

ŗ

JGR Space Physics

RESEARCH ARTICLE

10.1029/2020JA028032

Special Section:

Probing the Magnetosphere through Magnetoseismology and Ultra-Low-Frequency Waves

Key Points:

- Large-scale 2.6 mHz Pc5 waves are detected simultaneously by ground magnetometers, SuperDARN radars, and several GPS/TEC receivers
- Relationship between geomagnetic and ionospheric velocity oscillations is interpreted using theory of MHD wave interaction with ionosphere
- Observed ratio between rateof-change of TEC and Doppler velocity amplitudes can be explained by occurrence of local steep gradient

Correspondence to:

V. A. Pilipenko, pilipenko_va@mail.ru

Citation:

Kozyreva, O. V., Pilipenko, V. A., Bland, E. C., Baddeley, L. J., & Zakharov, V. I. (2020). Periodic modulation of the upper ionosphere by ULF waves as observed simultaneously by SuperDARN radars and GPS/TEC technique. *Journal of Geophysical Research: Space Physics*, *125*, e2020JA028032. https://doi.org/ 10.1029/2020JA028032

Received 20 MAR 2020 Accepted 30 APR 2020 Accepted article online 14 MAY 2020

©2020. The Authors.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

Periodic Modulation of the Upper Ionosphere by ULF Waves as Observed Simultaneously by SuperDARN Radars and GPS/TEC Technique

Olga V. Kozyreva¹, Vyacheslav A. Pilipenko^{1,2}, Emma C. Bland^{3,4}, Lisa J. Baddeley^{3,4}, and Victor I. Zakharov^{1,5}

¹Institute of Physics of the Earth, Moscow, Russia, ²Space Research Institute, Moscow, Russia, ³Arctic Geophysical Department, University Centre in Svalbard, Longyearbyen, Norway, ⁴Birkeland Centre for Space Science, Bergen, Norway, ⁵Physics Department, Moscow State University, Moscow, Russia

Abstract Recent work has demonstrated that global Pc5 pulsations observed by ground-based magnetometers may be accompanied by periodic oscillations in the total electron content (TEC) of the ionosphere measured by GPS receivers. These TEC observations may provide new insights into magnetosphere-ionosphere coupling mechanisms, especially when combined with other ground-based observational techniques. Presented in this paper is a large-scale morning sector Pc5 event which was observed simultaneously by ground-based magnetometers, two high-frequency Super Dual Auroral Radar Network (SuperDARN) radars, and several Global Positioning System (GPS)/TEC receivers. The transient 2.6 mHz pulsations observed by the ground magnetometers and radars are accompanied by periodic fluctuations in the time rate-of-change of TEC (ROT) at the same frequency. To investigate possible mechanisms for the TEC modulation by ultralow frequency (ULF) waves, we determine the ratios between the spectral amplitudes of the magnetic, ionospheric Doppler velocity and ROT oscillations. The relationship between the simultaneous magnetic field and ionospheric Doppler velocity oscillations can be reasonably well interpreted using the theory of Alfven wave interaction with the thin ionospheric layer. Though the observed ratio between ROT and Doppler velocity amplitudes can be explained by the occurrence of local steep gradient of the topside ionosphere plasma at auroral latitudes, the responsible modulation mechanism cannot be considered as firmly established.

1. Introduction: ULF Wave Modulation of the Ionospheric Electrodynamics

The space community has obtained much of the information about ultralow frequency (ULF) waves in the near-Earth environment using ground- and satellite-based magnetometers. However, the capabilities of magnetometers are limited because they cannot measure in situ long-period ULF waves in the region where the energy transfer from the magnetosphere into the upper atmosphere occurs, namely, the ionosphere. Moreover, small-scale structures (<100 km) are screened by the ionosphere from ground magnetometers (Baddeley et al., 2005). That is why ionospheric radars have become such a valuable tool, providing additional information about magnetohydrodynamic (MHD) wave interaction with the ionosphere (Fenrich et al., 2006). The Super Dual Auroral Radar Network (SuperDARN) and ground magnetometers were found to be very effective in studies of latitudinal structure and azimuthal propagation characteristics of Pc3–5 waves (Ponomarenko et al., 2001; Ziesolleck et al., 1998). Some indications have been obtained that information on total electron content (TEC) of the ionosphere from global navigational satellite systems (GPS, GLONASS, etc.) can similarly provide a new clue on the modulation of the ionospheric plasma by ULF waves (Pilipenko et al., 2014; Watson et al., 2015).

Pc5 waves with periods 3–10 min are the most powerful wave process in the terrestrial environment, and they can significantly modulate the ionosphere, comprising the ionospheric electric field **E** and plasma convection velocity **V** (Lester et al., 2000; Norouzi-Sedeh et al., 2015; Sakaguchi et al., 2012); field-aligned current **j** (Fenrich et al., 2019); *E* layer electron density and ionosphere conductance (Belakhovsky et al., 2016); electron and ion temperatures in both *F* and *E* layers (Lathuillere et al., 1986; Pitout et al., 2003), and finally TEC (Davies & Hartman, 1976; Hamada et al., 2015; Okuzawa & Davies, 1981). However, a possible mechanism of the modification of the ionosphere by magnetospheric ULF disturbance has not yet been established.



Therefore, an examination of the impact on the ionosphere by disturbances of different physical nature, with simultaneous data from magnetometers and various ionosphere sounding techniques: radars, riometers, and GPS receivers, may provide an insight into the mechanism of the magnetosphere-ionosphere coupling.

Moreover, ULF wave activity in the ionosphere observed by radar is not just a replica of geomagnetic waves observed on the ground. Some obtained results are puzzling and still have not been comprehended. Ponomarenko et al. (2003) identified Pc4–5 activity in ~20% of scatter data, and only half of these radar oscillations had similar frequency spectra to those of magnetic fields observed by a nearby ground magnetometer. Sakaguchi et al. (2012) found that oscillations of ionospheric Doppler plasma velocity in the Pc5 band had the maximum of occurrence probability around the midnight, and almost no oscillation was observed on the dayside. These results indicated that the nighttime Pc5 oscillations. Therefore, the Pc5 wave power distributions obtained by radar observations may provide features different from those obtained from magnetic field observations. Therefore, the physics of the ionospheric ULF pulsations cannot be considered as firmly established.

In this case study we compare simultaneous magnetometer, TEC, and SuperDARN observations during the Pc5 wave event that occurred on 2 March 2002 (Baddeley et al., 2007). A possible correspondence between those instruments may help to determine the mechanism of the ionosphere modulation by magnetospheric disturbances.

2. Instrumentation and Data Analysis

Figure 1 shows the locations of the instrumentation used in this study. The magnetometer locations are indicated as blue triangles and are marked by their three-letter IAGA codes. The red dots with four-letter codes indicate the locations of the GPS receivers. The fields of view (FOV) of the King Salmon (KSR) and Kodiak (KOD) SuperDARN radars are shown as black and brown dots, respectively. These data sets are described in further detail below.

2.1. Ground-Based Magnetometer Network

The magnetometer data used in this study were obtained from the SuperMAG data portal (http://supermag. jhuapl.edu). The 2-D array of stations allows a construction of the latitudinal and longitudinal profiles of the ULF wave activity at a variety of LT. These data have a time resolution of 1 min and are provided in a local magnetic coordinate system $\mathbf{B} = \{X, Y\}$, where the *X* component corresponds in geomagnetic coordinates to the north–south (meridional) direction, and the *Y* component corresponds to the east–west (azimuthal) direction. The key magnetometers in the region under study are as follows: Pevek (PBK) with geographic coordinates 70.1°N, 170.9°E at geomagnetic latitude $\Phi = 65.4^{\circ}$ (LT noon at 01:30 UT); College (CMO) with coordinates 64.9° N, 212.1° E at $\Phi = 65.1^{\circ}$ (LT noon at 23:14 UT); and Barrow (BRW) with coordinates 71.30° N, 203.25° E at $\Phi = 70.0^{\circ}$ (LT noon at 00:11 UT).

2.2. GPS/TEC Data

To characterize the TEC variations we use the standard data with 30-s resolution from the array of GPS receivers from the international GNSS service (http://www.igs.org). Dual-frequency GPS methods use the phase information from the L1 (1575.42 MHZ) and L2 (1227.60 MHz) frequencies for estimating the slant TEC. The slant TEC has been recalculated into the vertical TEC $N_{\rm T}$, measured in TEC units (1 TECu = 10^{16} e/m^2), according to the relationship $N_{\rm T} = \text{TEC}_{\rm SLANT} \cdot \sin\alpha$, where α is the satellite elevation angle. To avoid uncertainties related to the determination of absolute values of N_T, we derived from GPS data the rate of TEC changes (ROT) $dN_{\rm T}/dt$ using the phase measurements only. A radio path between a ground receiver *STN* and GPS satellite with the pseudo-random-number *N* is denoted as *STN/N*.

2.3. SuperDARN High-Frequency Radars

The Kodiak and King Salmon radars are part of the SuperDARN, a global network of over 30 coherent scatter radars designed for studying global ionospheric convection. The radar technique allows high temporal and spatial resolution observations of ionospheric flow vectors \mathbf{V} in both the *E* and *F* regions of the ionosphere over a wide latitudinal and longitudinal area. The KOD radar covers western and Arctic Canada, and the KSR radar covers Alaska and eastern Arctic Russia. Each radar scans clockwise through 16 beams with an





Figure 1. Array of magnetometers and GPS receivers in the Northern Hemisphere used in the study. Magnetometers (three-letter codes) are denoted with blue triangles, GPS receivers (four-letter codes) are shown with red dots. The polar projection of the FOV of the SuperDARN radars Kodiak (KOD) and King Salmon (KSR) are plotted with dotted lines (beam numbering starts from 0, their beams #0 are highlighted). The solid bold red lines denote the ionospheric pierce points of the GPS-receiver radio paths (in the format STN/PRN) between a receiver STN and satellite with PRN number. The pierce-point of FAIR/28 radio path is shown with yellow line. Geomagnetic coordinates are shown with solid thin lines, geographic coordinates are shown with dotted lines.

azimuthal separation 3.24°. Each radar runs through a 16 beam scan with a dwell time of 3 s or 7 s, resulting in a full scan once every 1 min (KSR) or 2 min (KOD). Each beam is divided into 75 range gates with 45-km range resolution. A radar beam *N* is further denoted as KOD/*N* or KSR/*N* beam. The radars detect coherent backscatter from *F* region electron density irregularities and the measured Doppler velocity **V** corresponds to the component of the $\mathbf{E} \times \mathbf{B}_0$ drift velocity along the radar beam line of sight. ULF wave signatures are identified in the radar data as periodic fluctuations in the Doppler velocity which are superposed on the background convection flow.

3. Pc5 Event Occurred on 2 March 2002

On 2 March 2002 world-wide magnetometers record several activations of ULF activity in the Pc5 band. This global Pc5 wave activity occurs under an extended period of northward IMF ($B_z \sim 10$ nT), when the energy supply into the magnetosphere via the reconnection process is suppressed. The ongoing auroral activity (the SuperMAG SME index is ~150 nT) is probably fed by viscous interactions at the magnetopause and wave energy transfer into the magnetosphere. For a detailed analysis we concentrate on the time interval 15–17 UT.

To identify the time interval and region for in-depth analysis we plot snapshots of global distribution of 0.5-hr wave power (geomagnetic X component) in the band 1.7–7.0 mHz (Figure 2). These snapshots show that "epicenter" of Pc5 wave power is predominantly in the morning-noon sector, though Pc5





Figure 2. Snapshots of global distribution wave power of geomagnetic *X* component in the band 1.7–7.0 mHz (estimated with the Hilbert transform) during time interval (top, middle, bottom) 15–17 UT.

activations can be seen around noon and in the postnoon hours at 1600–1630 UT. Pc5 wave power intensification occurs in two latitudinal regions: around $\Phi \sim 66^{\circ}$ and $\Phi \sim 80^{\circ}$. As will be shown later, these regions correspond to different types of Pc5–6 pulsation activity.

4. Spatial Structure of Geomagnetic and Ionospheric Pulsations in the Pc5 Band

The entire event 04–18 UT was examined by Baddeley et al. (2007) using 5 magnetometer chains (covering 60–80° geomagnetic latitudes) in Scandinavia, Greenland, Canada, Alaska, and Russia. The characteristic resonant amplitude-phase latitudinal structure was identified in the dawn flank at resonant frequencies 1.7, 2.6, 3.3, 4.2, and 5.4 mHz. The data from a longitudinal profile indicated an antisunward propagation in both the dawn and dusk flanks with a moderate azimuthal wave number $m = 8 \pm 3$.

To examine the latitudinal and longitudinal structure of geomagnetic and ionospheric pulsations, we have constructed the profiles in geomagnetic coordinates from magnetometers and radar beams shown in Figure 1. During selected time interval 15–17 UT the KOD and KSR radars are in the morning sector.

The only available magnetometer latitudinal profile BRW-FYU-CMO-GAK along the geomagnetic longitude $\Lambda \sim 265^{\circ}$ is at Alaska (local noon is between 23–24 UT). The longitudinal profile along $\Phi \sim 65^{\circ}$ is formed by stations PBK-CMO-DAW-FSP-FMC in the range $\Lambda \sim 264-308^{\circ}$ (local noon is at 0130-2315-2300-2100-2000 UT, that is all stations are in the morning sector). The stacked magnetograms (X components) from the longitudinal profile along $\Phi \sim 65^{\circ}$ and latitudinal profile along $\Lambda \sim 265^{\circ}$ are shown in the left-hand and right-hand panels of Figure 3, respectively. During the time interval under consideration, two bursts of transient Pc5 pulsations are observed, starting at approximately 1530 UT and 1600 UT. The interplanetary OMNI data show that the geomagnetic and ionospheric ULF wave activities have been stimulated by jumps of the solar wind density from $\sim 2 \text{ cm}^{-3}$ to $\sim 8 \text{ cm}^{-3}$ around 1530 UT and 1600 UT on the background of steady solar wind velocity ~380 km/s (Figure 3, upper panels). Magnetograms from the longitudinal magnetometer profile indicate an antisunward wave propagation in the azimuthal direction (Figure 3, left-hand panel). The magnetometer latitudinal profile at

Alaska shows that Pc5 activity is concentrated in the range of geomagnetic latitudes ~63–67° (Figure 3, right-hand panel). At higher latitudes $\Phi \ge 70^{\circ}$ (BRW station), long-period quasi-periodic variations can be seen. These variations may be attributed to the specific daytime high-latitude irregular pulsations at cusp latitudes (IPCL) (Pilipenko et al., 2018).

From the available SuperDARN radar 2-D data for various beams and ranges we have constructed the Doppler velocity profiles along the geomagnetic north-south (N-S) and east-west (E-W) directions. Since SuperDARN radars measure only the line-of-sight (LOS) component of the velocity, these profiles have been constructed using data only from the beams which were closely aligned to the geomagnetic N-S and E-W directions. At KOD radar, the Doppler velocity shows periodic variations that start around 1530 UT and 1600 UT (Figure 4). Beams 4–5 of KOD correspond to the meridional direction, so they characterize the meridional component of the velocity pulsations, that is $V \sim V_x$. From a latitudinal profile of Doppler velocity oscillations constructed of the KOD data for various gates (Figure 4, right-hand panel), one can see that Pc5 waves are observed in the range of latitudes <70°, whereas at higher latitudes more intense (peak-to-peak amplitudes ~300–600 m/s) and irregular variations occur. These variations are the ionospheric signatures of IPCL. The SuperDARN FOV covers a wider range of latitudes as compared with





Figure 3. The magnetograms (B_x components) from the longitudinal along $\Phi \sim 65^\circ$ (left-hand panel) and latitudinal along $\Lambda \sim 260^\circ$ (right-hand panel) profiles. Two upper curves show the solar wind plasma density from the OMNI database. Geomagnetic coordinates are indicated near the station codes.

the available magnetometer array. Thus, the KOD/05 radar beam reveals besides Pc5 oscillations at $\Phi \sim 66-69^\circ$, irregular and intense quasiperiodic variations at higher latitudes 71–73°.

From the KSR multibeam radar data the longitudinal profile along $\Phi \sim 67^{\circ}$ may be constructed (Figure 5). Doppler velocity along the beam KSR/03 nearly corresponds to the azimuthal direction at $\Lambda \sim 63^{\circ}$, that is $V \sim V_y$. The observed pulsations are more monochromatic, having peak-to-peak amplitudes $V_y \sim 300$ m/s.

Ionospheric oscillations in the Pc5 band can be seen from the range-time-intensity (RTI) plots at all radars (Figure 6). An inclined pattern of the observed Doppler velocity indicates an apparent poleward propagation of the ionospheric Pc5 pulsations.

The large longitudinal extent of the wave activity extended over several beams in the radar FOV during this event enabled Baddeley et al. (2007) to ascertain the wave azimuthal scale size. Throughout the entire interval (~14 hr) when the wave was observed by radars the azimuthal number remained approximately constant, $m = 8 \pm 3$. The sign of phase delay indicated that the wave propagated in the westward (antisunward) direction along the ionosphere. The azimuthal scale of the wave was estimated to be $\lambda_y \sim 1,500$ km.

5. Comparison of Simultaneous Magnetometer, Radar, and TEC Variations

TEC data from various radio paths between GPS satellites and ground receivers have been compared with the simultaneous magnetometer and radar data. We present several examples of colocated magnetometer, radar, and TEC data for the 2 March 2002 event under consideration. We use the beam KSR/03, corresponding to the azimuthal direction, and the beam KOD/04, corresponding to the meridional direction.





Figure 4. The spatial structure of the Doppler velocity field for KOD radar during time interval 1,500–1,630 UT. (left-hand panel) The velocity from longitudinal along $\Phi \sim 67^{\circ}$ profile (beam number is shown near right-hand *Y* axis); (right-hand panel) the velocity along latitudinal along $\Lambda \sim 260^{\circ}$ profiles (gate numbers are indicated near right-hand axis).

Comparison of waveforms of KOD/04 beam Doppler velocity (upper panel), *ROT* from FAIR/08 track (middle panel), and magnetic field (*X* component) at CMO station (bottom panel) shows that transient Pc5 pulsations manifest themselves in all instruments (Figure 7, left-hand panel) with peak-to-peak amplitudes $V_x \sim 200 \text{ m/s}$, *ROT* ~ 0.2 TECu/min, and *X* ~ 15 nT. The pierce point is nearly above the magnetic station CMO. Spectra of simultaneous variations of magnetic field, ionospheric meridional velocity, and *ROT* from a radio path FAIR/08 during time interval 1520–1550 UT are shown in the same figure, but in the right-hand panel. Dominant frequency ~ 2.6 mHz (period ~6.4 min) is observed in time series from all instruments.

A similar comparison of waveforms of KOD/10 beam Doppler velocity (upper panel), *ROT* from INVK/23 track (middle panel), and magnetic field (*X* component) at BRW station (bottom panel) confirms a good correspondence between Pc5 signatures in all instruments (Figure 8, left-hand panel). Beam KOD/10 goes across the pierce point of the INVK/23 radio path. The meridional direction corresponds to the beam 04, where $V \sim V_x$, but variations at nearby beam 10 are very similar. BRW magnetometer is far from the pierce point, but at the same geomagnetic latitude. All variations are nearly in-phase. The peak-to-peak amplitudes of variations are $V_x \sim 300$ m/s, *ROT* ~ 1.0 TECu/min, and $X \sim 20$ nT. Spectra of both ionospheric and magnetic field variations (Figure 8, right-hand panel) confirms the occurrence of coherent Pc5 pulsations with frequency ~2.6 mHz.

Comparison of waveforms of KSR/03 beam Doppler velocity corresponding to the azimuthal direction (upper panel), ROT from BILI/18 track (middle panel), and magnetic field (*X* component) at PBK station (bottom panel) shows that transient Pc5 pulsations are observed by all instruments (Figure 9, left-hand panel) with peak-to-peak amplitudes $V_y \sim 300$ m/s, *ROT* ~ 0.06 TECu/min, and $X \sim 15$ nT. The GPS





Figure 5. The Doppler velocity at the longitudinal profile along $\Phi \sim 67^{\circ}$ (gate number is shown near right-hand *Y* axis) for KSR/03 radar.

pierce point of the BILI/18 radio path is nearly above PBK magnetic station. The corresponding spectra for the time interval 1520–1550 UT are shown in the right-hand panel of Figure 9. Pulsations with a dominant frequency of ~2.6 mHz are observed both in geomagnetic field and in the ionosphere.

Finally, a comparison of waveforms of Doppler radar velocity, *ROT* from two nearby radio paths, and magnetic field confirms a correspondence between Pc5 signatures in all instruments (Figure 10). The KOD/04 beam velocity (corresponding to V_x component) shows two bursts of transient Pc5 waves: starting at ~1530 UT with peak-to-peak amplitude ~300 m/s, and at ~1600 UT with amplitude ~70 m/s. Although the radio paths FAIR/28 and FAIR/08 are very close to each other (Figure 1), their *ROT* waveforms are not identical. The FAIR/08 *ROT* responds to both Pc5 transient pulsations with amplitudes ~0.4 TECu/min at ~1530 UT, and ~0.3 TECu/min at ~1600 UT, whereas the FAIR/28 *ROT* has a clear response only to the second Pc5 transient. The amplitude of simultaneous ground magnetic oscillations (X component) at CMO is ~10–15 nT.

Now let us summarize the results of the presented above examples. The ratio between the Doppler velocity **V** (either azimuthal or meridional components) and magnetic variations **B** (*X* and *Y* components) varied widely depending on a selected instrument pair. This ratio has been estimated as the ratio between the amplitude spectral densities at central frequency 2.6 mHz (right-hand panels of Figures 7–9). The results are as follows:

- 1. KOD radar: V_x/X (CMO) ~ 7 (m/s)/nT; V_x/X (DAW) ~ 12 (m/s)/nT,
- 2. KSR radar: V_y/X (PBK) ~ 25 (m/s)/nT.

The ratio of spectral densities between pulsations of the *ROT* and ionospheric velocity also varies in a wide range depending on a selected pair s follows:

- of instruments. The results are as follows:
- 1. ROT (FAIR/08)/ V_x (KOD/04) ~ 7.6 $\cdot 10^{-4}$ (TECu/min)/(m/s);
- 2. ROT (INVK/23)/ V_x (KOD/10) ~ 34·10⁻⁴ (TECu/min)/(m/s),
- 3. ROT (BILI/18)/ V_y (KSR/03) ~3.4·10⁻⁴ (TECu/min)/(m/s).

The obtained results provide a valuable information for modelers trying to interpret the effects of the ULF wave modulation of the ionosphere.

Here we have considered the amplitude relationships only. Phase relationships can be seen visually, for example, variations of ROT(t) and $V_y(t)$ are predominantly in-phase, whereas variations of $V_y(t)$ and magnetic X(t) component on the ground are out-of-phase; and some time delay between ionospheric Pc5 oscillations recorded along different paths can be seen. However, the phase relationships are not considered here.

6. Possible Mechanisms of the Ionosphere Modulation by ULF Waves

Several mechanisms of modulation of the ionospheric plasma and electromagnetic field by ULF wave may operate. The modulated precipitation of energetic electrons, causing ionization and polarization of the lower ionosphere and responsible for a disturbance recorded by riometers, can influence the bottom E and D layers making a patch with enhanced ionization (Spanswick et al., 2005). A resulting polarization electric field may penetrate from the E layer into the F layer and modify plasma in the upper ionosphere (Shalimov & Kozlovsky, 2015). However, during the event under consideration, a precipitation of energetic electrons and ionization of the lower ionosphere turn out to be weak, as evidenced by the MARIA riometers (http://www.sp-agency.ca/www/maria.htm) and cannot contribute noticeably into the ionospheric variations.





Figure 6. RTI plots for 15–17 UT on 2 March from the Kodiak (KOD) and King Salmon (KSR) HF radars. Each panel shows color-coded representation (flow away from the radar [negative velocity] is red, with flow toward the radar [positive velocity] blue) of the LOS ionospheric velocity measured by a single beam of each radar as a function of time over magnetic latitudes of 63–76°N.

The modulation of the ionospheric electrodynamics may be caused by the electric field of an incident MHD wave. The radar observations of ULF waves in the upper ionosphere can detect oscillations of the ionospheric plasma with velocity $\mathbf{V}=[\mathbf{E} \times \mathbf{B}_0]/B_0^2$, induced by a wave electric field \mathbf{E} . The corresponding \mathbf{E} field can be obtained as $\mathbf{E} = -[\mathbf{V} \times \mathbf{B}_0]$ from the radar \mathbf{V} data (the order of magnitude estimate is $V [\text{m/s}] = 20^{\circ} E [\text{mV}/\text{m}]$). At high latitudes the radar backscatter is sensitive to near-horizontal plasma motion $\mathbf{V} = \{V_x, V_y\}$. The horizontal components of the wave electric field as $V_x = (E_y/B_0) \sin I$, and $V_y = (E_x/B_0)/\sin I$. The geomagnetic field \mathbf{B}_0 is inclined to the ionosphere by the inclination angle *I*. A small contribution from V_z component, which can be obtained from a ground scatter, for the event under consideration is weak.

Here we provide simple order-of-magnitude estimates of the correspondence between the ionospheric velocity **V**, disturbances of TEC (*ROT*), and ground magnetic field **B**. We suppose that wave space-time structure is mimicked by a wave harmonic $\propto \exp(-i\omega t + ik_x x + ik_y y)$. On the ground, the theoretically modeled B_x component corresponds to the measured X component, and B_y component corresponds to Y component.

The interaction of ULF waves (Pc4–5 band) with the compound system magnetosphere – ionosphere-atmosphere-ground can be considered under the thin ionosphere approximation (Alperovich & Fedorov, 2007; Hughes & Southwood, 1976). Upon the interaction of an Alfven wave with the anisotropically conductive ionosphere, a secondary compressional mode is excited. This mode has an evanescent vertical structure, decaying with altitude *z* as $\alpha \exp(-kz)$. The excitation of this mode becomes noticeable only for rather small transverse scales, $k \ge 10^{-3}$ km⁻¹. In our event the Pc5 azimuthal and meridional scales in the ionosphere are $\lambda_y \sim 1,500$ km, and $\lambda_x \sim 600$ km (Baddeley et al., 2007), so the corresponding wave vectors are $k_y = 2\pi/\lambda_y \sim 4 \cdot 10^{-3}$ km⁻¹, and $k_x = 2\pi/\lambda_x \sim 10^{-2}$ km⁻¹. For such transverse scales (<600 km), the contribution of the secondary fast mode into the ULF wave structure in the *F* layer ($z \sim 200$ km) is less 10%. For a larger scale, the decay of wave amplitude

with altitude is not so dramatic, but excitation rate of the evanescent mode is low and it does not contribute to the dominant Alfven component E_x in the upper ionosphere. Therefore, it is fair to suppose that Pc5 electric field in the ionosphere is nearly totally composed from the Alfven wave mode. In a large-scale toroidal Alfven mode ($k_x \gg k_y$) the dominant horizontal components in the ionosphere are to be B_y , E_x , V_y . This mode is excited by MHD disturbances from the distant magnetosphere via the field line Alfven resonance.

From the general theory of the Alfven wave interaction with the thin ionosphere it follows that, upon the wave transmission through the ionosphere to the ground, the polarization ellipse rotates by $\pi/2$, so $B_y^{(m)} \rightarrow B_x$, and $B_x^{(m)} \rightarrow B_y$. The rate of the ground magnetic response to magnetospheric Alfven waves is controlled by the factor $\exp(-k_y h)$, where *h* is the height of the *E* layer. In our event $m \sim 5-11$ (Baddeley et al., 2007), which for $\Phi = 70^{\circ}$ is less than the critical value $m^* = (R_E/h)\cos\Phi \sim 22$, when a substantial screening by the ionosphere begins.

The excitation of Alfvenic field line oscillations takes place owing to the resonant MHD mode coupling in the magnetosphere. On the ground, a radial (latitudinal) structure of the resonant component $B_x(x)$ (corresponding to V_y component of plasma velocity in the ionosphere) in the vicinity of the resonant magnetic shell with coordinate x_0 produced by the mode conversion can be modeled as

$$B_x(x) = -B^{(m)} \frac{\Sigma_H}{\Sigma_P} \sin I \frac{i\delta_m}{x - x_o + i(\delta_m + h)}$$
(1)





Figure 7. (left-hand panels) Waveforms of KOD/04 radar radial Doppler velocity (upper panel), *ROT* from FAIR/08 track (middle panel), and magnetic field (B_x component) at CMO (bottom panel); (right-hand panels) spectra of simultaneous variations of the ionospheric Doppler velocity, ROT, and magnetic field, shown in the left-hand panel, during the time interval 1,520–1,550 UT.

Here δ_m is the width of the resonant peak above the bottom ionosphere, and $B^{(m)}$ is the peak value of resonant structure. The ground magnetic response to the magnetospheric resonant structure has the same spatial form as an incident wave, but the peak amplitude is somewhat reduced and smeared. The nonresonant component $B_y(x)$ (and corresponding V_x component in the ionosphere) should not reveal resonant features. In a coupled MHD structure, the Alfvenic part, described by Equation 1, dominates in the vicinity of the resonant peak.

In the SuperDARN ionospheric backscatter observations only the LOS velocity component is available. Therefore, if a beam is exactly aligned with a magnetic longitude (e.g., beam 5–8 of KOD), the poloidal wave component of the velocity V_x is seen, so the resonant features may be missed. If, on the other hand, a beam is aligned with a magnetic latitude (e.g., beam KSR/03) to see the toroidal wave component, V_y , one does not see the amplitude-phase resonant features across the resonance, but only the phase change is associated with the azimuthal propagation. Thus, the phase structure corresponding to Equation 1 (e.g., an apparent poleward propagation) can be seen in the SuperDARN data only, thanks to a "contamination" of nonresonant component by a resonant one.





Figure 8. (left-hand panels) Waveforms of KOD/10 radar Doppler radial velocity (upper panel), ROT from INVK/23 track (middle panel), and magnetic field (*X* component) at DAW (bottom panel); (right-hand panels) Spectra of simultaneous variations of the ionospheric Doppler velocity, ROT, and magnetic field, shown in the left-hand panel, during the time interval 1,520–1,550 UT.





Figure 9. (left-hand panels) Waveforms of KSR/03 radar Doppler azimuthal velocity (upper panel), ROT from BILI/18 track (middle panel), and magnetic field (*X* component) at PBK (bottom panel); (right-hand panels) Spectra of simultaneous variations of the ionospheric Doppler velocity, ROT, and magnetic field, shown in the left-hand panel, during the time interval 1,520–1,550 UT.

6.1. Doppler Velocity and Ground Magnetic Field Responses

If the Alfvenic structure is not very narrow, $\delta_m > h$, the experimentally measured ratio for the toroidal Alfven mode V_y component in the ionosphere to the ground magnetic disturbance, Bx, near the spatial maximum $(x \rightarrow x_o)$ is to be (Pilipenko et al., 2012)

$$\frac{V_y}{B_x} = \frac{V_H}{B_o \sin^2 I} = \left(\mu_o \Sigma_H B_0 \sin^2 I\right)^{-1} \tag{2}$$

The characteristic ionospheric velocities $V_{P,H} = (\mu_o \Sigma_{P,H})^{-1}$ (where magnetic constant $\mu_o = 4\pi \cdot 10^{-7}$ H/m) are determined by the height-integrated Pedersen Σ_P and Hall Σ_H conductances. For the order of magnitude





Figure 10. A comparison of waveforms of Doppler radar velocity (KOD/04 beam), ROT from two nearby radio paths FAIR/28 and FAIR/08, and magnetic field ($B_{\rm x}$ component) at CMO.

estimate the following relationships can be used $V[\text{km/s}] \approx 800/\Sigma[\text{S}]$ and $V[\text{m/s}]/X[\text{nT}]^{-1}4\Sigma_H^{-1}$. As predicted by Equation 2, for the same magnetic oscillation amplitude, the Alfven wave electric field and velocity amplitudes in the ionosphere must be higher under low conductivity.

In the ideal theoretical limit $(k_x \gg k_y)$, the wave components in the ionosphere, V_x and $B_y^{(m)}$, induced upon the toroidal Alfven wave interaction with the ionosphere, are to be much weaker than the components V_y and $B_x^{(m)}$. More realistically, finite E_y and $B_x^{(m)}$ components may emerge owing to a finite *m* value. A simple estimate of these components can be derived from the following consideration. Because in an incident Alfven wave $B_{\parallel} \propto |\nabla \times \mathbf{E}|_{\parallel} = k_x E_y - k_y E_x = 0$, for such a spatial structure $|V_x/V_y| \approx \sin^2 I |E_y/E_x| - \sin^2 I |k_y/k_x|$. From the ground observations $|k_y/k_x| \sim 0.4$, so V_x and *Y* components must be about 2 times weaker than V_y and *X* components. In fact, on the ground the $Y (\propto V_x)$ component is just ~20% weaker than the *X* component ($\propto V_y$) (see spectra in Figures 7–10).

No measurements of the exact ionospheric parameters Σ_P , Σ_H are available. The CMO station, during the event (~16 UT) is just before the apparent sunrise (~17 UT), whereas the PBK station is under a dark ionosphere, well before the sunrise (~20 UT) (https://www.esrl.noaa.gov/gmd/grad/solcalc). The ionospheric conductances predicted by the IRI-2016 model (http://wdc.kugi.kyoto-u.ac.jp/ionocond/sigcal) are rather low: Above CMO $\Sigma_P = 0.8$ S and $\Sigma_H = 0.6$ S, whereas above PBK $\Sigma_P = 0.3$ S and $\Sigma_H = 0.3$ S. The geomagnetic field in Alaska region is $B_0 \sim 56,000$ nT and its inclination is $I \sim 80^\circ$.

According to the estimate 2 for the IRI-predicted ionospheric conductances, during event the ratio, V_x/B_x , between the radial velocity

in the ionosphere (KOD) and ground magnetic response (CMO) must be ~23 (m/s)/nT. The observed ratio V_x/X between the KOD/10 beam and CMO magnetometer is ~7 (m/s)/nT (Figure 7), and for the KOD/04 beam and DAW magnetometer is ~12 (m/s)/nT (Figure 8). For the KSR/PBK pair, the V_y/B_x ratio for the IRI-predicted ionospheric parameters must be ~47 (m/s)/nT. In our event, the V_y/X ratio between the amplitude of the azimuthal ionospheric velocity at KSR/03 beam and ground magnetic response is ~25 (m/s)/nT (Figure 9). The observed relations qualitatively agree with the theoretical estimate with an accuracy ~50%, keeping in mind the simplicity of the model, uncertainty of the ionospheric background parameters, and mismatch between the radar backscatter location and position of a ground magnetometer.

6.2. TEC and Doppler Velocity Pulsations

Now let us consider the modulation of the ionospheric plasma density due to the interaction of an incident MHD wave with the ionosphere-atmosphere-ground system. Possible mechanisms of TEC modulation by incident fast compressional and Alfven waves are very different. The compressional mode induces the plasma compression, whereas the electric field of this mode in the ionosphere is weak (Teramoto et al., 2014). During our event the magnetospheric MHD wave may be a coupled Alfven and fast compressional mode. No satellite data in this sector are available to examine this possibility, so we suppose that a magnetospheric mode, especially in the vicinity of the resonance maximum, is predominantly composed from Alfvenic mode.

A plausible mechanism of TEC modulation may be related to field-aligned plasma transport (Belakhovsky et al., 2016). The field-aligned current and thermal electron flux transported by an Alfven wave causes a depletion or accumulation of plasma in the ionosphere. These electrons do not ionize the ionospheric plasma, but just pump/deplete the ionospheric plasma content. As a result, the plasma density in a region with a strong vertical gradient of $N_e(z)$ may increase/decrease. An upper estimate of variation of plasma density integrated along a flux tube, N_T , can be obtained from the height-integrated balance equation $\partial_t N_T = j_z/e$, where $e = 1.6 \cdot 10^{-190}$ C is the electron charge. The current j_z entering the upper ionosphere



by an Alfven wave is related to the transverse electric field \mathbf{E}_{\perp} in the ionosphere as follows: $j_z = -\text{Div}(\Sigma_P \mathbf{E}_{\perp})$, or by the order of magnitude, $|j_z| \approx \Sigma_P k_x |E_x|$. Combination of the balance equation with this estimate yields

$$\left|\frac{ROT}{V_y}\right| \approx e^{-1} \sin I k_x B_o \Sigma_P; \qquad \left|\frac{ROT}{V_x}\right| \approx \frac{k_x B_o \Sigma_P}{e \sin I} \left(\frac{k_x}{k_y}\right) \tag{3}$$

Substituting in Equation 3 $I = 80^{\circ}$, $k_x = 2\pi/600 \text{ km}^{-1}$, $\Sigma_P = 1 \text{ S}$, $B_o = 5.6 \cdot 10^4 \text{ nT}$, one can obtain the order of magnitude estimate $ROT[\text{TECu/min}]/V_y[\text{m/s}] 2 \cdot 10^{-5}$. The relationship (3) predicts that the TEC modulation due to periodic field-aligned electron flux, transported by an Alfven wave, should be related to ground magnetic variations as $ROT(t) \propto B_x(t)$. Such correspondence between variations of ROT(t) and B(t) can be used as a signature of this mechanism. However, the predicted value is about an order of magnitude less than the observed relationship $ROT/V_y \sim 3 \cdot 10^{-4} (\text{TECu/min})/(\text{m/s})$ for the BILI/18-KSR/03 pair. For the ratio ROT/V_x the estimate 3 predicts $ROT/V_x \sim 6 \cdot 10^{-5} (\text{TECu/min})/(\text{m/s})$ for $k_x/k_y = 2.5$. This ratio also is about magnitude of order less than the observed values $(3-30) \cdot 10^{-4} (\text{TECu/min})/(\text{m/s})$. Thus, other mechanisms should be considered.

The ionosphere modulation may be associated with the heating of the ionospheric ions during the plasma dragging through neutrals (having velocity $V_n = 0$ and temperature T_n). This effect in the Pc5 frequency range can be estimated using the relation for the frictional heating by quasi-DC electric field (Lathuillere et al., 1986) for a typical *F* layer plasma

$$\Delta T_i - T_n = 7.4 \cdot 10^{-4} (\mathbf{V})^2 \tag{4}$$

During the Pc5 event considered here (Figures 7–9), the oscillatory velocity $V \sim \pm 150$ m/s (Baddeley et al., 2007). Assuming that |V| = 300 m/s, it follows from Equation 4 that the Joule heating can cause the ion temperature enhancement up to $\Delta T_i \sim 70^{\circ}$ K. The plasma heating may shift the ionization-recombination balance due to the temperature-dependent recombination coefficient $\beta(T)$ and cause plasma density variations. The reaction rates of dominant *F* layer ion O+ with O₂ and N₂ neutrals and, consequently, recombination coefficient β , depend strongly on the temperature $\beta \propto T$, therefore, $\Delta\beta/\beta = \Delta T/T$ (Pilipenko et al., 2014). The periodic ion heating of the *F* layer plasma will cause the increase/decrease of recombination and, consequently, the periodic plasma density variations. In the most favorable case, when the periodicity of the temperature oscillations is larger than the recombination time, $\omega < \beta$, the linearization of the balance equation yields $\Delta N_T/N_T \approx \Delta\beta/\beta \approx \Delta T/T$. According to this estimate, for $T \sim 10^3$ K, and $\Delta T \sim 70$ K, the expected plasma modulation depth is to be $\Delta N_T/N_T \approx 7\%$. According to the TEC maps in Alaska region the absolute TEC values must be around $N_T \sim 5$ TECu. Therefore, for $\Delta N_T \sim 0.3$ TECu, the estimated amplitude of the *ROT* variations with period $T \sim 6.4$ min is $ROT \sim 2\pi\Delta N_T/T \sim 0.3$ TECu/min. This estimate is within the range of observed magnitude of periodic TEC modulation, $ROT \sim 0.2-1.0$ TECu/min (Figures 7–9).

Another plausible TEC modulation mechanism may comprise a periodic drift with velocity **V** across a lateral gradient of the ionospheric plasma, namely $\partial N_T/\partial t = (\mathbf{V}\nabla)N_T$ (Waters & Cox, 2009). Assuming that a largest lateral gradient is in the N-S direction, that is at latitude distance $\Delta \Phi$ [deg] the TEC value varies by ΔN_T , the possible variations of TEC can be estimated as

$$\frac{ROT \ [\text{TECu/min}]}{V_x \ [\text{m/s}]} \approx 5 \cdot 10^{-4} \frac{\Delta N_T}{\Delta \Phi}$$
(5)

A latitudinal gradient of TEC for the event under consideration has been roughly estimated from global TEC maps from the portal (http://vt.superdarn.org) as $\Delta N_T / \Delta \Phi \sim 4$ TECu/deg. Thus, the expected normalized effect as follows from the estimate (5) may be $ROT/V_x \sim 2 \cdot 10^{-3}$ (TECu/min)/(m/s). Therefore, such latitudinal gradient of TEC may be sufficient to produce the observed TEC modulation by Alfven waves ~(0.8–3.0) \cdot 10^{-3} (TECu/min)/(m/s). The occurrence of a wide range of plasma inhomogeneities in the auroral upper ionosphere may explain a large variety of the observed TEC responses to Pc5 waves, even at close radio paths.



Modulated precipitation of soft electrons cannot be detected by riometers but can cause additional ionization in the F layer. However, this assumption cannot be validated because of lack of relevant data from any ground instrument (e.g., imagers) or LEO satellites.

7. Discussion

During the event under study, impulses of the solar wind density trigger transient Pc5 pulsations recorded by ionospheric radars and ground magnetometers. The GPS/TEC technique turns out to be sensitive enough to detect Pc5 waves even with a moderate amplitude on the ground, ~20 nT. The previously reported effects of TEC modulations by global Pc5 waves were observed for very intense pulsations, ~200 nT (Pilipenko et al., 2014). The relationships between amplitudes of simultaneous periodic variations of the ionospheric plasma velocity and geomagnetic field can be reasonably well interpreted on the basis of the theory of Alfven wave interaction with the thin ionospheric layer. At the same time, our brief theoretical consideration of several plausible mechanisms that may be responsible for TEC modulation by Pc5 waves, such as periodic plasma heating, convection across a steep gradient, and field-aligned electron transport, has shown that these mechanisms could interpret quantitatively the observed effects only under a very favorable set of parameters. The mechanism of TEC modulation owing to the plasma field-aligned transfer may produce a noticeable effect only under very high amplitudes (>100 nT) of Pc5 waves as in the events considered by Pilipenko et al. (2014) and Belakhovsky et al. (2016). The effect of TEC modulation by Pc5 waves possibly may be caused by a strong latitudinal gradient of the topside ionospheric plasma. The ion heating and consequent modification of the recombination coefficient may also contribute to the TEC modulation by the Alfven wave electric field. However, many ionospheric parameters used in the above estimates are unknown for the event under study, which does not allow us to make a definite judgment about validity of one or another mechanism. Any future theory must be capable to explain the observed relationships between the periodic variations of *ROT*, ionospheric Doppler velocity, and ground magnetic response.

The periodic increase in the F region electron temperature stimulated by Pc5 waves was observed by the EISCAT radar (Pitout et al., 2003). Modeling indicated that the heating was not as a result of electron precipitation (due to the fact that the electron energy was too low to account for the observed F region ionization) but was due to the electron thermal conductivity from the downgoing electron heat flux. The possibility that field-aligned currents are transported predominantly by low-energy electrons, which may produce ionization of the F region plasma, should be theoretically modeled. If this possibility is feasible then the GPS/TEC observations would be a tool to monitor precipitation of such electrons.

Besides classical Pc5 waves, considered here, radar analysis of other long-period ULF events revealed many puzzling wave phenomena. The morphological properties of these types of ionospheric oscillations in the Pc5 band were very different from those of classical geomagnetic Pc5 waves. Mtumela et al. (2016) found several Pc5-6 global events over an unusually large range of longitudes (>120°) on the afternoon/dusk side during very quiet geomagnetic conditions ($Dst \sim 0$). In contrast to typical geomagnetic Pc5 waves, their sense of azimuthal phase propagation was westward (sunward) with the azimuthal wave number $m \sim 7-12$. This sunward propagation was attributed to oscillations generated by earthward flows in the magnetotail, though no supporting data sets have been found for this suggestion. Ionospheric Pc5 oscillations presented in (Sakaguchi et al., 2012) also hardly can be associated with classical Pc5 waves. Oscillations of ionospheric Doppler velocity in the Pc5 band observed by the SuperDARN KSR radar had no relation with solar wind velocity, dynamic pressure, or geomagnetic indices, and local time distributions of the ionospheric Pc5 oscillations showed the maximal occurrence probability around the midnight, whereas backscatter echoes exhibited almost no oscillation on the dayside. These results indicated that the nighttime toroidal Pc5 oscillations in the ionospheric plasma flow do not represent well-known characteristics of Pc5 geomagnetic pulsations. Shi et al. (2018) found that ionospheric signatures of Pc5 waves (~2 mHz) dominated at high and polar latitudes in the dusk sector and during winter. The observed occurrence rate was very different from known geomagnetic Pc5 wave morphology. The existence of ionospheric oscillations in the Pc5/Pi3 band without a ground magnetic response were noticed in (Bland & McDonald, 2016; Kozyreva et al., 2019; Scoular et al., 2013). So far, the mechanisms of these ionospheric fluctuations and their association with geomagnetic pulsations still have not been established. Thus, ULF activity in the ionosphere is not just a replica of



geomagnetic ULF waves observed on the ground. A coordinated radar, GPS, and geomagnetic analysis of those long-period ULF events might be useful to reveal the physics of those puzzling wave phenomena.

In the event under consideration, high-latitude pulsations beyond the nominal Pc5 band (IPCL-type) have been detected by the KOD radar and high-latitude magnetometer (BRW). The possibility of TEC response to IPCL cannot be examined owing to the lack of appropriate GPS receivers at high latitudes in this region and will be considered elsewhere.

8. Conclusion

Impulses of the solar wind density trigger transient Pc5 pulsations on the morning flank of the magnetosphere both in geomagnetic field and ionospheric plasma. GPS/TEC technique has turned out to be sensitive enough to detect Pc5 waves even with a moderate amplitude on the ground, ~20 nT. The presented results are the first simultaneous observations of Pc5 waves by radar, GPS, and magnetometer. The measured ratios between spectral amplitudes of Doppler velocity, TEC, and ground magnetic field oscillations can be a basis for future theories of ULF wave modulation of the ionosphere. The relationships between amplitudes of periodic variations of the ionospheric Doppler velocity and geomagnetic field have been reasonably well interpreted on the basis of the theory of Alfven wave interaction with the thin ionosphere. Although the presented observational results have provided additional evidence of substantial modulation of the ionosphere TEC by ULF waves, one still cannot say that responsible modulation mechanism is well comprehended. The considered mechanisms, such as the periodic ion heating and field-aligned plasma transport, seemingly cannot alone interpret the observed effects. Assuming the occurrence of local steep gradient of the top-side ionospheric plasma, larger than ~1 TECu/deg, may be sufficient to produce the observed TEC modulation by Alfven waves. So far, the effect of TEC modulation by Pc5 waves is a challenge for the MHD wave theory, because the responsible mechanism of such modulation has not been firmly established yet. Combined usage of magnetometers, ionospheric radars, and GPS/TEC is a very perspective way to reveal the physical mechanism of the ionosphere modulation. It may open a possibility to monitor a modulated precipitation of soft electrons, which cannot be detected by riometers.

Data Availability Statement

- 1. SuperDARN radar data from the British Antarctic Survey data mirror (https://www.bas.ac.uk/ project/superdarn).
- 2. One minute publicly available magnetometer data from SuperMAG (http://supermag.jhuapl.edu) and INTERMAGNET (http://www.intermagnet.org) arrays.
- 3. GPS 30-s open data from IGS (http://www.igs.org).
- 4. TEC maps are publicly available via the Virginia Tech website (http://vt.superdarn.org).
- 5. OMNI (https://omniweb.gsfc.nasa.gov).

References

- Alperovich, L. S., & Fedorov, E. N. (2007). Hydromagnetic waves in the magnetosphere and the ionosphere. In Astrophysics and Space Science Library 353 (p. 456). The Netherlands: Springer. https://doi.org/10.1007/978-1-4020-6637-5
- Baddeley, L. J., Yeoman, T. K., McWilliams, K. A., & Wright, D. M. (2007). Global Pc5 wave activity observed using SuperDARN radars and ground magnetometers during an extended period of northward IMF. *Planetary and Space Science*, 55, 792–808.
- Baddeley, L. J., Yeoman, T. K., & Wright, D. M. (2005). HF Doppler sounder measurements of the ionospheric signatures of small scale ULF waves. Annales Geophysicae, 23, 1807–1820.
- Belakhovsky, V., Pilipenko, V., Murr, D., Fedorov, E., & Kozlovsky, A. (2016). Modulation of the ionosphere by Pc5 waves observed simultaneously by GPS/TEC and EISCAT. *Earth, Planets and Space*, 68, 102. https://doi.org/10.1186/s40623-016-0480-7
- Bland, E. C., & McDonald, A. J. (2016). High spatial resolution radar observations of ultralow frequency waves in the southern polar cap. *Journal of Geophysical Research: Space Physics*, 121, 4005–4016. https://doi.org/10.1002/2015JA022235
- Davies, K., & Hartman, G. K. (1976). Short-period fluctuations in total columnar electron content. *Journal of Geophysical Research*, *81*, 3431–3434.
- Fenrich, F. R., Gillies, D. M., Donovan, E., & Knudsen, D. (2019). Flow velocity and field aligned current associated with field line resonance: SuperDARN measurements. *Journal of Geophysical Research: Space Physics*, 124, 4889–4904. https://doi.org/10.1029/ 2019JA026529
- Fenrich, F. R., Waters, C. L., Connors, M., & Bredeson, C. (2006). Ionospheric signatures of ULF waves: Passive radar techniques. In Magnetospheric ULF waves: Synthesis and new directions, Geophysical Monograph (pp. 259–271). Washington, DC: AGU.
- Hamada, A. M., Mahrous, A. M., Fathy, I., Ghamry, E., Groves, K., & Yumoto, K. (2015). TEC variations during geomagnetic storm/substorm with Pc5/Pi2 pulsation signature. *Advances in Space Research*, *55*, 2534–2542.

Acknowledgments

This study was supported by the Grant 20-05-00787 from the Russian Fund for Basic Research (O. V. K. and V. A. P.), Grant ES647692 from the program INTPART of Research Council of Norway (L. J. B.), and Contract 223,252/ F50 from the Research Council of Norway (E. C. B.).



- Hughes, W. J., & Southwood, D. J. (1976). The screening of micropulsation signals by the atmosphere and ionosphere. Journal of Geophysical Research, 81(19), 3234–3240.
- Kozyreva, O., Kozlovsky, A., Pilipenko, V., & Yagova, N. (2019). Ionospheric and geomagnetic Pc5 oscillations as observed by the ionosonde and magnetometer at Sodankylä. Advances in Space Research, 63, 2052–2065. https://doi.org/10.1016/j.asr.2018.12.004
- Lathuillere, C., Glangeaud, F., & Zhao, Z. Y. (1986). Ionospheric ion heating by ULF Pc 5 magnetic pulsations. *Journal of Geophysical Research*, 91, 1619–1626.
- Lester, M., Davies, J. A., & Yeoman, T. K. (2000). The ionospheric response during an interval of Pc5 ULF wave activity. *Annales Geophysicae*, 18, 257–261.
- Mtumela, Z., Walker, A. D. M., Stephenson, J. A. E., & Kosch, M. J. (2016). Large-scale coordinated observations of Pc5 pulsation events. Annales Geophysicae, 34, 857–870. https://doi.org/10.5194/angeo-34-857-2016.
- Norouzi-Sedeh, L., Waters, C. L., & Menk, F. W. (2015). Survey of ULF wave signatures seen in the Tasman International Geospace Environment Radars data. *Journal of Geophysical Research: Space Physics*, *120*, 949–963. https://doi.org/10.1002/2014JA020652
- Okuzawa, T., & Davies, K. (1981). Pulsations in the total columnar electron content. *Journal of Geophysical Research*, *86*, 1355–1363.
 Pilipenko, V., Belakhovsky, V., Kozlovsky, A., Fedorov, E., & Kauristie, K. (2012). Determination of the wave mode contribution into the ULF pulsations from combined radar and magnetometer data: Method of apparent impedance. *Journal of Atmospheric and Solar Terrestrial Physics*, *77*, 85–95.
- Pilipenko, V., Belakhovsky, V., Murr, D., Fedorov, E., & Engebretson, M. (2014). Modulation of total electron content by ULF Pc5 waves. Journal of Geophysical Research: Space Physics, 119, 4358–4369. https://doi.org/10.1002/2013JA019594
- Pilipenko, V. A., Kozyreva, O. V., Lorentzen, D. A., & Baddeley, L. J. (2018). The correspondence between dayside long-period geomagnetic pulsations and the open-closed field line boundary. *Journal of Atmospheric and Solar - Terrestrial Physics*, 170, 64–74. https://doi.org/ 10.1016/j.jastp.2018.02.012
- Pitout, F., Eglitis, P., & Blelly, P.-L. (2003). High-latitude dayside ionosphere response to Pc5 field line resonance. *Annales Geophysicae*, 21, 1509–1520.
- Ponomarenko, P. V., Menk, F. W., & Waters, C. L. (2003). Visualization of ULF waves in SuperDARN data. Geophysical Research Letters, 30(18), 1926. https://doi.org/10.1029/2003GL017757
- Ponomarenko, P. V., Waters, C. L., Sciffer, M. D., & Fraser, B. J. (2001). Spatial structure of ULF waves: Comparison of magnetometer and Super Dual Auroral Radar Network data. Journal of Geophysical Research, 106, 10,509–10,517.
- Sakaguchi, K., Nagatsuma, T., Ogawa, T., Obara, T., & Troshichev, O. A. (2012). Ionospheric Pc5 plasma oscillations observed by the King Salmon HF radar and their comparison with geomagnetic pulsations on the ground and in geostationary orbit. *Journal of Geophysical Research*, 117, A03218. https://doi.org/10.1029/2011JA016923
- Scoular, G., Ponomarenko, P. V., & St.-Maurice, J. P. (2013). A new type of Doppler velocity fluctuations in HF ground scatter from the polar cap. *Geophysical Research Letters*, 40, 4992–4997. https://doi.org/10.1002/grl.50960
- Shalimov, S., & Kozlovsky, A. (2015). High-latitude E and F region coupling signature: A case study results from rapid-run ionosonde. *Journal of Geophysical Research: Space Physics, 120,* 3033–3041. https://doi.org/10.1002/2014JA020589
- Shi, X., Ruohoniemi, J. M., Baker, J. B. H., Lin, D., Bland, E. C., Hartinger, M. D., & Scales, W. A. (2018). Survey of ionospheric Pc3-5 ULF wave signatures in SuperDARN high time resolution data. *Journal of Geophysical Research: Space Physics*, 123, 4215–4231. https://doi. org/10.1029/2017JA025033
- Spanswick, E., Donovan, E., & Baker, G. (2005). Pc5 modulation of high energy electron precipitation: Particle interaction regions and scattering efficiency. Annales de Geophysique, 23, 1533–1542.
- Teramoto, M., Nishitani, N., Pilipenko, V., Ogawa, T., Shiokawa, K., Nagatsuma, T., et al. (2014). Pi2 pulsation simultaneously observed in the *E* and *F* region ionosphere with the SuperDARN Hokkaido radar. *Journal of Geophysical Research: Space Physics*, *119*, 3444–3462. https://doi.org/10.1002/2012JA018585
- Waters, C. L., & Cox, S. P. (2009). ULF wave effects on high frequency signal propagation through the ionosphere. *Annales Geophysicae*, 27, 2779–2788.
- Watson, C., Jayachandran, P. T., Singer, H. J., Redmon, R. J., & Danskin, D. (2015). Large-amplitude GPS TEC variations associated with Pc5–6 magnetic field variations observed on the ground and at geosynchronous orbit. *Journal of Geophysical Research: Space Physics*, 120, 7798–7821. https://doi.org/10.1002/2015JA021517
- Ziesolleck, C. W. S., Fenrich, F. R., Samson, J. C., & McDiarmid, D. R. (1998). Pc5 field line resonance frequencies and structure observed by SuperDARN and CANOPUS. *Journal of Geophysical Research*, *103*(A6), 11,771–11,785. https://doi.org/10.1029/98JA00590