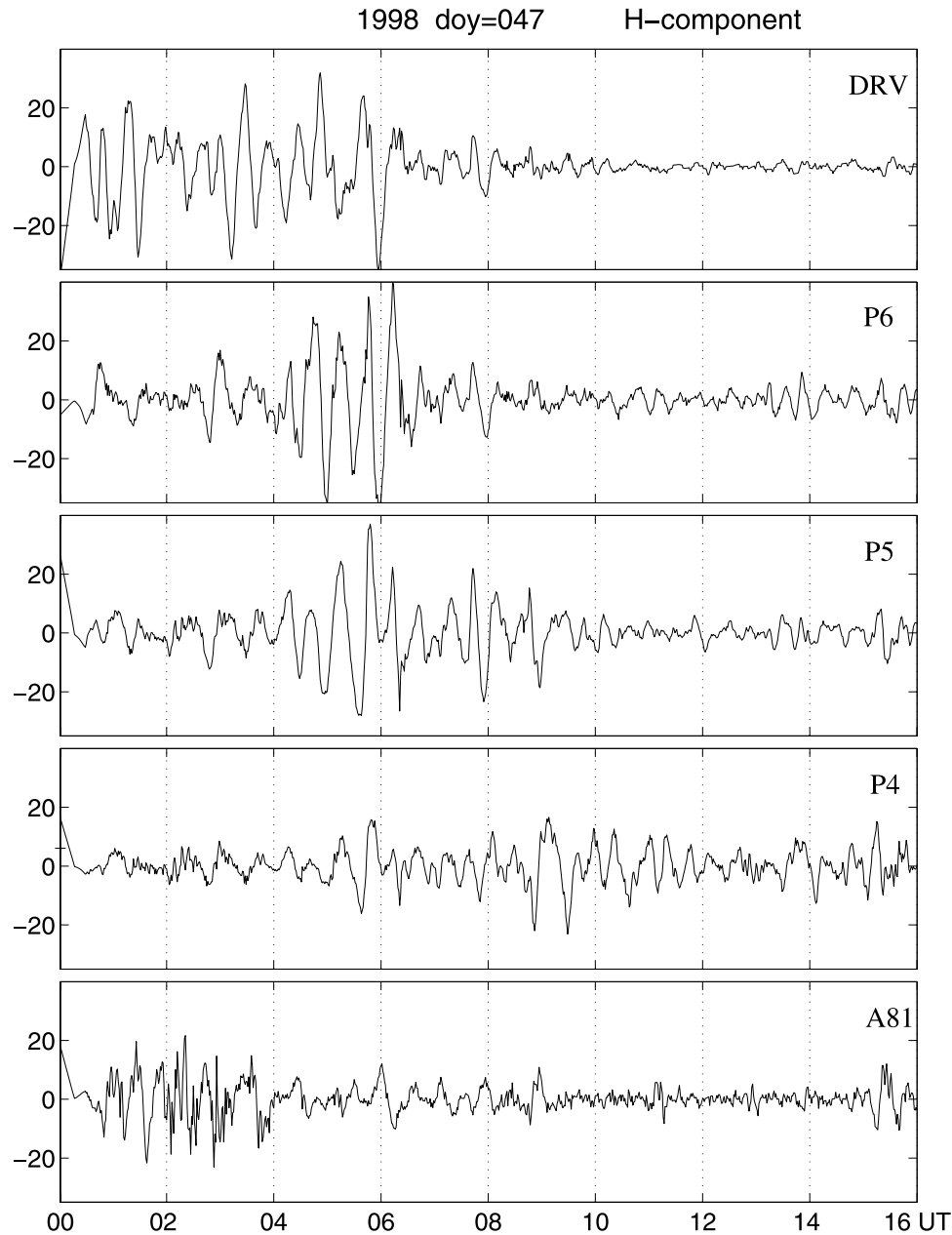


Figure 2. An example of Pi_{cap3} pulsations (high-pass filtered above 0.7 mHz) observed on 16 February 1998 (DOY = 047) along the trans-Antarctic profile of magnetometers.

side auroral ULF activity (station A81) or to dayside ULF disturbances (station DRV).

4.1. Two-Dimensional Distribution of Wave Power and Coherence

[26] Two-dimensional patterns of the ULF spatial structure are shown on plots combining information about both wave power and interstation coherence, using the technique described in Section 3. For all stations the total horizontal spectral power, T_f^2 , and the invariant coherence, γ , for all station pairs have been calculated in the 1.0–1.5 mHz frequency band. The values averaged over February 1998 are shown in Figure 3 for four time intervals: 0–6, 6–12, 12–18, and 18–24 UT. Pulsation power is denoted by open circles with radii $\propto \log_{10} T_f^2$, and interstation coherence

(if $\gamma \geq 0.5$) is shown by the connecting lines with two grades in thickness.

[27] The largest radii of circles are found around noon and at auroral latitudes around local midnight. This is evidence that the dayside cusp and nighttime substorm activity are the most intense sources of long-period disturbances at polar latitudes.

[28] There is an evident dependence of γ on the interstation distance. However, the coherence between stations with similar separations has been found to depend on the individual station's location and LT. The interstation coherence “net” shows clearly that the ULF activity at polar cap stations (with center at P5) is decoupled from that at the auroral stations (A81 and MAW). The region of coherent long-period pulsations at high latitudes is shifted from the

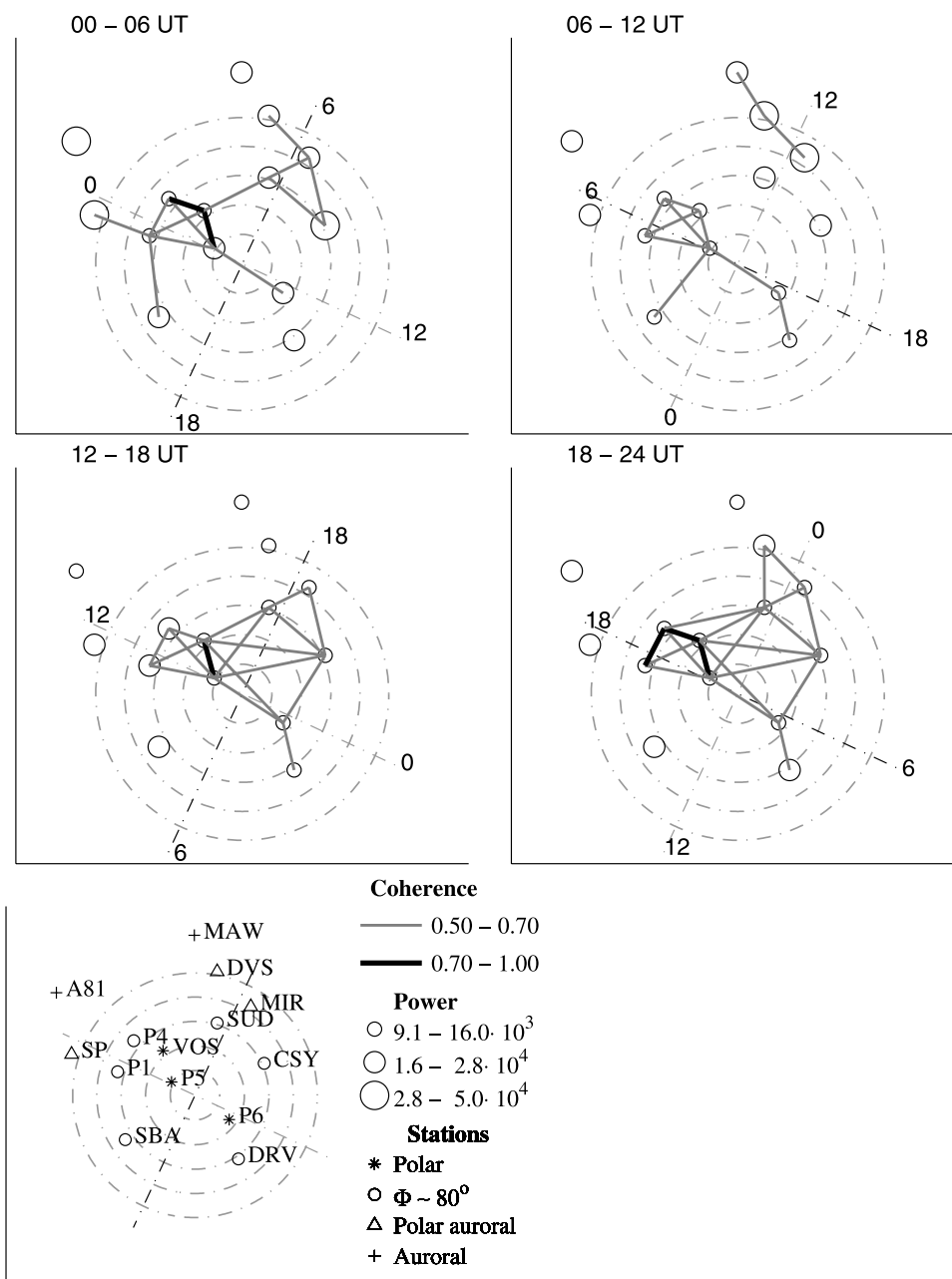


Figure 3. The February 1998 month-averaged T_f^2 in the 1–1.5 mHz frequency band for all stations and interstation coherence γ for four time intervals: 0–6, 6–12, 12–18, and 18–24 UT. Pulsation power (nT^2/Hz) is shown by circles with radii $\propto \log_{10} T_f^2$, and γ (when above 0.5) is shown by the connecting lines with two gradations in thickness.

geomagnetic pole to the MLT night side. A minimum of γ is found between the polar-most stations and those located near local noon at $\Phi \simeq 80^\circ$, where the maximum of power occurs (this is best seen in the 12–18 UT sector when the station distribution is optimum to show this feature). Therefore, despite the high intensity of ULF variations at the dayside near-cusp stations, the coherence between them and pulsations inside the polar cap is low. We assume that the region of high coherence at the polar-most stations corresponds to specific polar cap pulsations. In the next paragraph the properties of the polar cap-associated pulsations are studied and compared with pulsations in the adjacent regions.

[29] The above analysis has been repeated for the same season (February) in 1997 to minimize the influence of seasonal variation. The 2-D graph of spectral coherence and power is shown in Figure 4. The general pattern of the coherent spot position is similar to the one obtained for 1998, although the numerical values of γ and T_f are somewhat higher in 1997 than in 1998.

[30] To demonstrate more clearly the main features of the pulsation distribution, we have selected from the 2-D array of stations a trans-Antarctic 1-D latitudinal profile A81-SP-P1-P5-P6-DRV. The month-averaged (February 1998) values of spectral power and coherence along this

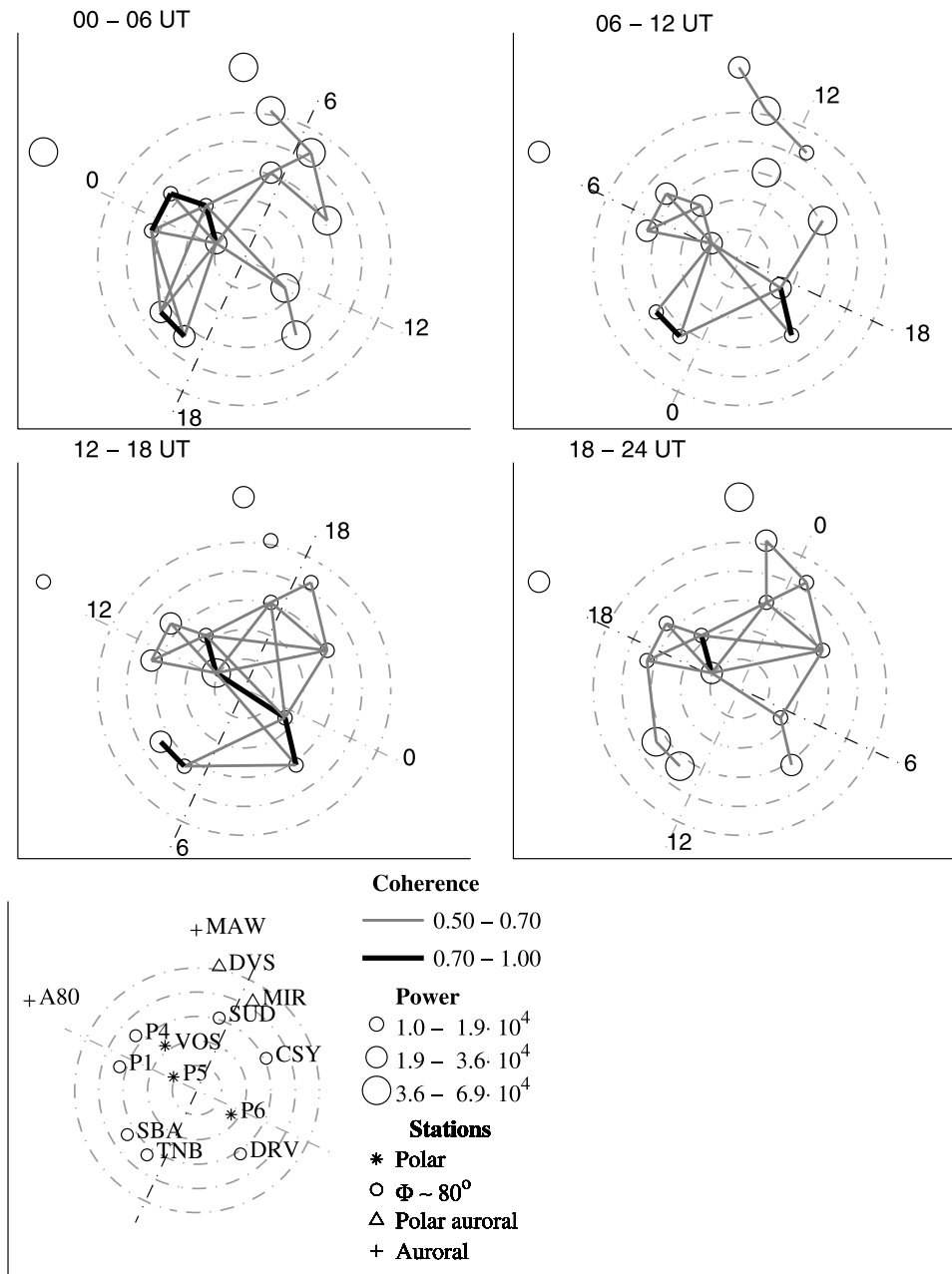


Figure 4. The February 1997 month averaged T_f^2 for all Antarctic stations and interstation coherence γ for four UT intervals: 0–6, 6–12, 12–18, and 18–24 UT, shown in the same format as in Figure 3.

quasi-meridional cross section of the Antarctic array are shown in Figure 5. Two UT intervals when the profile is directed along the noon-midnight meridian are taken.

[31] DRV and P6 are in the noon sector and P5-P1-SP-A81 are in the night sector during the 00–04 UT interval. This UT interval is characterized by amplitude maxima in the nightside auroral zone (A81, SP) and on the dayside at 80° (DRV). However, the spectral coherence between nearby stations in these regions is low ($\gamma < 0.5$); higher values ($\gamma \sim 0.65$) are found deep in the polar cap, between the P5–P1 pair on the nightside (80° – 86°).

[32] For the 12–16 UT interval in Figure 5 the profile goes only to 80° on the nightside (DRV) while on the dayside it reaches 68° (A81). The expected power peak on the nightside is beyond the profile (i.e., latitude lower than 80°) and on the

dayside it is at SP ($\Phi \simeq 75^\circ$). The coherence is again maximal (~ 0.7) between stations in the polar cap: P5 (dayside, 86°) and P6 (nightside, 84°). This meridional profile again shows that the power of disturbances is maximal in the regions corresponding to the nominal ionospheric projections of the dayside cusp/cleft ($|\Phi| \simeq 75^\circ$) and the nightside auroral zone ($|\Phi| \simeq 70^\circ$). At the same time, the maximal coherence is found at polar cap latitudes with a peak shifted toward the nightside from the geomagnetic pole.

4.2. Diurnal Variation of Spectral Power at Different Latitudes

[33] The data set used in the present paper provides an opportunity to compare the simultaneous diurnal variations at stations located at different geomagnetic latitudes: auro-

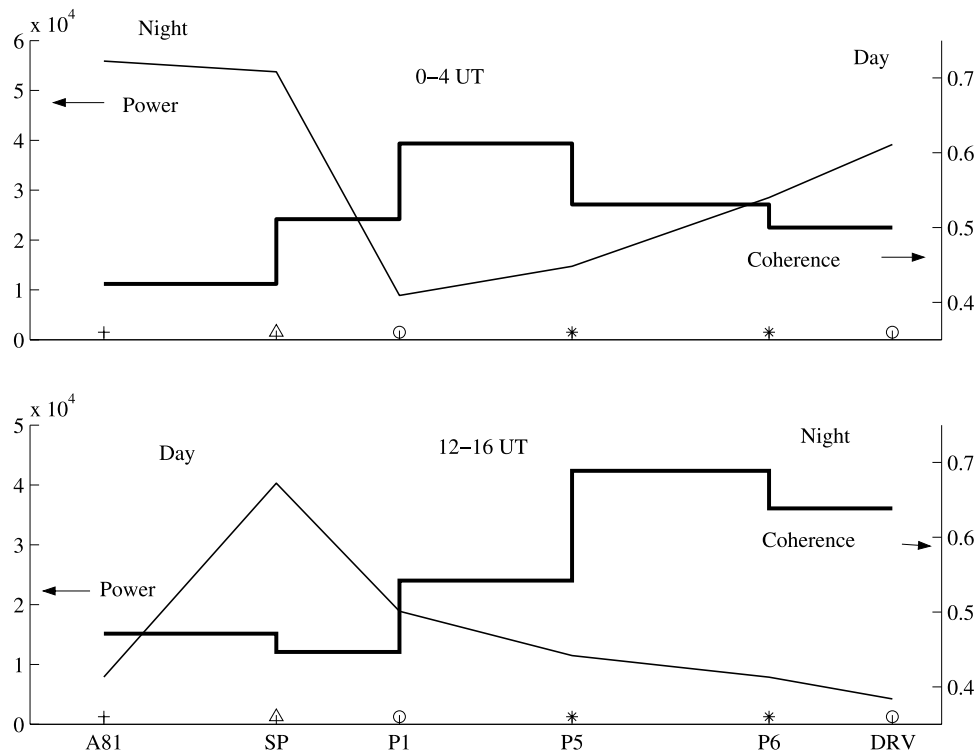


Figure 5. The distribution of month-averaged T_f^2 (thin line) and γ (thick line histogram) along the trans-Antarctic day-night profile. Station codes and latitude groups are indicated below: stars, polar; circles, $\Phi \simeq 80^\circ$; triangles, polar auroral; pluses, auroral.

ral, cusp, and polar cap. The MLT dependence of $T_f(t)$ in the frequency band 1–1.5 mHz is shown in Figure 6. The most polar stations (P5, VOS, P6) are given in the upper panel. Four stations along the $\sim 80^\circ$ longitudinal profile (P4, SUD, DRV, and SBA) covering all the LT quarters are shown in the second panel. Three stations with $|\Phi| \simeq 74^\circ\text{--}77^\circ$: MIR, SP and DVS are grouped in the third panel, and two auroral stations: A81 and MAW, are in the bottom panel.

[34] The form of the diurnal variations of $T_f(t)$ changes along a meridian from the typical auroral distribution with two maxima at early morning and evening hours to the cusp-related variation with the only maximum near the local noon, and further to a weak MLT dependence in the polar cap. Rising from auroral to polar latitudes one can see the change of MLT dependence from a bimodal distribution at $|\Phi| \simeq 70^\circ$ to a single-peaked one at $\sim 80^\circ$. The MLT dependence at $\sim 75^\circ$ (third panel) stations is intermediate between these two types. At these stations, the morning maximum shifts to later hours (SP, DVS) and at MIR the evening maximum vanishes. Figure 6 indicates that the geomagnetic latitude is not the only parameter that controls the form of diurnal variations. For example, the MLT dependence at polar cap station P6 is closer to the dependencies at stations along 80° , and to that at MIR as well.

4.3. Azimuthal Asymmetry of Diurnal Variations

[35] The three sites (VOS, P5, P6) that are at similar $83^\circ < |\Phi| < 87^\circ$ high geomagnetic latitude, but have different geomagnetic longitudes, differ strongly in their geographic latitudes and solar LT for the same MLT. This provides the

opportunity to compare the influence of geodetic and geomagnetic latitudes and LT on pulsation properties.

[36] The comparison of diurnal variations at the highest latitude stations (first panel in Figure 6) shows a strong azimuthal asymmetry. While at VOS and P5 the ratio between maximal and minimal power is about 3, at P6 it is nearly 10. The diurnal variation at P6 has the same character as that at the $\sim 80^\circ$ profile with a clear local daytime maximum, while at VOS and P5 it is very weak. This effect cannot be explained by the geomagnetic latitudes of the stations because the latitude of P6 (-84.9°) is intermediate between the latitudes of P5 (-86.7°) and VOS (-83.3°).

[37] This asymmetry is reproduced at the stations of the longitudinal profile at $\sim 80^\circ$ latitude as well. The maximal to minimal power ratio is ~ 15 at DRV (235° meridian) and only ~ 4 at P4 (40° meridian). The time of maximal power is ~ 12 MLT at DRV and ~ 2 hours earlier at P4 and SUD. The diurnal variation of wave power at SBA is characterized by a very slow decrease of power in the afternoon and evening hours. The values of maximal to minimal power ratio at SUD and SBA, stations with intermediate geographic latitudes, lie between those at DRV and P4. This azimuthal asymmetry effect can still be seen even at lower latitudes (third panel): the diurnal variation at SP (along the P5 meridian) is smaller than at DVS (along the SUD meridian).

[38] The effects of azimuthal asymmetry in the power distribution along the $\sim 80^\circ$ MLAT profile are summarized in Figure 7. This plot shows the 2-D dependence of month-averaged (February 1998) pulsation power on the MLT and

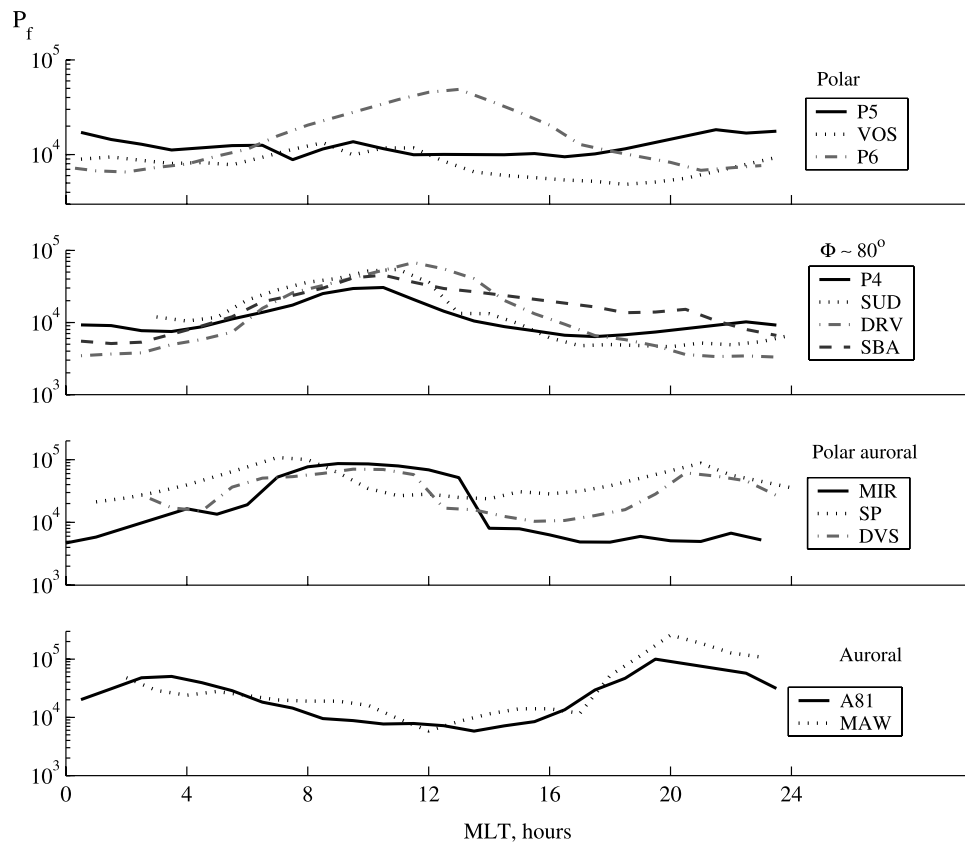


Figure 6. MLT dependence of T_f averaged over February 1998. The most polar stations (P5, VOS, P6) are given in the first panel; four stations of the longitudinal profile along $\sim 80^\circ$ MLAT (P4, SUD, DRV, SBA) are shown in the second panel; three polar auroral stations with 74° – 77° MLAT (MIR, SP and DVS) are given in the third panel, and two auroral stations (A81 and MAW) are given in the fourth panel.

the difference between solar and magnetic local times $MLT-UT$ for all the stations along the longitudinal profile at 80° MLAT. The power contours are inclined to the upper right from the vertical direction indicating the existence of some UT control. The clear amplitude maximum and the highest contrast between day and night amplitudes are seen at the stations CSY and DRV that have the smallest difference between magnetic and solar local time (< 2 hours) and the lowest geodetic latitudes ($\sim 66^\circ$). This result was confirmed by a similar analysis of the diurnal variations of the power for February 1997.

4.4. Distinguishing Pulsations From Different Sources

[39] The previous sections established that pulsations at $|\Phi| \geq 80^\circ$ are incoherent with auroral pulsations, and that their spectral power varies with time in a different way as well. These analyses suggest the existence of independent sources of geomagnetic disturbances in the different regions. The present section provides further evidence for the existence of independent sources of polar pulsations, using the technique outlined in Section 3.3.

[40] Cross-correlation analysis was applied to the power variation $T_f(t)$ in the band 1–1.5 mHz from all the station pairs in the interval 00–04 UT (February 1998) to minimize the influence of diurnal variations (e.g., see Figure 6). In this UT interval, the stations at geomagnetic longitudes $\lambda \simeq 20^\circ$ – 40° (P5, P1, P4, SP and A81) are in the midnight sector; the stations at $\lambda \simeq 100^\circ$ – 120° (SUD, MIR and

DVS) are at local morning; P6, CSY, and DRV are near local noon, and SBA is in the evening MLT sector.

[41] The dispersion of $T_f(t)$ variation, $\sigma(T_f)$, from different stations and the cross-correlation coefficients, R , between power variations at all station pairs are shown in Figure 8a in the same format as the spectral power and coherence in Figures 3 and 4. The size of the open circles at each station in Figure 8 are $\propto \log_{10} \sigma(T_f)$, and R , if above 0.5, for a station pair is shown with a line connecting the stations. The power variance in this UT interval at auroral stations (A81, MAW), nightside polar auroral station (SP) and dayside $\sim 80^\circ$ stations (CSY, DRV) exceeds several times the power variance at nightside polar stations.

[42] Figure 8a also shows that R is higher than 0.8 for polar and $\sim 80^\circ$ stations in local night, morning and evening MLT sectors. This result is expected from the high values of spectral coherence for station pairs within this group. The $R \simeq 0.6$ – 0.7 between polar nightside and near-noon stations (the P5–P6 and P5 - CSY pairs) and it decreases to ~ 0.5 for the P5 - DRV pair. The power variance at DRV, located near the nominal cusp in this UT interval, exceeds that at the polar stations while the correlation between DRV and all the other stations is relatively low.

[43] A low correlation with all the other stations is found also for the SP station located on the nightside near the nominal polar boundary of the auroral zone, whereas the power variation at this station is intense.

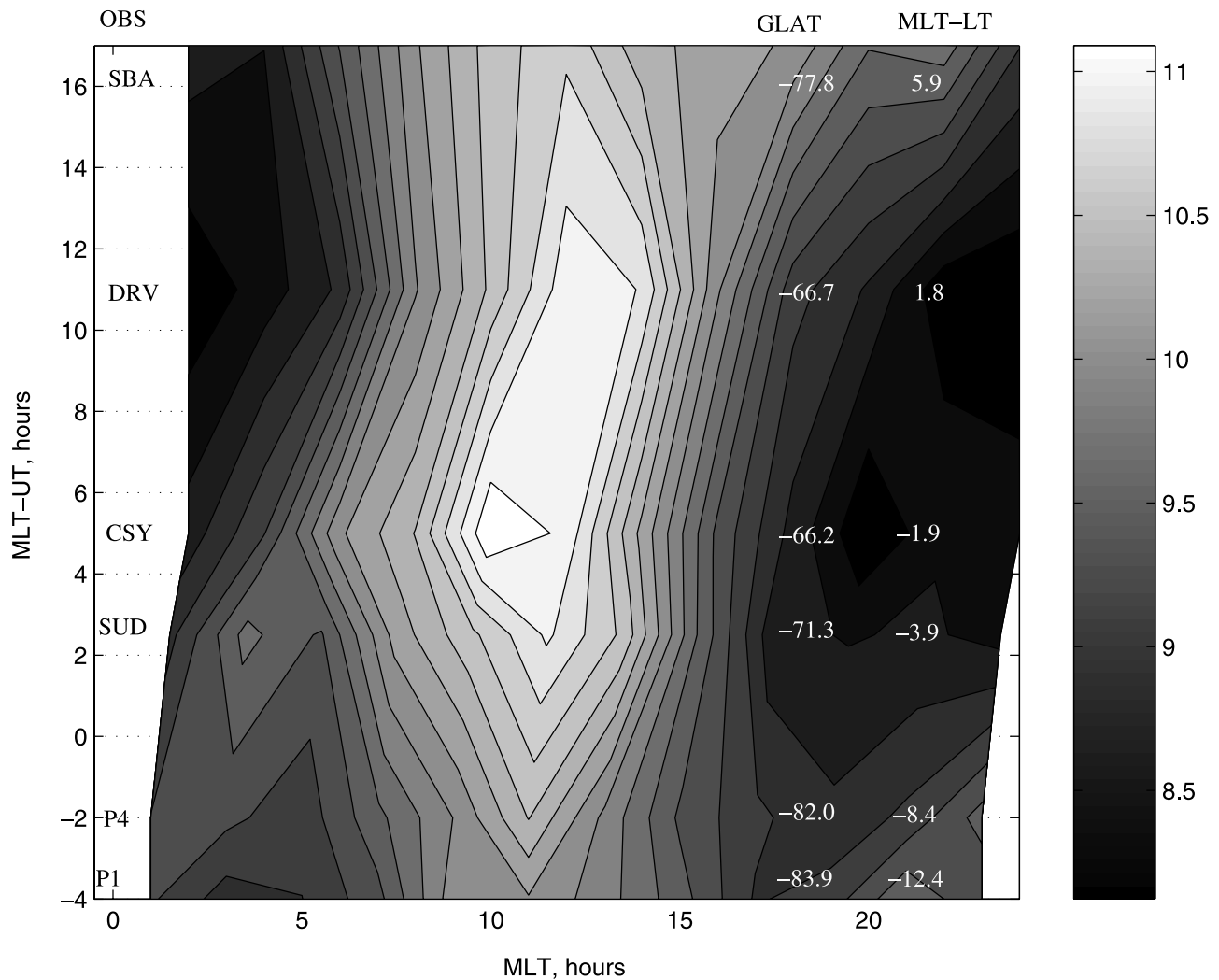


Figure 7. Dependence of Pi3 wave power, namely, $\log_{10} T_f$, during February 1998 at $\sim 80^\circ$ MLAT stations on MLT and MLT-UT difference. The geodetic latitudes and MLT-LT differences for the stations are shown by the white numbers.

[44] Between polar nightside stations and auroral stations A81 and MAW R is ~ 0.5 – 0.6 . The relatively high correlation between $T_f(t)$ at polar cap stations and other groups of stations indicates the existence of a common source for the high latitude pulsations from the auroral zone to the geomagnetic pole.

[45] The existence of a more local source for the cap pulsations is examined by excluding the auroral and cusp components from the $T_f(t)$ and subsequent analysis of the cross-correlations for the residual power variation. DRV ($|\Phi| \simeq 80^\circ$, MLT noon) has been taken as typical polar dayside (cusp) station. MAW ($|\Phi| \simeq 70^\circ$, MLT morning) and A81 ($|\Phi| \simeq 70^\circ$, MLT night) that cover the MLT sectors of the auroral oval when the pulsation power is maximal, have been taken as reference auroral stations.

[46] The magnitude of auroral and dayside $T_f(t)$ variation is found to be high in comparison with that at nightside polar stations. This enables us to neglect the possible influence of the polar disturbances on variations in the auroral and cusp regions and therefore to use a simplified regression analysis. At the first stage, the fraction of $T_f(t)$ at

polar stations that is linearly independent from the $T_f(t)$ at auroral latitudes was retrieved with the help of the linear regression procedure. The dispersion of $T_f(t)$, $\sigma(T_f)$, and interstation correlations for the auroral-independent fraction of the $T_f(t)$ are shown in Figure 8b.

[47] The R for this fraction within the group of nightside polar stations remain nearly the same as before the expansion. The $\sigma(T_f)$ of the auroral-independent part for this group of stations is $\sim 0.5 \cdot \sigma(T_f)$ at these stations.

[48] This procedure was then repeated to retrieve the fraction of $T_f(t)$ at polar nightside stations independent from both auroral and polar dayside variations (Figure 8c). Correlation for the polar stations, except those on the dayside (P6 and CSY), after the exclusion of the fraction proportional to the dayside polar (DRV) variations remain high, $R \geq 0.75$. The R decreases by 10–20% for the P5–P6 and P5–CSY pairs. The $\sigma(T_f)$ for polar nightside stations decreases by 10–20% only after this expansion, i.e., the influence of auroral-independent cusp activity on the nightside polar pulsations is relatively low.

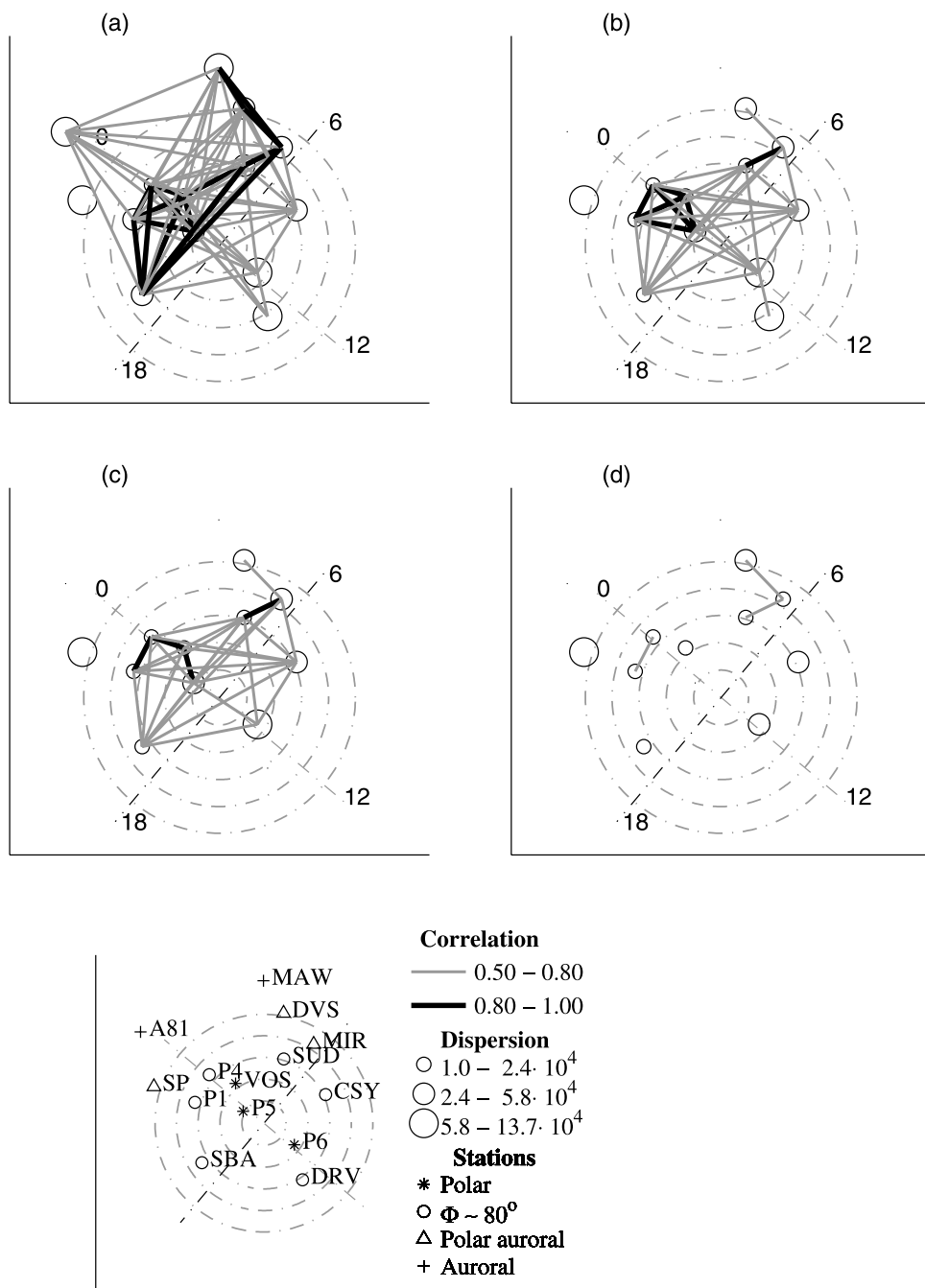


Figure 8. Dispersion $\sigma(T_f)$ and interstation R of power variations, February 1998, 00–04 UT, for different fractions: (a) total power variations, (b) auroral-independent fraction (the part proportional to MAW and A81 excluded), (c) pure nightside polar fraction (DRV excluded), and (d) residual activity (P5 excluded). Station codes and legend are given at the bottom. Marker size is $\propto \log_{10}\sigma(T_f)$, and R (if ≥ 0.5) is shown by a line connecting the stations.

[49] These stages of analysis have shown that $Pi3$ power variation at polar cap latitudes contains the auroral and cusp related fractions. The pure polar cap fraction is independent of auroral and cusp disturbances and is well correlated over the polar cap region.

[50] The polar most station P5 has the highest correlation with the other polar stations and can be taken as the center of specific polar cap activity. The expansion of pure polar cap $T_f(t)$ into P5-proportional and P5-independent fractions

makes it possible to determine whether there is only one source of pure-cap pulsations or whether there might be several sources with smaller spatial scales. Figure 8d illustrates the $T_f(t)$ variations after the P5-proportional component is excluded. The low correlation between almost all the station pairs shows that this residual activity is very local, i.e., its spatial scale is small in comparison with the interstation distance. For the polar cap stations the $\sigma(T_f)$ of residual activity is $\sim 25\text{--}30\%$ of that of the total $\sigma(T_f)$.

[51] Thus the variation of the pulsation power in the polar cap can be expanded into the following independent components: (1) auroral, (2) cusp, (3) pure polar cap, and (4) local noise. The contribution of auroral, cap and local components to the power variation in the polar cap are comparable; the influence of the cusp component is lower.

[52] Applying the above results to the whole high latitude region from polar to auroral latitudes the regional scale sources can be described as: (1) auroral, manifesting itself everywhere from the auroral zone to the geomagnetic poles; (2) cusp related, localized in the dayside region at latitudes about 80° ; (3) pure cap, covering all the nightside polar region, and (4) polar auroral, localized near local midnight at $|\Phi| \sim 75^\circ$. It is, probably, rather local and its spatial scale cannot be estimated with the station network used.

5. Discussion

[53] The interpretation of ULF disturbances at high latitudes as specific polar cap pulsations on the basis of observations only along a meridional chain has some ambiguity. Additional amplitude maxima in the polar cap and different spectral content and diurnal variation of spectral parameters are to be considered as just indirect arguments in favor of the occurrence of specific polar cap-related pulsations, because these features might also be explained by the penetration of auroral or cusp pulsations from other MLT sectors into the polar cap. Analysis of 2-D spatial and temporal distributions of spectral power and coherence of high latitude ULF disturbances has shown that polar cap pulsations do exist, whereas pulsations in the polar cap have both related and independent components from auroral and cusp sources.

[54] Analysis of the spectral coherence and cross correlation between spectral power variations enables us to group all the stations into three regions with specific ULF disturbances. According to their position on Earth's surface and their magnetospheric projections we define them as polar dayside (cusp), polar nightside (polar cap), and auroral ULF pulsations. Polar cap-associated pulsations are coherent within the polar night hemi-circle, and a lack of coherence is found between them and auroral and cusp disturbances. Long-period variations even at stations across the dipole pole location, P5 and P6, are rather well coherent. The location of the coherent area of these pulsations is similar to that of the polar cap. The minimum of the spectral coherence between nearby dayside stations may correspond to the separatrix between tailward and sunward field lines. This effect, together with the maximum of spectral power [Rostoker *et al.*, 1972], can be used as an additional indicator of the equatorward dayside cusp boundary.

[55] The pulsation power (with diurnal variation excluded) varies in time with a non-negligible correlation throughout the whole high latitude region from auroral latitudes to the geomagnetic pole, whereas an intermediate ($\gamma \simeq 0.5$) correlation is observed for the pulsation power at polar and auroral latitudes. These results agree with the analysis of Heacock and Chao [1980] who claimed the occurrence of two components of ULF activity at high latitudes: one associated with substorms and a second, residual one that does not depend on geomagnetic activity. Our analysis has shown that the auroral independent, polar cap-correlated,

component of ULF power variations (pure polar cap pulsations) at polar stations is comparable with the auroral component.

[56] The distinctions between pulsations in the different regions can be interpreted either as a common source and different propagation paths, or as independent sources. The correlation analysis of power variation at different groups of stations has shown the coexistence of both scenarios. On one hand, a non-negligible correlation between the ULF power variations at polar cap stations and those in the cusp and auroral regions is found, indicating the existence of a common source of ULF activity. On the other hand, the existence of the fraction of $P_{i_{cap}3}$ power variations that are linearly independent of the variations of cusp and auroral pulsation power and are highly coherent within the polar cap proves that the specific cap pulsations do exist.

[57] An interesting morphological feature of $P_{i_{cap}3}$ pulsations is the strong azimuthal asymmetry of pulsation power (UT control). The highest day-to-night power ratio occurs at stations with the lowest geographic latitude for which the difference between solar and magnetic local times is minimal. Diurnal variations are weakest at stations between the geodetic and geomagnetic poles. These stations have the highest geographic latitudes, and their solar and magnetic local times are nearly opposite. This asymmetry grows with increasing geomagnetic latitude and is maximal between VOS/P5 and P6. A similar asymmetry can be seen in the results of Ballatore *et al.* [1998], though this effect was not discussed by the authors. The fewer intervals of high power at P4 and MCM (almost the same location as SBA in the present paper) in comparison with CSY and DRV is seen from their Figures 2–3.

[58] To comprehend a possible mechanism of this asymmetry it is proper to recall that the signals observed at the ground surface are controlled by the amplitude of magnetospheric signals and by the screening properties of the ionosphere. The tracing of field lines with the T-96 model from the stations along the 80° CGM latitude at various MLT does not reveal a systematic difference between the tail projections of these stations. Thus the azimuthal asymmetry cannot be explained by a difference in the magnetospheric projections of the observational sites.

[59] The transmission properties of the ionosphere depend on the ionospheric height-integrated Hall conductivity. This conductivity at high latitudes is controlled by the solar illumination and electron precipitation. The geomagnetic activity during February 1998 was not high and the solar component, as calculated from the [Heppner and Maynard, 1987] model, would be expected to dominate in the total Hall and Pedersen conductances, Σ_H and Σ_P , at geomagnetic latitudes $\geq 80^\circ$. The altitude profile of the ionospheric plasma parameters from the IRI-96 model has been used to calculate the local conductivities, and then variations of Σ_H and Σ_P with season, local time and geodetic latitude. The maximum-to-minimum ratio of both Σ_H and Σ_P at a high geomagnetic latitude depends strongly on the geodetic latitude. At 85° geomagnetic latitude, this ratio is about 20 for 70° geodetic latitude (solar and magnetic local time are nearly the same on the P6 meridian) and the ratio decreases to 1.4 for 78° geodetic latitude (solar and geomagnetic local time are opposite at the P5 meridian). Thus the observed difference in the diurnal variations of pulsation

amplitudes along a geomagnetic latitude can be attributed, at least partly, to the diurnal variations of the ionospheric conductivity.

[60] The source of the auroral-related fraction of polar pulsations is most probably related to the sporadic extension of the auroral activity to very high latitudes. Similarly, intense dayside ULF activity in the cusp/cleft region, conjugate to the magnetospheric dayside boundary layers, results in the observed cusp-related polar cap pulsations. The intense cusp-associated oscillations are spatially incoherent and decay rapidly into the polar cap. Similarly, the low coherency spatial scale of cusp-related pulsations in the Pc3-Pi1 band was noticed by *Olson and Szuberla* [1997]. No specific excitation mechanism of cusp magnetic activity has yet been identified, despite several theoretical attempts. The primary source of the cusp-associated fraction of the polar pulsation activity is, likely, magnetosheath turbulence. Magnetosheath turbulence can leak into the mantle and tail lobes, thus ensuring the occurrence of the cusp-related fraction of the ULF activity on the field lines conjugate to the polar cap.

[61] $Pi_{cap}3$ signals are likely related to waves/transients in the mantle or in the tail lobes. The penetration and conversion of magnetosheath turbulence inside these regions may occur in two ways [*Pilipenko and Engebretson*, 2002]. Compressional modes can penetrate into the tail lobes or just buffet it, and resonantly convert into leaking Alfvén waves. However, to date, a particular conversion mechanism that can operate on open field lines has not been identified, despite some theoretical indications of the feasibility of such a process [*Allan and Wright*, 2000]. However, this mechanism is unlikely to produce pulsations that are very coherent throughout nearly the entire polar cap. At the same time, owing to the finite viscosity of turbulent magnetosheath plasma, the geomagnetic field lines at very high latitudes can be reconnected with the magnetosheath field. Thus Alfvénic turbulence can directly leak into the polar cap along reconnected field lines. In both scenarios ground oscillations can be stimulated by bursts of magnetosheath turbulence, caused either by a direct response to solar wind pressure pulses or to the intermittency of internal turbulence. The proposed channel of ULF pulsation transmission and conversion in the region of the mantle/cap, in the region with open field lines, may provide ground magnetic activity in the polar cap.

[62] Some contribution to the nightside high-latitude long-period ULF pulsations can be provided by the auroral poleward boundary intensifications (PBIs), which often occur repetitively [*Lyons et al.*, 2002]. The quasiperiodic PBIs may be a manifestation of a large-scale ULF oscillation mode that strongly perturbs the plasma sheet and the auroral ionosphere [*Sanchez et al.*, 1997]. This quasiperiodic process may reveal itself in the occurrence of the polar auroral source that has been retrieved in section 4.4.

[63] Finally, the proper polar cap fraction of $Pi_{cap}3$ pulsations may be caused by global oscillations of the tail lobes. Magnetosheath turbulence, as well as bursty processes in the plasma sheet, can be drivers of the oscillatory response of the tail lobes. So far, theoretical models of oscillatory magnetotail modes have considered a plasma cylinder, simulating the tail as a whole [*Patel*, 1966; *McKenzie*, 1970;

Ershkovich and Nusinov, 1972], and a plasma slab-plasma sheet [*McKenzie*, 1970]. It might be appropriate to consider oscillations of a half-cylinder that mimics a tail lobe. The expected typical period of such oscillations is expected to be about R/V_A , where R is the radius of the tail lobe. For $R \simeq 8 R_E$ and $V_A \simeq 10^2$ km/s, one obtains $T \simeq 9$ min, corresponding to the typical timescale of $Pi_{cap}3$ pulsations, though this estimate evidently may vary over a rather wide range.

[64] The polar cap area is dominated mainly by low-amplitude coherent pulsations practically over the entire polar cap. According to the nomenclature used in this paper, $Pi_{cap}3$ pulsations comprise the cusp- and aurora-independent part of high latitude variations (proper polar cap pulsations), as well as the polar cap extension of the intense spatially incoherent cusp-associated pulsations and the auroral ULF activity (Pi3, Pc5).

[65] Some of the morphological properties of $Pi_{cap}3$ are similar to those of the soft electron precipitation (polar rain) commonly observed in the polar cap [*Gussenhoven et al.*, 1984], which exhibits an amplitude maximum at the dayside polar cap at local summer. The quasi-periods of particle flux fluctuations reported by *Shinohara and Kokubun* [1996] are comparable with the periods of $Pi_{cap}3$. This similarity is not surprising with the recognition that both phenomena may be caused by direct geomagnetic coupling of the magnetosheath plasma and the polar ionosphere through reconnected field lines. Direct comparison of ULF ground observations with field and particle measurements in the mantle and magnetosheath will be needed to further clarify the nature of $Pi_{cap}3$ pulsations.

6. Conclusion

[66] A new category of high-latitude ULF pulsations, which we have designated $Pi_{cap}3$, has been analyzed with the use of 2-D intensity-coherence patterns constructed from the data of a set of magnetometers arrayed across Antarctica. It is not possible to have such an array at these high latitudes in the northern polar regions. The amplitude of pulsations in the range 1–4 mHz commonly has a maximum at the probable latitude of the dayside cusp. Intense cusp-related pulsations have low coherence with pulsations in the polar cap. The Pi3 pulsations in the polar cap region are highly coherent inside the polar cap and decoupled from the auroral and cusp pulsations. The region of high coherence spans much of the central part of the polar cap. Regression analysis reveals three main sources of $Pi_{cap}3$ pulsations related to the dayside cusp, nightside auroral region, and magnetotail lobe. Probable mechanisms of these pulsation types have not been established yet, but they are possibly related to auroral activity, magnetosheath turbulence in the dayside boundary layers, and tail lobe oscillations. ULF modes would be a significant component of tail dynamics and night side magnetosphere coupling to the ionosphere.

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