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# MECHANISMS OF THE CUSP-RELATED PC3-4 WAVES

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**Abstract.** Pc3-4 pulsations are an ubiquitous element of dayside ULF wave activity both at low-latitude and in the cusp region. We compare simultaneous observations of Pc3-4 wave activity by magnetometers at three locations on Svalbard, covering geomagnetic latitudes 74°-76°, and by low-latitude SEGMA magnetometer array (36°-43°). The cross-spectrum between low-latitude stations shows a typical amplitude-phase gradient pattern – maximal phase delay at specific resonance frequency, which confirms that the ground response is formed due to the conversion of external band-limited disturbances into standing field line oscillations. At the same time, the gradient analysis shows no specific mode conversion pattern near the cusp region. The amplitude gradient has the same direction at all frequencies, and the phase delay does not show any consistent pattern. This behavior corresponds to the occurrence of a localized peak in the latitudinal distribution of Pc3-4 power not under the cusp proper, as was previously thought, but about few degrees southward from the equatorward cusp boundary.

## Introduction

The most intense Pc3-4 wave activity (10-100 mHz) is observed in the region of the ionospheric projection of the magnetospheric dayside boundary layers (called the cusp for brevity) [*Bolshakova and Troitskaya,* 1984] and at mid-latitudes in the daytime-morning hours. The prevailing viewpoint is that the primary source of magnetospheric Pc3 pulsations is the waves upstream of the magnetospheric bow shock. Upstream waves are assumed to be convected by the solar wind flow through the turbulent magnetosheath to the magnetopause, and further they propagate as fast compressional waves into the inner magnetosphere. In the equatorial magnetosphere, broad-band waves are resonantly converted into narrow-frequency Alfven field line oscillations. This field line resonance (FLR) acts as a natural band-pass filter/amplifier producing narrow-band signals at middle latitudes.

At the same time a physical mechanism of cusp-related Pc3-4 pulsations has not been firmly established yet. It is still uncertain whether these two kinds of pulsations in the same frequency band – cusp-related Pc3 and mid-latitude Pc3, are caused by the same primary source?

Any mechanism of propagation will be related to the specific Pc3-4 spatial structure on the ground. The conversion from isotropically propagating compressional disturbances into guided Alfven field line oscillations is inevitably related to the formation of resonant structure with a peculiar amplitude and phase space-frequency pattern, which cannot be produced by any other localized source.

In order to get additional clues about the mechanisms of high-latitude ULF waves, in this paper we compare Pc3-4 waves in the polar cusp and at middle-low latitudes. The cusp location for a particular event is determined using SuperDARN data. We compare the gradient analysis results for simultaneous Pc3-4 events observed by the near-cusp Svalbard array and low-latitude SEGMA array.

## Observational facilities and data analysis

To identify the ionospheric projections of the cusp, we use the data from CUTLASS radar. The closely-spaced array of magnetometers at Svalbard forms a latitudinal profile along ~110° geomagnetic meridian (noon ~09 UT). The SEGMA array is 4 stations spaced equally in latitude with a step of ~2° along a

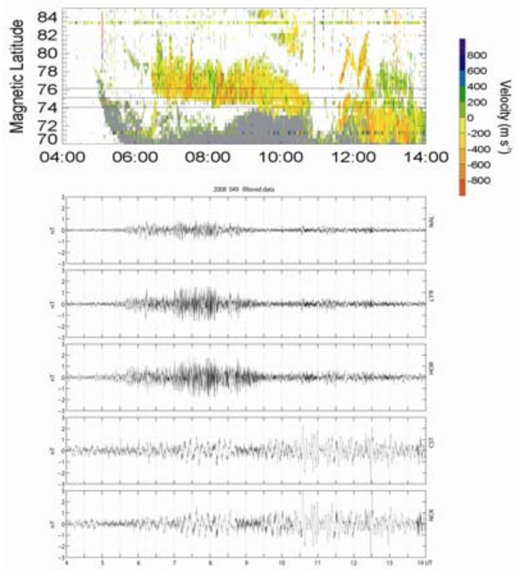


**Fig. 1**. Line-of-sight ionospheric plasma velocity determined by the SuperDARN radar (upper panel), and magnetograms (0.5-0.001 Hz band-filtered H-component) from the near-cusp stations NAL, LYR, HOR and mid-latitude stations CST, NCK (bottom panel) for the event 2008/02/18 (049), 04-14 UT.

geomagnetic meridian (noon ~1020 UT).

Dynamic gradient analysis for the Svalbard pair of stations LYR-HOR and the SEGMA pair of stations CST-NCK gives the spectral power *H(f)* at both stations, spectral coherency $\gamma(f)$ between them, phase difference $\Delta\varphi(f)=\varphi^{(N)}-\varphi^{(S)}$, and amplitude difference $\Delta H(f)=H^{(N)}(f)-H^{(S)}(f)$.

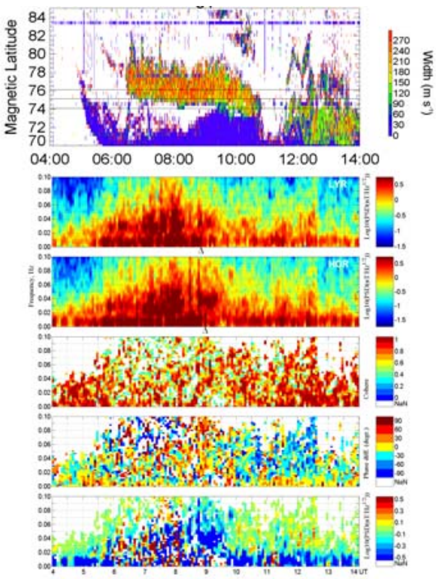


**Fig. 2.** Radar and magnetometer observations at Svalbard during 2008/02/18 (“cusp overhead”) event in the time interval 04-14 UT. Upper panel shows the Doppler width of the radar return signal. Horizontal thin lines denote the magnetometer latitudes. The bottom panel shows (from top to bottom): the dynamic spectra (H-component) in 0-100 mHz frequency band at LYR and HOR; spectral coherence $\gamma(f)$; phase difference $\Delta\varphi(f)$, difference of spectral powers $\Delta H(f)$. Triangle signs indicate local noon.

### 2008/02/18 (049): typical “cusp above” case

SuperDARN radar observations (Fig. 1) show that the equatorward cusp boundary in the interval 07-11 UT is clearly identified at ~75$^{o}$, just between HOR and LYR. Thus, this event may be considered as a typical “cusp overhead” case – the ionospheric projection of the equatorward cusp boundary is above the magnetometer array. At the near-cusp stations an enhancement of wide-band Pc3-4 activity is observed during the daytime from ~05 UT until ~10 UT, and then the wave power gradually decreases until ~14 UT. The Pc3-4 activity at NAL was always weakest as compared with LYR and HOR.

Fig. 2 shows the results of gradient analysis as applied to Svalbard magnetometer pair LYR-HOR. The phase gradient is chaotic, varying around 0, though the coherence between signals is significant. The gradient of amplitude is dominantly negative before ~06 UT ($H_{LYR}>H_{HOR}$), however from ~06 UT till ~08 UT Pc3-4 power at HOR peaks relative to LYR as the cusp crosses overhead. The amplitude difference after ~08 UT became negative again.

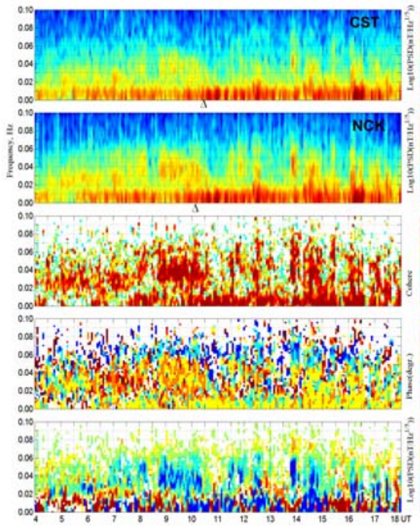


**Fig. 3.** The results of the gradient analysis during the event 2008/02/18 04-18 UT for the pair of SEGMA stations CST-NCK (from top to bottom): the dynamic spectra $H_{CST}(f)$ and $H_{NCK}(f)$ in 0-100 mHz frequency band; spectral coherence $\gamma(f)$; phase difference $\Delta\varphi(f)$, and difference of spectral power $\Delta H(f)=H_{CST}(f)-H_{NCK}(f)$. Triangle signs indicate local noon.

At L=1.8 (CST-NCK) the gradient analysis reveals a resonant feature – an extreme value of phase difference at a resonant frequency ~60 mHz from 07 until 16 UT (Fig. 4). The amplitude difference also demonstrates a regular pattern – the sign change of $\Delta H(f)$ at *f*~60 mhz. The consistent phase and amplitude behavior in the band around 60 mHz confirms that this frequency is the resonant frequency of the magnetospheric Alfven resonator.

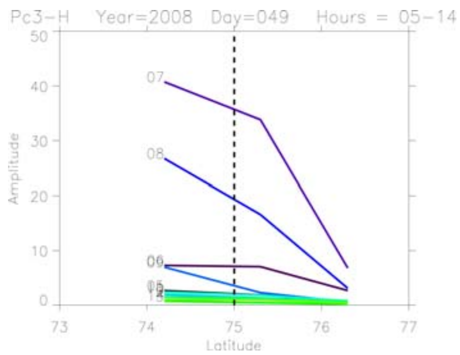


**Fig. 4.** The latitudinal distribution of the hourly values of band-integrated Pc3 spectral power (20-100 mHz) for day 049 (‘cusp overhead”) 05-14 UT along the array HOR, LYR, NAL. The vertical dotted line denotes the position of the equatorward cusp boundary.

To characterize the latitudinal distribution of Pc3-4 wave power in the cusp region we have calculated for each station HOR, LYR, NAL the hourly values of the spectral power band-integrated in the 20-100 mHz band for the H component. The latitudinal distribution for the day, when the cusp is not very far from the array, is shown in Fig. 5. The magnetometer array scans only the high-latitude edge of the ULF power distribution, which gives no possibility to locate the exact position of the ULF power maximum. Nonetheless, there is no doubt that this maximum is shifted at least by ~3$^o$ equatorward from the equatorward cusp boundary.

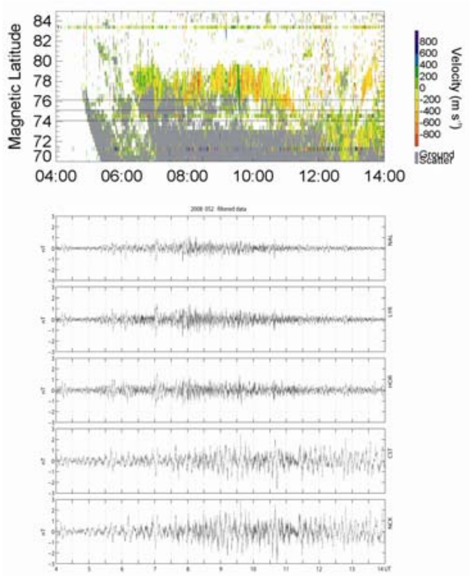


**Fig. 6.** Line-of-sight ionospheric plasma velocity determined by SuperDARN radar (upper panel), and magnetograms from near-cusp stations NAL, LYR, HOR, and mid-latitude stations CST, NCK (bottom panels) for the event 2008/02/21 (052), 04-14 UT.

The radar return signal in Fig. 6 shows that the cusp equatorward boundary is at high latitude ~76-77$^o$ during 06-11 UT, beyond the magnetometer array. Therefore, this case may be considered as an example of a "far-poleward cusp" situation.

The gradient analysis (Fig. 7) shows that during the dayside Pc3-4 activity enhancement (07-10 UT) the amplitude gradient is dominantly positive, e.g. $H_{LYR}>H_{HOR}$. Beyond this time interval the background ULF noise amplitude decreases poleward, which corresponds to the negative $\Delta H(f)$. This pattern means that Pc3-4 activity at LYR is strongest early on, but it becomes strongest at HOR as the cusp moves equatorward.

At low latitudes (L=1.8) the gradient analysis of the CST-NCK pair (not shown) reveals a typical field line resonance pattern around $f$~60 mHz: the occurrence of the minimum value of $\Delta\varphi(f)$ and sign change of $\Delta H(f)$, observed from 06 UT until 15 UT.

For such a case, when the cusp is located relatively far from the array (around 80$^o$) the latitudinal distribution of ULF power is also shifted to higher latitudes (Fig. 8). In this case the Pc3 pulsation peak at 75.3$^o$ (LYR) becomes evident.

## Possible scenarios of cusp-related Pc3-4 waves

The cross-spectrum between low-latitude SEGMA stations shows a typical pattern – maximal phase delay is observed at specific mid-station resonance frequency, varying from 60 mHz to 70 mHz. These results confirm once again that the ground ULF response at middle and low latitudes is formed due to the conversion of external band-limited disturbances into standing field line oscillations.

At the same time, gradient analysis shows that no specific mode conversion pattern is observed at cusp latitudes. The amplitude gradient indicates an increase of spectral power at all frequencies between LYR and HOR. Only during the periods when the cusp is shifted to very high latitudes, the amplitude gradient may change sign. This behavior corresponds well to the occurrence of a peak in the meridional distribution of Pc3 power somewhere southward from the equatorward cusp boundary. The phase delay is chaotic and does not show any consistent pattern; no highlighted frequency can be revealed.

The local latitudinal distributions of band-integrated power in the Pc3 ranges in respect to the equatorward cusp boundary as observed at Svalbard magnetometers show that in fact the "cusp Pc3-4 pulsations" are not related to the cusp proper. The peak of their power distribution is shifted several degrees southward from the equatorward cusp boundary, probably into the projection of the entry layer or in the region of the last closed field lines. This is in contrast to suggestions in early studies [*Troitskaya,* 1985] that the cusp is a conduit of the upstream waves and the source of dayside Pc3 pulsations.

So far, there is an ambiguity in mechanisms of cusp-related Pc3-4 pulsations. A primary source is supposed to be the upstream turbulence/waves, but possible channels of upstream wave propagation to the ground might be different. Pc3-4 pulsations observed at high latitudes were often supposed to be higher harmonics of standing field line oscillations on the last closed field lines [*Tonegawa et al., 1984; Howard and Menk,* 2005]. However, the gradient analysis of data from the local meridional array in Svalbard has shown that the standard FLR mechanism does not operate for the generation of Pc3-4 pulsations observed at high latitudes. Therefore, we have to consider other channels of the Pc3-4 wave energy transmission from the magnetosheath to the high-latitude dayside ionosphere:

(1) Direct wave penetration via mode conversion in the high-altitude entry layer [*Pilipenko et al.,* 1999]. Alfven running wavelets leaking from the high-latitude entry layer propagate along field lines towards the high-latitude ionosphere. Upon this process the phase information is lost;

(2) Driving of near-noon Pc3-4 activity at near-cusp latitudes via the quasi-periodic modulation of precipitating electron fluxes ("ionospheric transistor model" by *Engebretson et al.* [1991]). ULF fluctuations leak from the magnetosheath into the entry layer of the magnetosphere in a compressional

mode and cause modulation of precipitating electron fluxes. The compressional mode energy eventually is dispersed throughout the magnetosphere, whereas modulated fluxes of precipitating electrons can reach the ionosphere, where they cause variations of ionospheric currents. The expected ground signal can be estimated as follows

$$\frac{b^{(g)}}{B^{(g)}} \simeq \frac{b_{\|}}{2B_o} \cdot \frac{1}{(1-i\omega\tau)}$$

This estimate shows that compressional Pc3 fluctuations with amplitude $b_{\|}/B_0 \sim 0.1$ leaking from the magnetosheath into the entry layer of the magnetosphere will modulate the precipitating electron fluxes, which produce the noticeable ground response.

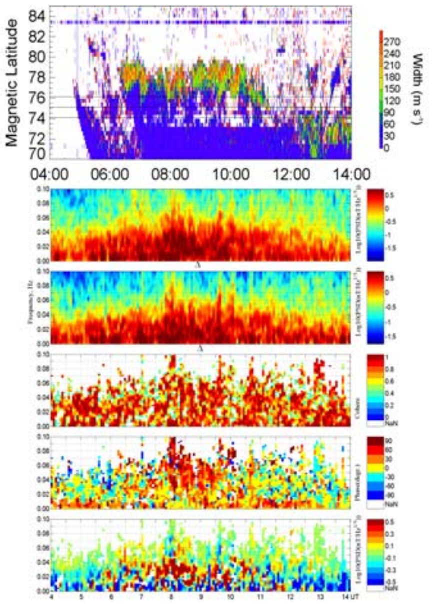


**Fig. 7.** Radar and magnetometer observations during the 2008/02/21 (052) event in the time interval 04-14 UT. The upper panel shows the Doppler width of the radar return signal. Horizontal thin lines denote the magnetometer latitudes. The bottom panel shows (from top to bottom): the dynamic spectra from LYR and HOR stations (H-component); spectral coherence $\gamma(f)$; the phase difference $\Delta\varphi(f)$, and the difference of spectral power. The triangle signs indicate local

## Conclusion

The local meridional structure of Pc3-4 waves simultaneously recorded by magnetometers at Svalbard, covering near-cusp latitudes (74°-76°), and by the low-latitude SEGMA array (36°-43°) has been examined using the amplitude-phase gradient technique. The cross-spectrum between the low-latitude stations shows a typical resonant pattern, which confirms that the ground ULF response at these latitudes is formed due to the conversion of external band-limited disturbances into standing field line oscillations. At the same time, the gradient analysis shows that no specific mode conversion pattern exists near the cusp region. The phase delay is chaotic and does not show any consistent pattern. The amplitude gradient indicates the occurrence of a localized latitudinal maximum of daytime Pc3-4 southward from the equatorward cusp boundary, but not under the cusp proper. We suggest that compressional Pc3 fluctuations leaking from the magnetosheath into the entry layer of the magnetosphere can modulate precipitating electron fluxes, which produce the ground response in the region of closed field lines.

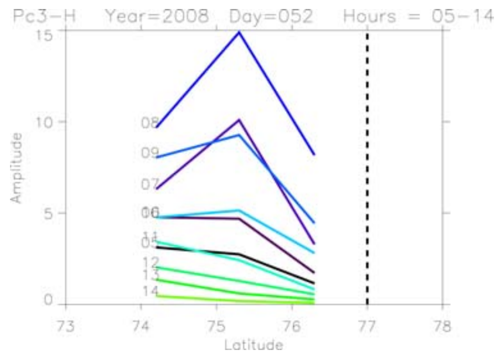


**Fig. 8.** The latitudinal distribution of the hourly values of the band-integrated Pc3 spectral power (20-100 mHz) for the day 052 ("far cusp") 05-14 UT along the array HOR, LYR, NAL for H component. Vertical dotted line denotes position of the equatorward cusp boundary.

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