

RESEARCH ARTICLE

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Survey of Ionospheric Pc3-5 ULF Wave Signatures in SuperDARN High Time Resolution Data

Key Points:

- Pc5 waves occur predominantly at high and polar latitudes with a most probable frequency of 2.08 plus-minus 0.07 mHz, while Pc3-4 waves are relatively more common at midlatitudes on the nightside with a most probable frequency of 11.39 plus-minus 0.14 mHz
- At high latitudes, Pc4-5 wave occurrence rate peaks in the duskside ionosphere and during winter
- At midlatitudes, Pc3-4 wave occurrence rate peaks premidnight and during equinox

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Abstract Ionospheric signatures of ultralow frequency (ULF) wave in the Pc3-5 band (1.7–40.0 mHz) were surveyed using ~6-s resolution data from Super Dual Auroral Radar Network (SuperDARN) radars in the Northern Hemisphere from 2010 to 2016. Numerical experiments were conducted to derive wave period-dependent thresholds for automated detection of ULF waves using the Lomb-Scargle periodogram technique. The spatial occurrence distribution, frequency characteristics, seasonal effects, solar wind condition, and geomagnetic activity level dependence have been studied. Pc5 wave events were found to dominate at high and polar latitudes with a most probable frequency of 2.08 ± 0.07 mHz, while Pc3-4 waves were relatively more common at midlatitudes on the nightside with a most probable frequency of 11.39 ± 0.14 mHz. At high latitudes, the occurrence rate of Pc4-5 waves maximizes in the dusk sector and during winter. These events tend to occur during low geomagnetic activity and northward interplanetary magnetic field. For the category of radially bounded but longitudinally extended Pc4 events in the duskside ionosphere, an internal driving source is suggested. At midlatitudes, the poloidal Pc3-4 occurrence rate maximizes premidnight and during equinox. This tendency becomes more prominent with increasing auroral electrojet (AE) index and during southward interplanetary magnetic field, which suggests that many of these events are Pi2 and Pc3-4 pulsations associated with magnetotail dynamics during active geomagnetic intervals. The overall occurrence rate of Pc3-5 wave events is lowest in summer, which suggests that the ionospheric conductivity plays a role in controlling ULF wave occurrence.

1. Introduction

Ultralow frequency (ULF) waves are magnetohydrodynamic (MHD) plasma waves in the frequency band of roughly 1 mHz to several hertz. They are ubiquitous and have been observed in geospace and on the ground for over 50 years (e.g., Dungey, 1954; Saito, 1969). ULF waves were originally called micropulsations or magnetic pulsations since they were first observed by ground magnetometers. ULF pulsations are classified into two types: pulsations continuous (Pc) and pulsations irregular (Pi) with several subclasses (Pc1-5 and Pi1-2) according to their frequencies and durations (Jacobs et al., 1964). With respect to polarization, ULF waves can be categorized into three modes: poloidal (ΔB_r , ΔE_ϕ), compressional ($\Delta B_{//}$, ΔE_ϕ), and toroidal (ΔB_ϕ , ΔE_r). Here $B_r(E_r)$, $B_{//}$, and $B_\phi(E_\phi)$ are the radial, parallel (or compressional), and azimuthal components in the local magnetic field system, respectively. ULF waves are believed to play important roles in magnetospheric plasma energization and loss and energy transfer from the solar wind to the Earth's magnetosphere and ionosphere (Elkington et al., 1999; Mathie & Mann, 2000; Zong et al., 2009).

Numerous studies have used ground magnetometer and spacecraft measurements to study ULF pulsation occurrence statistics and source mechanisms (e.g., Anderson, 1994). Several theories have been proposed for the excitation mechanisms of ULF waves observed in the Earth's magnetosphere. For example, it has been shown that poloidal Pc4 (6.7–22.2 mHz) waves, which are believed to be an example of a second harmonic field line resonance (FLR; Hughes & Grard, 1984; Takahashi & McPherron, 1984), are most often seen in the afternoon sector and are associated with localized sources (e.g., Anderson et al., 1990). Compressional and poloidal Pc5 (1.7–6.7 mHz) waves are usually observed on the nightside and flanks of the magnetosphere and are related to internal driving sources such as the drift mirror instability (Hasegawa, 1969) and the drift/drift-bounce resonance instability (Dai et al., 2013; Southwood et al., 1969; Southwood & Kivelson, 1982).

The internal sources are expected to generate poloidal waves with high azimuthal wave numbers (high- m). Toroidal Pc5 waves of fundamental mode FLR are more often seen on the dawn and dusk flanks and are often associated with external driving sources such as variations in the solar wind dynamic pressure (Hudson et al., 2004; Kepko & Spence, 2003) and Kelvin-Helmholtz waves at the magnetopause (Anderson et al., 1990; Lin et al., 2014). The externally driven waves mostly propagate antisunward with low azimuthal wave numbers (low- m). Modeling has shown that many external or internal mechanisms can be viable under appropriate conditions (Kivelson & Southwood, 1985; Lee & Lysak, 1989; Ozeke & Mann, 2001); however, positively identifying a source mechanism has proven to be rather difficult due to limited measurements.

ULF waves in the ionosphere have been studied using radars. The Super Dual Auroral Radar Network (SuperDARN) is a global network of ground-based high-frequency (HF: 3–30 MHz) radars designed primarily for studying ionospheric plasma convection (Chisham et al., 2007). The line-of-sight velocity measured by SuperDARN radars can be used to detect and monitor ionospheric ULF wave signatures with both high- and low- m (Fenrich et al., 1995; James et al., 2013) and with a total geographical coverage area that cannot be achieved with any other ground- or space-based instrumentation. Based on a new data display technique developed by Ponomarenko et al. (2003), SuperDARN-detected ULF wave signatures have been characterized in a few recent studies (e.g., Bland et al., 2014; Norouzi-Sedeh et al., 2015; Sakaguchi et al., 2012). These studies have been largely limited to the Pc5 range since SuperDARN radars are normally scheduled for 1-min azimuthal sweeps in the common mode (e.g., Bland et al., 2014; Sakaguchi et al., 2012). ULF wave studies using higher time resolution SuperDARN data have been either case studies (e.g., Shi et al., 2017) and/or statistical studies using one or two radars covering a limited range of latitudes (e.g., Norouzi-Sedeh et al., 2015). The lack of comprehensive studies could be partially attributed to the absence of a database of high time resolution observations and no efficient way to identify ULF wave signatures in the SuperDARN data set. Recently, Bland et al. (2014) presented a method for automatically detecting signatures of ULF waves in SuperDARN radar data, which used the Lomb-Scargle periodogram to identify periodic fluctuations in the Doppler velocity. In this study we improve upon this method and apply it to 7 years of high time resolution data from 17 SuperDARN radars in the Northern Hemisphere. We investigate the occurrence and frequency characteristics of ULF wave signatures in the Pc3-5 band and discuss possible source mechanisms for these waves.

2. Instrumentation and Event Detection Method

2.1. SuperDARN

SuperDARN is an international network consisting of more than 30 low-power HF (8–20 MHz) coherent scatter radars at middle to polar latitudes in both hemispheres that look into Earth's ionosphere (Baker et al., 2007; Chisham et al., 2007). The radars measure Doppler shifts of ionospheric irregularities at F region altitudes undergoing $\vec{E} \times \vec{B}$ plasma drift. When ULF waves pass through the ionosphere, the associated electric field produces a Doppler velocity oscillation that can be measured by the radars.

Normally, the SuperDARN radars are scheduled for 1-min azimuthal sweeps in the “common” mode. The step in azimuth between adjacent beams is 3.24° and the range resolution is 45 km. Sometimes, radars are scheduled to operate in a special mode called Time History of Events and Macroscale Interactions during Substorms “THEMIS” mode, in which a camping beam is sampled at a higher rate of ~ 6 s by interleaving soundings on the camping beam with successive beams of the normal scan. Figure 1 shows the fields of view of 17 Northern Hemisphere SuperDARN radars in Altitude Adjusted Corrected Geomagnetic (AACGM) coordinates (Baker & Wing, 1989). Only radars which have been operated regularly in the THEMIS mode in channel A during the interval 2010–2016 are shown, and the camping beam for each radar is highlighted in cyan. An example period of THEMIS mode observations from beam 6 of the Saskatoon (SAS) radar during 03:30–04:30 UT on 16 February 2015 is shown in Figure 2. ULF signatures manifest themselves as alternating red and blue stripes in the range-time intensity plot in Figure 2a with positive (blue-green) values corresponding to motion toward the radar. Figure 2b shows the time series of Doppler velocity measured in range gate 13, where wave-like signatures with a few gaps are visible.

2.2. Data Processing and Event Selection

The data processing procedures are similar to those in Bland et al. (2014). First, we select for ionospheric backscatter and reject ground scatter by requiring backscatter to satisfy one of the following conditions: (1) Doppler velocity $|V| \geq 50$ m/s; (2) spectral width $W \geq 50$ m/s; (3) backscatter is flagged as ionospheric backscatter by the standard SuperDARN ground/ionospheric condition (Blanchard et al., 2009). Next, poor quality data are filtered out if backscatter power is less than 3 dB or errors in Doppler velocity or spectral width

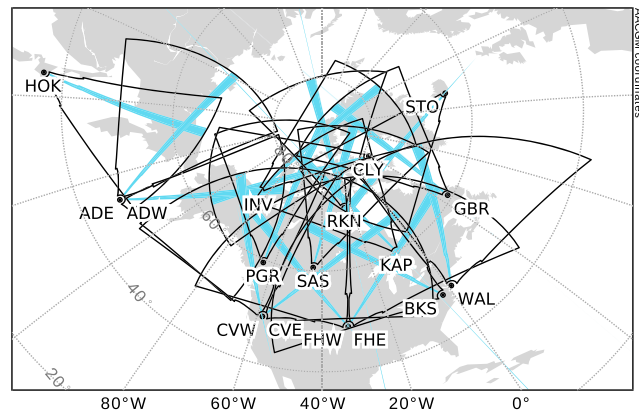


Figure 1. Fields of view of 17 Northern Hemisphere SuperDARN radars in AACGM coordinates. Cyan highlighted beams indicate the camping beams. AACGM = Altitude Adjusted Corrected Geomagnetic; SuperDARN = Super Dual Auroral Radar Network.

is greater than 100 m/s. Data from ranges less than 765 km are excluded to minimize contamination from meteor and *E* region scatter. To search for Pc5 (Pc3-4) signatures, a 1-hr (0.5-hr) interval is used which is incremented by 15 (7.5) min iteratively. The ionospheric backscatter time series is high-pass filtered by subtracting the median value of a sliding window of 10 (5) min length for Pc5 (Pc3-4). Further restrictions are applied to the candidate intervals to weaken large data gap effects: (1) the largest time step between consecutive records should be less than 10% of the time interval (i.e., 6 min for Pc5 and 3 min for Pc3-4); (2) the number of measurements should be no less than 400 for Pc5 and 200 for Pc3-4 (i.e., two thirds of the total number assuming a 6-s sampling rate). Qualified intervals are selected as valid ionospheric backscatter measurements and tested for periodic behavior in the Doppler velocity.

Data gaps occur in the radar time series complicating the application of Fourier spectral analysis. While data interpolation can be applied, spurious spikes in the spectrogram are likely to mislead the identification of wave period. We instead applied the Lomb-Scargle periodogram technique for ULF wave signature identification, which is especially advantageous for unevenly sampled signals (Lomb, 1976; Scargle, 1982). A sufficiently high value of the normalized peak power (NPP) of a Lomb-Scargle periodogram indicates the existence of a wave signature at the associated period. In order to establish the significance of spectral peaks resulting from the Lomb-Scargle periodogram analysis and implement the automated algorithm to search wave signatures,

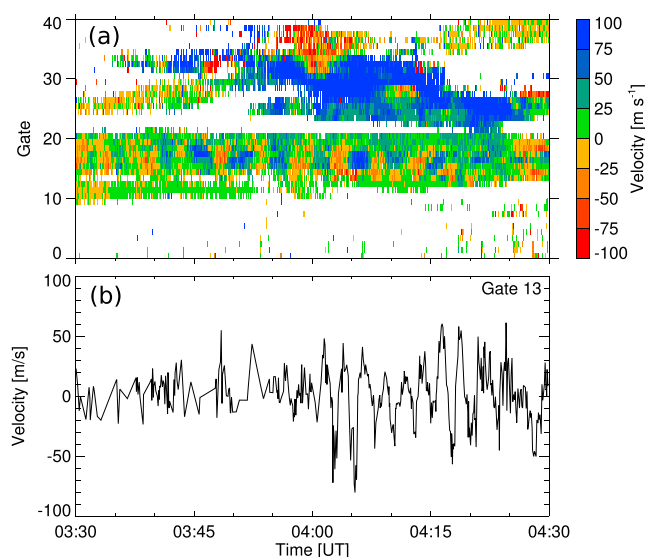


Figure 2. Time series of Time History of Events and Macroscale Interactions during Substorms mode data measured on beam 6 of the Saskatoon radar on 16 February 2015 from 03:30 to 04:30 UT: (a) Range-time intensity plot of Doppler velocity; (b) time series of Doppler velocity for range gate 13.

Table 1*Empirical Equations of Threshold NPP Dependence on Wave Period With Signal Length From 66.7% to 133.3% of Ideally Even Sampled Length in the Pc3-4 and Pc5 Range*

N_{pts}	Pc3-4	N_{pts}	Pc5
200	$\text{NPP} = 0.72\tilde{T}_{\text{sin}} + 6.8$	400	$\text{NPP} = 0.49\tilde{T}_{\text{sin}} + 16.7$
250	$\text{NPP} = 0.94\tilde{T}_{\text{sin}} + 6.3$	500	$\text{NPP} = 0.60\tilde{T}_{\text{sin}} + 19.0$
300	$\text{NPP} = 1.09\tilde{T}_{\text{sin}} + 6.5$	600	$\text{NPP} = 0.71\tilde{T}_{\text{sin}} + 21.2$
350	$\text{NPP} = 1.25\tilde{T}_{\text{sin}} + 6.6$	700	$\text{NPP} = 0.82\tilde{T}_{\text{sin}} + 23.8$
400	$\text{NPP} = 1.40\tilde{T}_{\text{sin}} + 7.0$	800	$\text{NPP} = 0.95\tilde{T}_{\text{sin}} + 25.0$

wave period-dependent spectrum thresholds are derived based on a series of numerical experiments. Details about the derivation of threshold NPP can be found in the Appendix A.

A ULF wave event is identified if the returned NPP is above the threshold listed in Table 1. The event is classified as Pc5 waves if the frequency is within 1.7–6.7 mHz and Pc3-4 waves if within 6.7–40.0 mHz. ULF wave event examples detected by the automated algorithm are shown in Figure 3. Left panels are measurements from beam 12 of the Prince George (PGR) radar during 01:00–01:30 UT on 25 January 2016, and right panels are measurements from beam 6 of the SAS radar during 03:30–04:30 UT on 16 February 2015. Comparing the first two rows shows that the ULF signatures are highlighted after median filtering and expansion of the color scale (Ponomarenko et al., 2003). The filtered Doppler velocity time series are illustrated for two range gates of each radar in the third row, and the Lomb-Scargle periodograms of these signals are shown in the fourth row. ULF oscillations are visible in PGR range gate 13 with ~ 300 -m/s amplitude (red) but are not obvious in range gate 15 (blue) as shown in Figure 3c. Dimensionless NPP values of 85.95 and 20.70 are returned at frequencies of 6.98 and 3.92 mHz for range gate 13 (red) and range gate 15 (blue) in Figure 3d. The horizontal dashed lines indicate the threshold NPPs for these two frequencies, which are 36.45 and 46.25 according to Table 1. A Pc4 event is therefore reported for PGR range gate 13, while a null event is reported for range gate 15. Similarly in Figure 3h, the Lomb-Scargle periodogram for the SAS radar range gate 16 returns an NPP of 156.43, which is much greater than the threshold value of 56.61 at 3.34 mHz, while gate 18 returns an NPP of 72.50, which is slightly greater than the threshold of 60.66 at 3.00 mHz. A Pc5 event is therefore reported for SAS range gate 16 and a marginal Pc5 event for range gate 18. These examples illustrate how the algorithm works and the sensitivity of event determination.

A few factors should be noted before statistically analyzing Pc3-5 oscillations in the Doppler velocity with the automated detection algorithm. First, the algorithm searches overlapping 1-hr or 0.5-hr intervals for ULF wave signatures from each individual range gate of every radar. Events with a long duration and/or a large spatial scale size will be counted multiple times. Second, only ionospheric scatter is analyzed because of difficulties in correctly identifying ground/sea backscatter. This produces a bias toward nightside events when ionospheric backscatter is dominant. Third, this method cannot distinguish between pulsation irregular and pulsation continuous. Finally, large amplitude short-lived Doppler velocity fluctuations other than ULF wave activity are another potential source of contamination.

3. Statistical Results

The automated detection algorithm was applied to THEMIS mode measurements collected with SuperDARN radars in the Northern Hemisphere from 2010 to 2016 to identify Pc3-4 events (0.5-hr intervals) and Pc5 events (1-hr intervals) separately. In total, we identified 5,182 Pc3-4 events, 2,518 events (48.6%) of which had NPP values greater than 1.2 times their NPP thresholds. For Pc5 events, 7,419 out of 17,580 events (42.2%) had NPP values greater than 1.2 times their NPP thresholds. In this section, we present statistical results regarding spatial occurrence of the observed ionospheric Pc3-5 ULF signatures, their frequency characteristics, seasonal effects, and dependence on solar wind and geomagnetic conditions.

3.1. Spatial Occurrence Distribution

Figure 4 shows the Pc3-4 (upper panels) and Pc5 (lower panels) occurrence statistics as a function of magnetic latitude (MLAT) and magnetic local time (MLT) in the Northern Hemisphere. The geomagnetic location of each event is obtained from standard ionospheric backscatter mapping in the AACGM coordinate system,

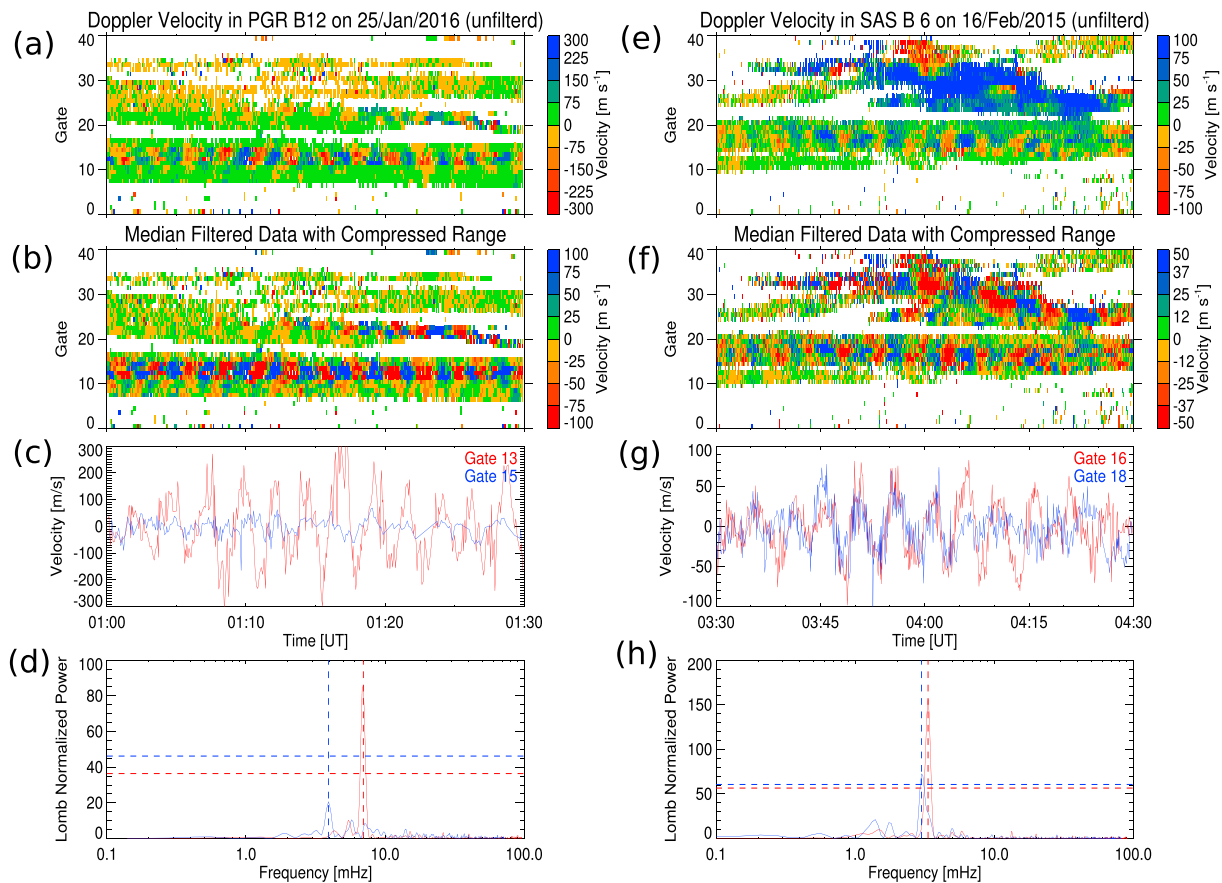


Figure 3. Event examples identified by the automatic detection algorithm using data collected on beam 12 of the PGR radar at 01:00–01:30 UT on 25 January 2016 (a–d) and beam 6 of the SAS radar at 03:30–04:30 UT on 16 February 2015 (e–h). (from top to bottom) RTI plots of unfiltered Doppler velocity; RTI plots of median filtered Doppler velocity; time series of filtered Doppler velocity for two particular range gates (red and blue); Lomb-Scargle periodograms of data shown in (c) and (g). PGR = Prince George; SAS = Saskatoon; RTI = range-time intensity.

assuming a virtual reflection height of 300 km. The MLAT-MLT maps are organized into bins of 1° MLAT and 0.5 hr MLT. Areas where no ionospheric backscatter was observed are shown in white, while black identifies regions where ionospheric backscatter was observed but the observation time in each MLAT-MLT cell was less than 50 hr. We exclude those black regions from further analysis due to insufficient backscatter echoes. The left, middle, and right panels show the distributions of ionospheric backscatter occurrence, ULF event occurrence, and the ULF occurrence probability, respectively. Here the ULF occurrence probability is defined as the ULF event occurrence normalized by the ionospheric backscatter occurrence. The upper panels show the results for Pc3-4 events and lower panels show Pc5 events.

Considering first the occurrence of ionospheric backscatter, measurements from 0.5-hr intervals (Figure 4a) and 1-hr intervals (Figure 4d) clearly show the coverage provided by the tiers of radars at polar, high, and middle latitudes. Ionospheric backscatter covers most MLTs in the polar region but is mostly seen on the nightside at midlatitudes with an extension to the afternoon sector at high latitudes. Turning now to consideration of ULF wave occurrence, Pc3-4 waves occurred predominantly at midlatitudes on the nightside and at high latitudes on the duskside (Figure 4b). Very few events were observed at polar latitudes despite the presence of sufficient ionospheric backscatter there (Figure 4a). In contrast to the Pc3-4 events, Pc5 events are detected mostly at high and polar latitudes (Figure 4e). Note that Pc5 events (Figure 4e) at high latitudes mainly occur in the afternoon and nightside and have a larger longitudinal and latitudinal extent than Pc3-4 events at high latitudes (Figure 4b). Finally, the occurrence probability suggests that Pc3-4 events (Figure 4c) at high latitudes have a peak occurrence probability of $\sim 7\%$ on the duskside (16–18 MLT) at 67° – 68° MLAT. While the occurrence rate of Pc3-4 events above 70° is essentially zero at almost all MLTs. At midlatitudes, the occurrence rates of Pc3-4 events are generally greater pre-midnight than post-midnight, except there is a peak right after midnight above 60° MLAT and another peak at predawn. For Pc5 events, the occurrence probability peaks at $\sim 70^\circ$

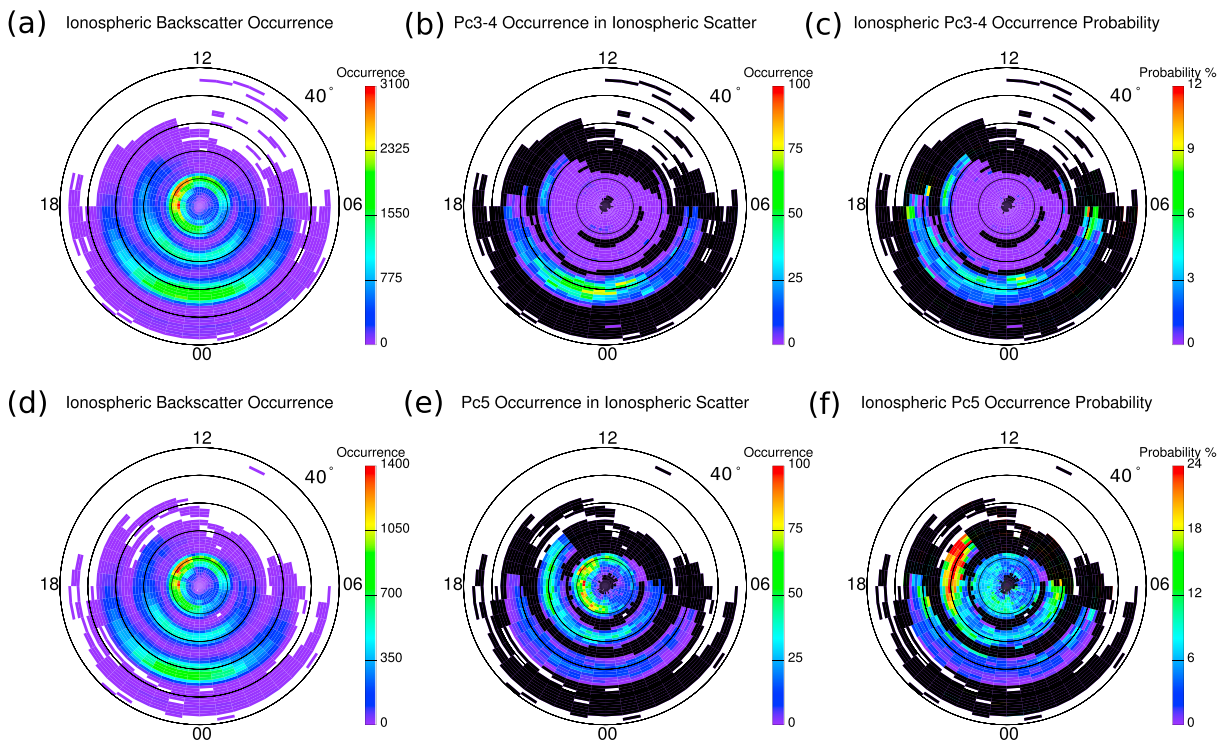


Figure 4. Magnetic latitude-magnetic local time maps of ionospheric backscatter occurrence (a and d), occurrence (b and e), and occurrence rate (c and f) of Pc3-4 (a–c) and Pc5 events (d–f).

MLAT on the duskside (Figure 4f). While in the polar region, the Pc5 occurrence rate peaks at $\sim 80\text{--}83^\circ$ MLAT in the premidnight sector. The overall occurrence rate of Pc5 events is much higher than that of Pc3-4 (note different occurrence probability color scales in Figures 4c and 4f).

3.2. Frequency Characteristics

Previous studies suggested that certain ULF frequencies show up more often than others, and the variation of frequency with latitude can be used to identify FLR (Fenrich et al., 1995). We applied the Lomb-Scargle periodogram with an oversampling rate of 4, which leads to a frequency resolution of ~ 0.07 mHz for 1-hr intervals and ~ 0.14 mHz for 0.5-hr intervals. While the Lomb-Scargle Periodogram technique could be used to identify multiple wave components, in this study we focus on the single component corresponding to the strongest spectrum power for a given time interval and range gate. Since we identify the Pc3-4 and Pc5 events separately with different high-pass filter windows; it is thus possible that a single time interval with multiple frequencies (e.g., harmonic frequencies) could be identified as separate events (e.g., Pc5 and Pc3-4).

The frequency distribution of Pc3-4 events within 6.7–40.0 mHz is shown in Figure 5a with the most probable frequency of 11.39 ± 0.14 mHz. The Pc3-4 frequency distribution also shows a steep rise with decreasing frequency below 8 mHz. The lower panels of Figure 5 show distributions of the frequency versus MLT (Figure 5b) and MLAT (Figure 5c). Pc3-4 events preferentially occur on the duskside and nightside (Figure 5b) and cover a broader frequency range at midlatitude than at high latitudes where the most probable frequency is ~ 7 mHz (Figure 5c). For Pc3-4 events at midlatitudes, a dominant 11-mHz peak exists from 54° to 62° MLAT with no obvious frequency variation with latitude. However, Pc3-4 events observed from high-latitude radars generally have lower frequencies (< 15 mHz) than those from midlatitude radars (Figure 5c). We thus put the Pc3-4 events from high-latitude radars into the category of Pc4 events.

Figure 6 shows the frequency distribution of Pc5 events in a similar format to Figure 5 but in the frequency range of 1.7–6.7 mHz. The most probable frequency is 2.08 ± 0.07 mHz (Figure 6a). The majority of Pc5 events were seen with frequencies below 4 mHz and in almost all MLT sectors and at middle, high, and polar latitudes. While the Pc5 events with frequencies above 4 mHz were more often observed on the duskside (Figure 6b) at high and middle latitudes (Figure 6c). For Pc5 events at high latitudes, the occurrence of lower-frequency events around 2-mHz peaks above 70° with a clear trend toward lower latitudes as the frequency increases.

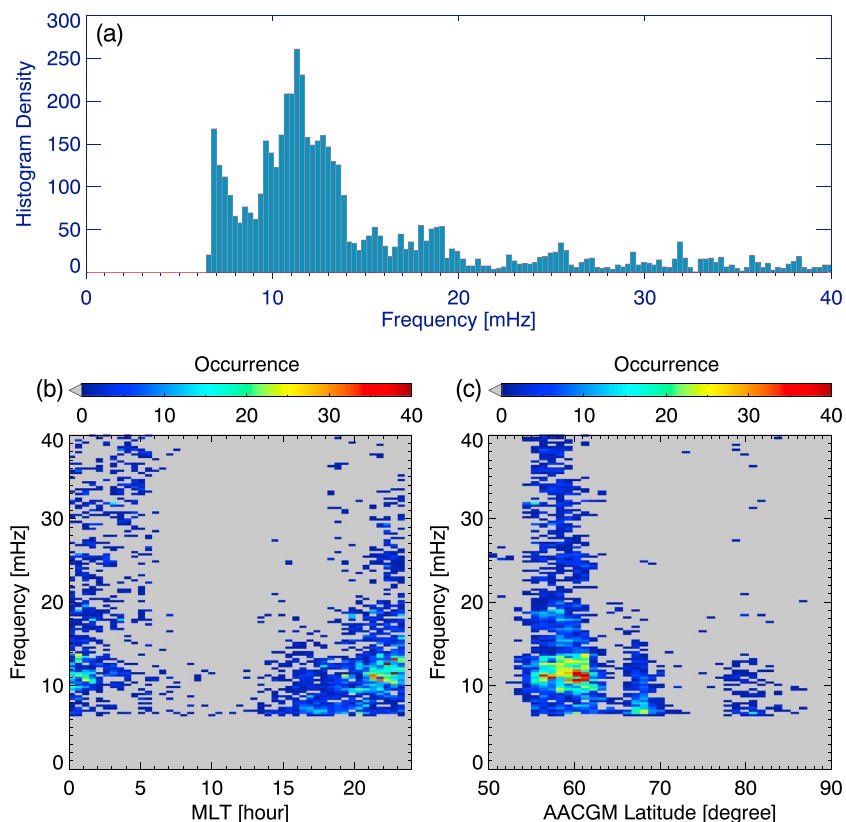


Figure 5. Frequency distribution of Pc3-4 events. Upper panel (a) shows the histogram of event frequencies while the lower panels show two-dimensional histograms of (b) frequency versus MLT and (c) frequency versus AACGM latitude. MLT = magnetic local time; AACGM = Altitude Adjusted Corrected Geomagnetic.

The 0.07-mHz frequency resolution should be sufficient to resolve discrete frequencies in the Pc5 range; however, we do not find strong evidence of preferred frequencies except perhaps the 2.36 ± 0.07 mHz when considering 506 Pc5 events with NPP values greater than 1.8 times the lower threshold (not shown).

3.3. Seasonal Effects

The ionospheric conductivity varies with season and may affect the ionospheric backscatter and ULF wave occurrence. To investigate these effects, ULF events were categorized by season: summer (May–August), equinox (March–April and September–October), and winter (November–February). Figure 7 shows the seasonal dependence of Pc3-4 (upper panels) and Pc5 (lower panels) occurrence rate. The overall spatial coverage of ionospheric backscatter is highest in winter and lowest in summer. The premidnight peak in occurrence of Pc3-4 events at midlatitudes becomes much more prominent at equinox (Figure 7b), while the predawn and postmidnight occurrence rate peaks of Pc3-4 events at midlatitudes appear to be features in winter (Figure 7c). Turning now to the Pc5 events, the duskside occurrence of Pc5 events peaks at high latitudes and becomes most prominent in winter (Figure 7f). For Pc5 events at polar latitudes, the overall occurrence rate is lowest in summer.

To better visualize the seasonal behaviors, line plots of Pc3-4 and Pc5 occurrence rate at specific latitudes are shown in Figure 8. The overall occurrence rate of polar latitude Pc5 events increases from summer to equinox and winter (Figure 8a). Figure 8b shows an occurrence rate peak of high-latitude Pc5 events during winter (red curve) reaching $\sim 30\%$ at about 15 MLT and another peak during equinox (blue curve) reaching $\sim 18\%$ at dusk. The premidnight occurrence rate peak of Pc3-4 at midlatitudes during equinox is clearly seen from the blue curve in Figure 8c.

3.4. Solar Wind and Geomagnetic Disturbance Dependencies

The manner in which ULF occurrence varies with solar wind and geomagnetic conditions can provide information about possible generation mechanisms. The Pc3-4 and Pc5 occurrence rate distributions are sorted

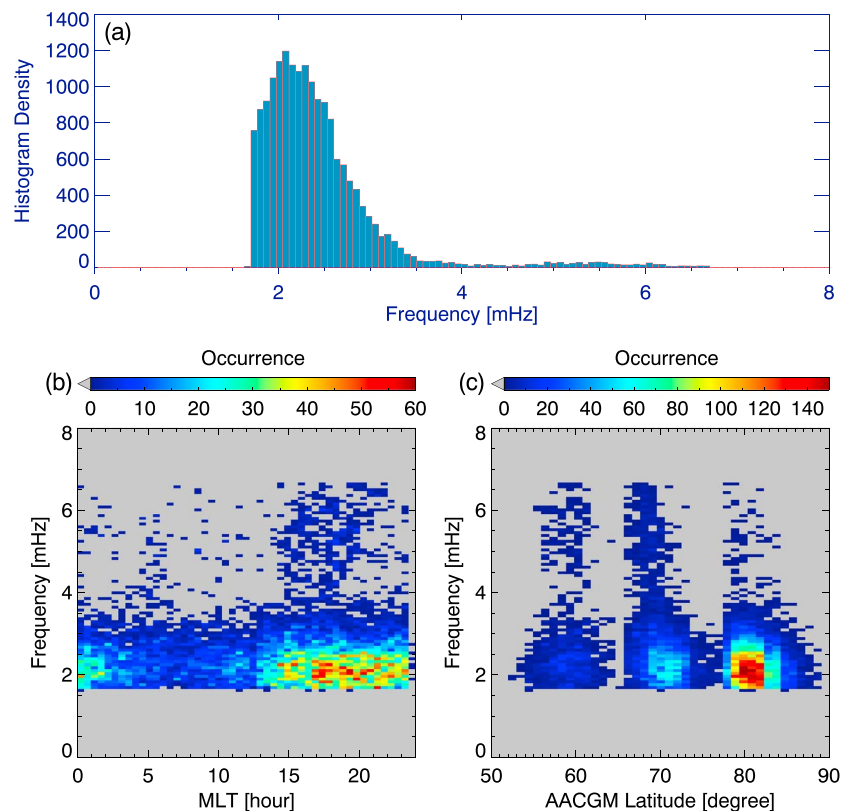


Figure 6. Frequency distribution of Pc5 events. Same format as Figure 5. MLT = magnetic local time; AACGM = Altitude Adjusted Corrected Geomagnetic.

by 0.5- and 1-hr average AE index and interplanetary magnetic field (IMF) B_z . Figure 9 shows that Pc4 events at high latitudes tend to occur during low geomagnetic activity as characterized by the AE index and have a higher occurrence rate during northward IMF than southward IMF. At midlatitudes, the premidnight peak in occurrence rate of Pc3-4 events becomes more prominent with increasing AE index value and during southward IMF. Figure 10 shows the dependence for Pc5 events in a similar format. Pc5 events at high latitudes tend to occur during low geomagnetic activity and northward IMF, which is similar to Pc4 events at high latitudes as shown in Figure 9.

To further help identify sources that generate categories of ULF waves, we show the time evolution of average AE index, SYM-H index, and IMF B_z before and after the occurrence time of ULF wave events in Figure 11. The results are shown in histograms color coded by count of the Pc3-4 events (left, 4,274 0.5-hr intervals) at midlatitudes (54° – 64°) on the nightside ($\text{MLT} \geq 18$ or $\text{MLT} \leq 6$), the Pc4 events (middle, 409 0.5-hr intervals) at 64° – 70° MLAT and 14–20 MLT, and the Pc5 events (right, 2,249 1-hr intervals) at high latitudes (65° – 75°) in the dusk sector (14–20 MLT). Solid black lines show the variation with time of the median values of AE index (top row), SYM-H index (middle row), and IMF B_z (bottom row). Note that the time span in Figure 11 varies with category of ULF wave depending on the type of geomagnetic activity that appears to be most relevant to it, for example, substorms, storms. Nightside Pc3-4 events (left) tend to occur at a sharp increase of AE index, a decrease of SYM-H index, and during southward IMF, which suggests that substorm activity favors their occurrence. By contrast, Pc4 events (middle) tend to occur at an AE minimum with a sharp AE drop several hours before the events and during positive IMF B_z . The gradual increase of SYM-H index suggests that these events occur during the recovery phase of geomagnetic storms. Pc5 events (right) mostly occur during quiet geomagnetic intervals as characterized by the AE and SYM-H indices and during positive IMF B_z . These quiet conditions usually occur long before the events and last several hours after the events.

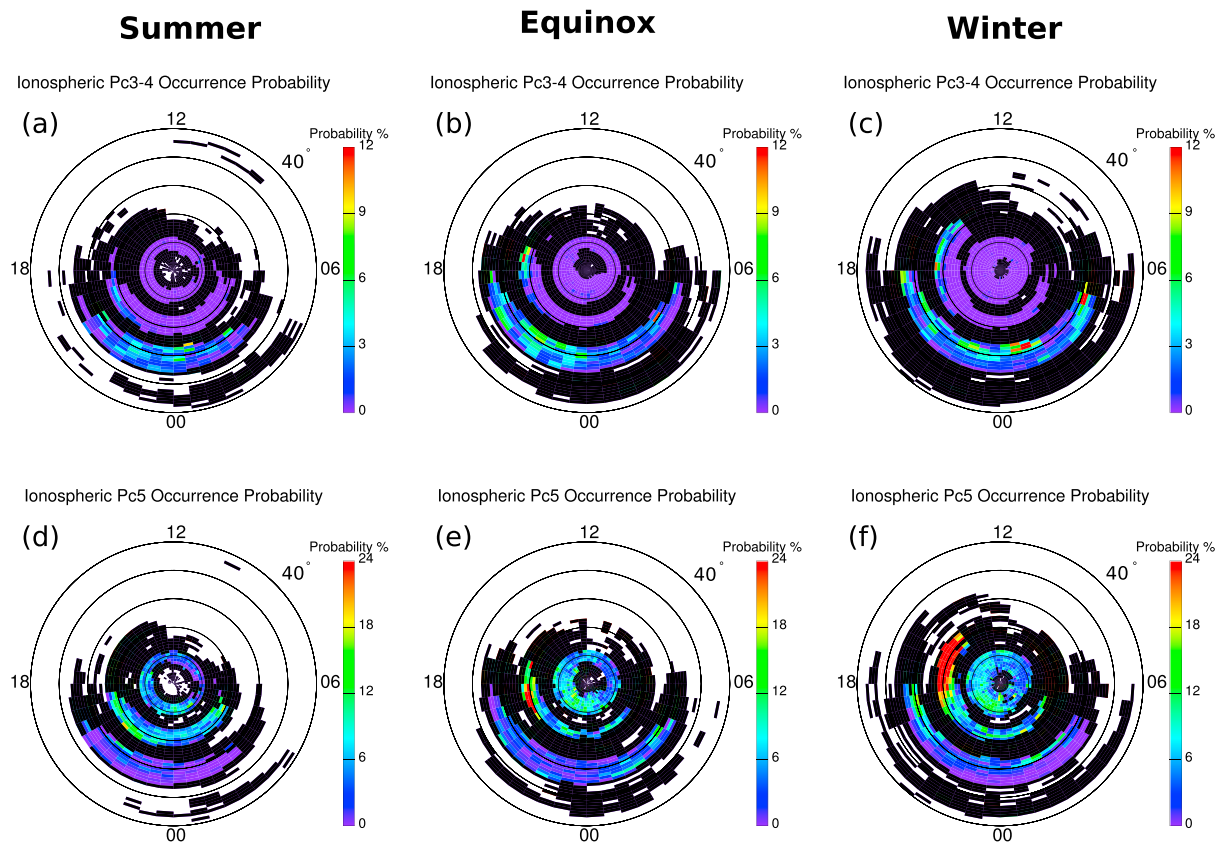


Figure 7. Magnetic latitude-magnetic local time maps of Pc3-4 (a–c) and Pc5 (d–f) event occurrence rate at different seasons: summer (a and d), equinox (b and e), and winter (c and f).

4. Discussion

In this study, an automated detection algorithm has been used to identify ionospheric signatures of Pc3-4 and Pc5 waves in 7 years of high time resolution SuperDARN radar data. Pc5 events were found to occur predominantly at high and polar latitudes with a most probable frequency of 2.08 ± 0.07 mHz, while Pc3-4 events were relatively more common at midlatitudes on the nightside with a most probable frequency of 11.39 ± 0.14 mHz. At high latitudes, Pc4-5 wave occurrence probability peaks in the dusk sector and in winter during low geomagnetic activity and under northward IMF. At midlatitudes, the occurrence probability of Pc3-4 events peaks premidnight and during equinox with this tendency being more prominent with increasing AE index value and under southward IMF.

For Pc5 events in the polar region, classical Pc5 waves observed at lower latitudes on closed field lines are rarely observed beyond the auroral oval inside the polar cap by ground magnetometers (Kozyreva et al., 2016). Since our algorithm cannot distinguish between irregular and continuous pulsations, it is likely that these events are distinct polar cap pulsations of ~ 2 mHz, designated as $\text{Pi}_{\text{cap}}3$ pulsations (Yagova et al., 2004). These polar Pc5/ $\text{Pi}_{\text{cap}}3$ events show a seasonal effect with the lowest occurrence rate in summer (Figure 8a). At high latitudes, Pc5 events were observed from afternoon to postmidnight (Figure 4e) with a peak occurrence rate in the duskside ionosphere (Figure 4f). This diurnal variation is generally consistent with a recent study using data from the SuperDARN Tasman International Geospace Environment Radars (TIGER) and the magnetometers located on Macquarie Island by Norouzi-Sedeh et al. (2015). The majority of ULF signatures seen in the radar data from a beam pointing toward the southern AACGM pole were detected between 15 and 21 local time in their study. The duskside occurrence rate peak of Pc5 events in our study becomes most prominent in winter as shown in Figures 7 and 8b. Both the diurnal and seasonal behaviors of Pc5 occurrence at high and polar latitudes imply that decreased ionospheric conductivity leads to increased amplitude of wave electric fields in the ionosphere (Pilipenko et al., 2012; Sakaguchi et al., 2012). The occurrence of ULF waves as measured by ground magnetometers is also sensitive to ionospheric conductivity, but in the opposite sense with

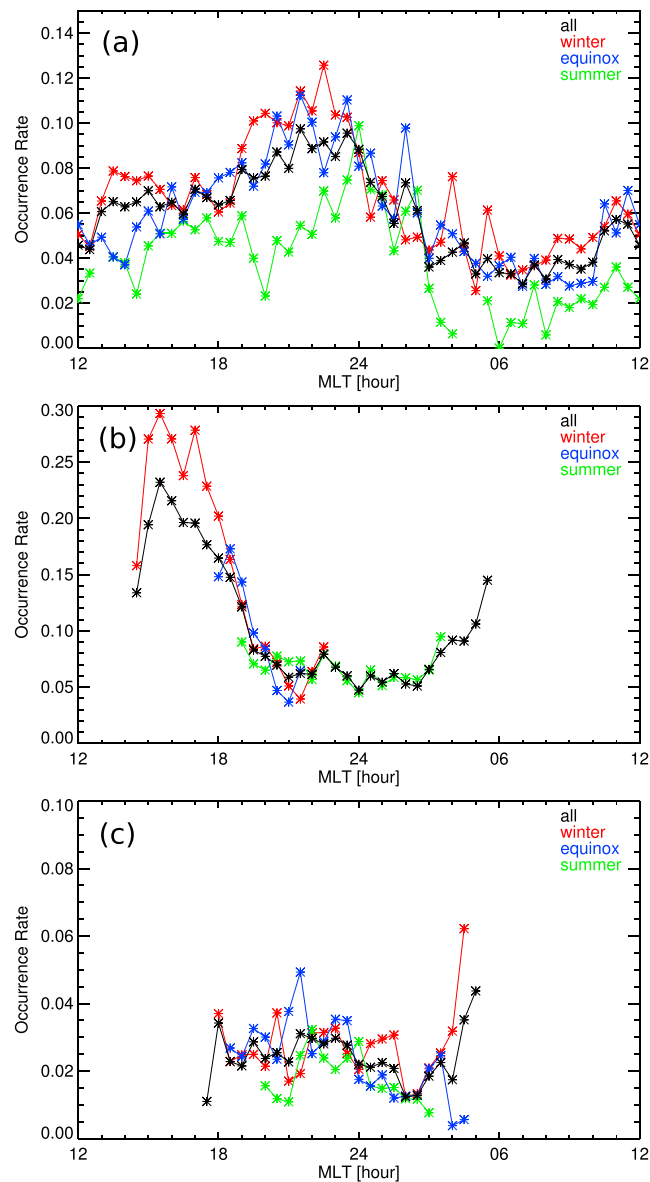


Figure 8. Occurrence rate variation as a function of magnetic local time (MLT) at specific latitudes color coded by season. Occurrence rate variation of (a) Pc5 at polar latitudes (79–83°), (b) Pc5 at high latitudes (66–74°), and (c) Pc3-4 at midlatitudes (54–62°). Black curves indicate data from all seasons.

HF radar measurements (see Figure 11 in Sakaguchi et al., 2012), that is, the occurrence peak is on the dayside (Baker et al., 2003).

Most Pc5 events in this study occurred in the range 1.7–4.0 mHz with a most common frequency of ~2 mHz, which is consistent with previous statistical results using SuperDARN data (Bland et al., 2014; Norouzi-Sedeh et al., 2015). Discrete frequencies at 1.6, 2.1, 2.9, and 3.3 mHz were reported by Norouzi-Sedeh et al. (2015) and earlier at 1.3, 1.9, 2.6, and 3.4 mHz by Samson et al. (1991) and Ruohoniemi et al. (1991). However, in this study the frequency distribution is continuous in the Pc5 range and no discrete frequencies were observed. The source of ~2-mHz dominance at almost all latitudes is unclear, but possible source mechanisms include linkage to dominant frequencies in solar wind perturbations (Kepko & Spence, 2003; Stephenson & Walker, 2002) and magnetospheric cavity/waveguide modes of natural frequencies varying with changes in the cavity topology (Baker et al., 2003; Kivelson & Southwood, 1985).

Pc4 events were mostly observed at 66–70° MLAT from the afternoon to the premidnight sector (Figure 4b). The radially bounded but longitudinally extended Pc4 events observed during quiet geomagnetic intervals

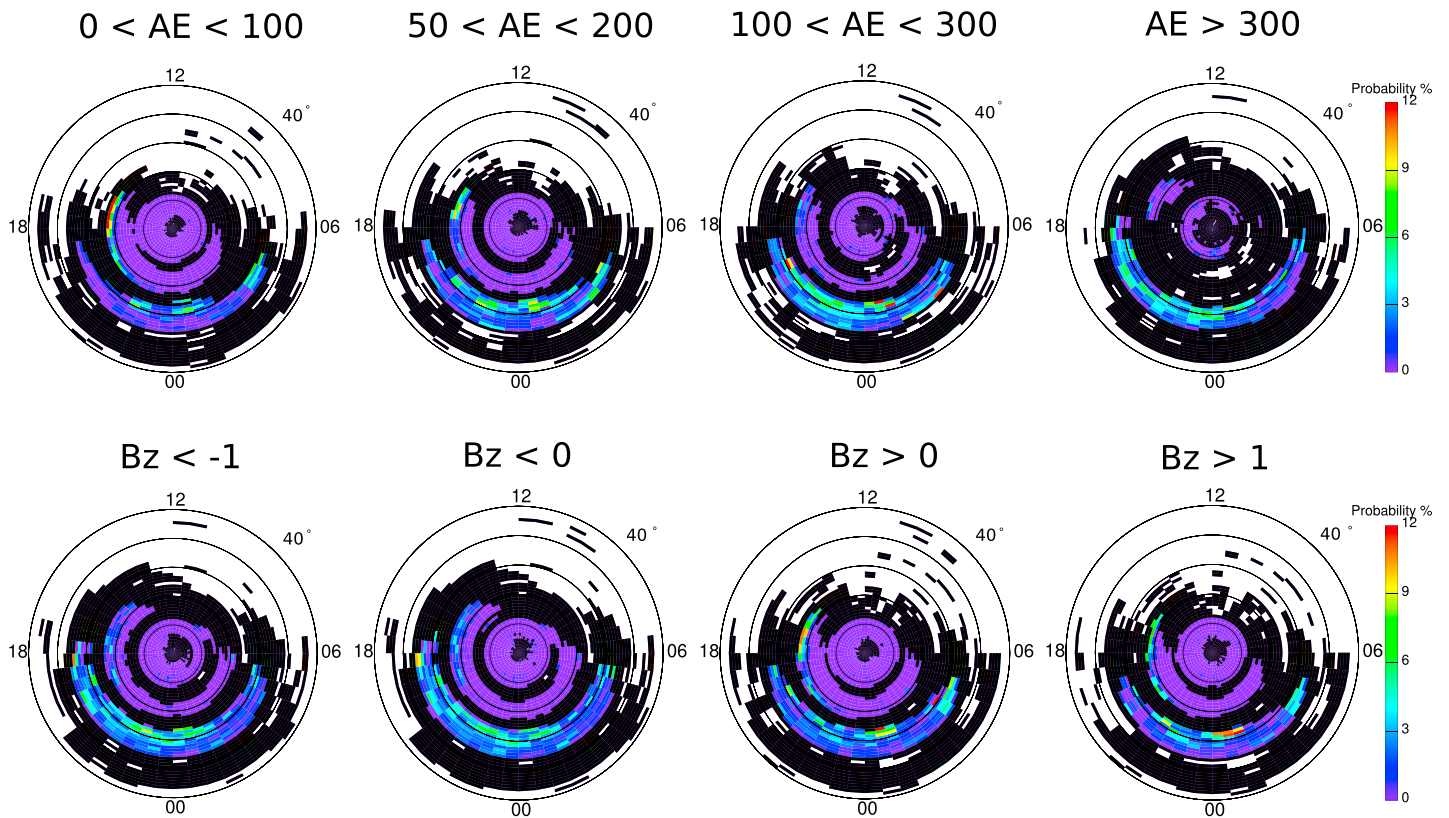


Figure 9. Magnetic latitude-magnetic local time maps of Pc3-4 event occurrence rate sorted by 0.5-hr average AE index (upper panels) and IMF B_z (lower panels).

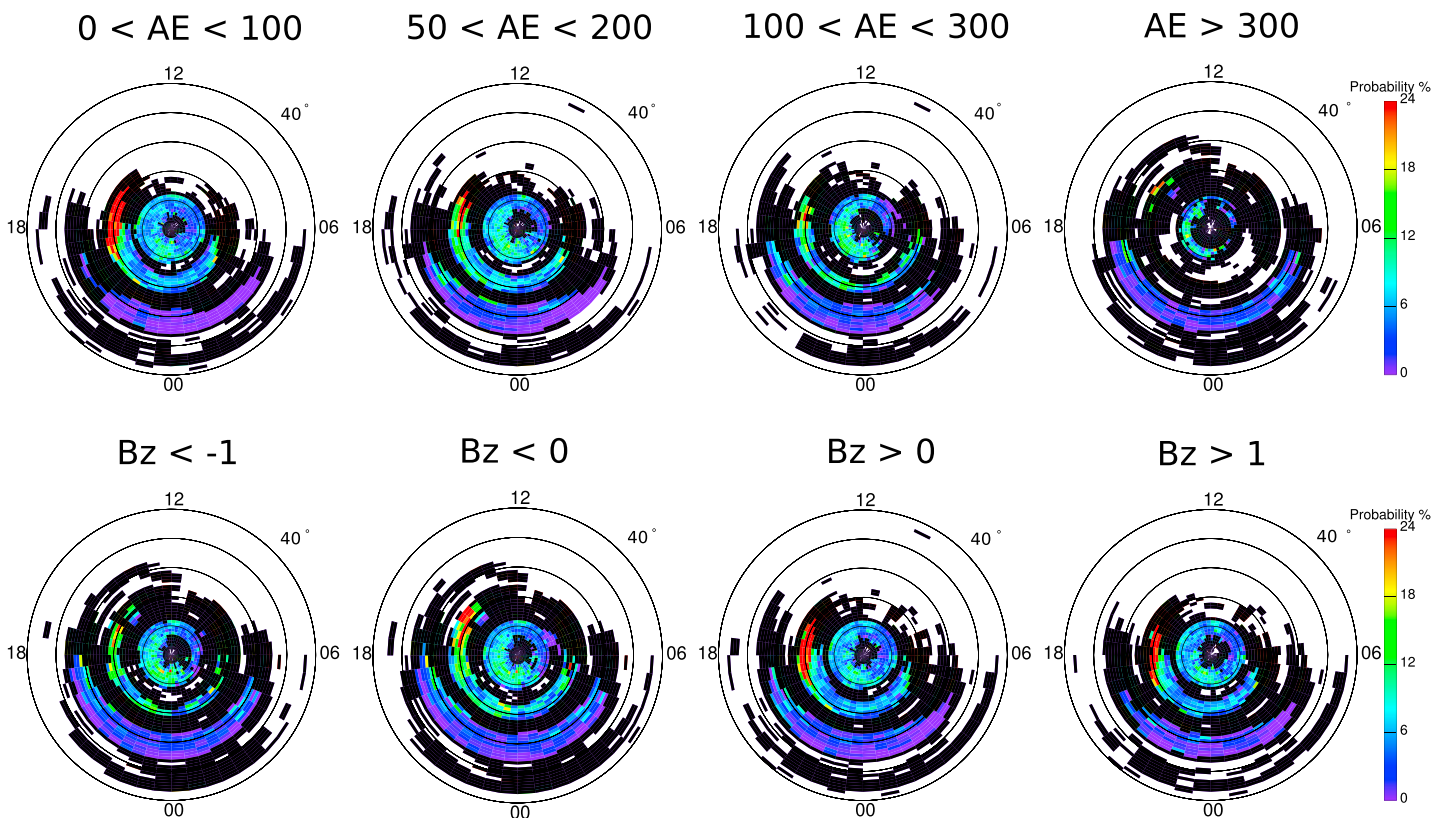


Figure 10. Magnetic latitude-magnetic local time maps of Pc5 event occurrence rate sorted by 1-hr average AE index (upper panels) and IMF B_z (lower panels).

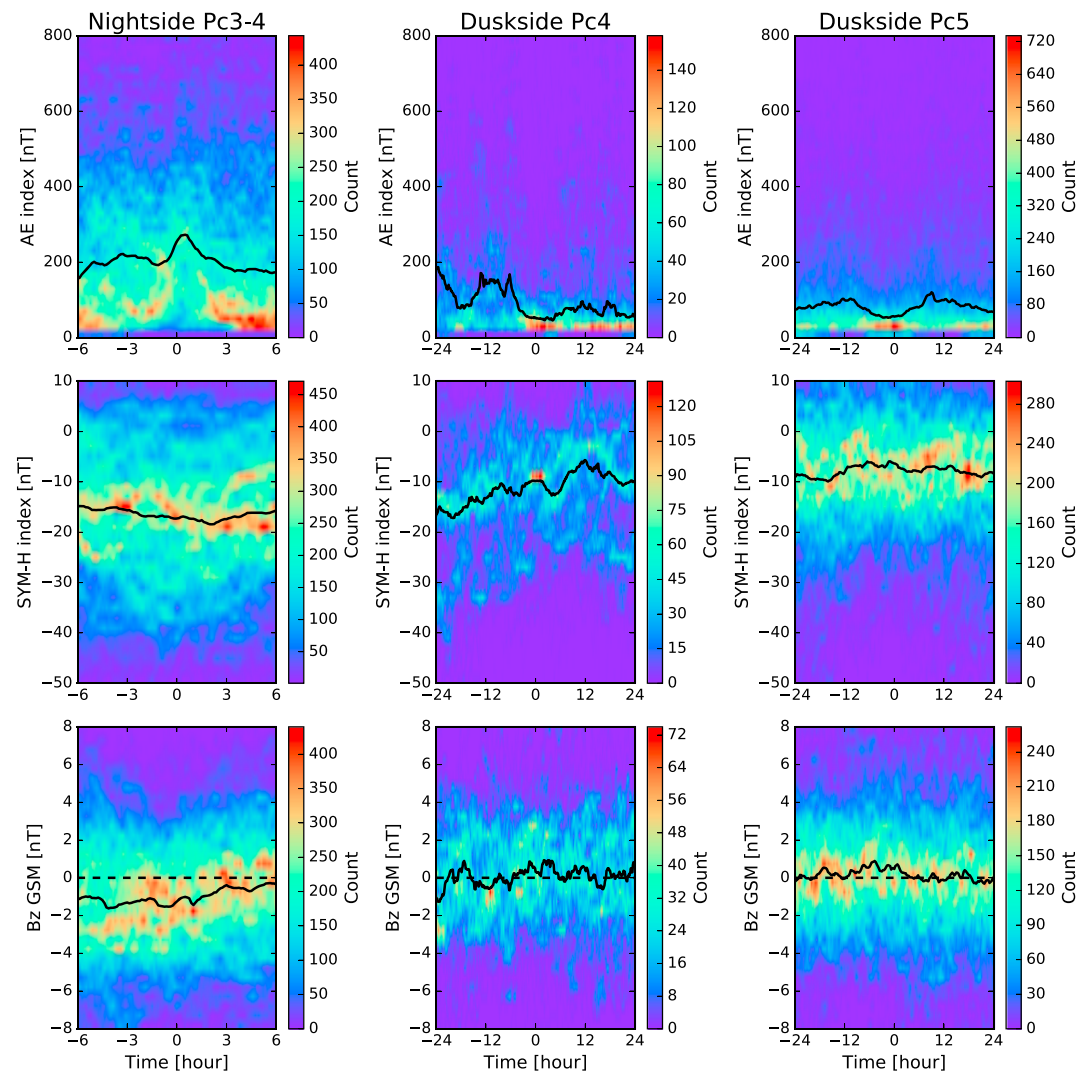


Figure 11. Time evolution of histograms of average AE index (top row), SYM-H index (middle row), and IMF B_z (bottom row) for Pc3-4 events at midlatitudes on the nightside (left column), Pc4 (middle column), and Pc5 (right column) events at high latitudes on the duskside. Zero hour indicates the ULF wave event occurrence time. Solid black lines show the median AE (top row), SYM-H index (middle row), and IMF B_z (bottom row) values. Dashed black lines in the bottom row indicate zero IMF B_z .

have been reported previously and were attributed to localized instabilities (Anderson et al., 1990; Engebretson et al., 1992). The sharp AE drop several hours before the Pc4 events and gradual increase of SYM-H index are consistent with ULF waves occurring during the late recovery phase of geomagnetic storms (Dai et al., 2015; Engebretson et al., 1992). This indicates a connection between the occurrence of Pc4 events with prior substorm activity and the decay of the ring current. Numerous studies have shown that poloidal ULF waves are capable of efficiently interacting with energetic particles in the ring current and the radiation belt during both geomagnetically quiet and active times (Chi & Le, 2015; Dai et al., 2015; Hudson et al., 2004; James et al., 2013). A small convection electric field at quiet times and plasmaspheric refilling during the recovery phase of geomagnetic storms might play roles in the generation of internal instabilities that drive these waves. Localized effects such as the drift or drift-bounce resonance instability are suggested to be possible sources of Pc4 pulsations at high latitudes in the duskside ionosphere.

Pc3-4 events at midlatitudes were seen on the nightside with a premidnight peak in the occurrence rate. The left column of Figure 11 shows that they occurred at a sharp increase of AE index, a decrease of SYM-H index and southward IMF. This evidence indicates that they are most likely Pi2 and Pc3-4 pulsations associated with magnetotail dynamics during geomagnetically active times such as substorm onsets or intensification.

The fact that the premidnight occurrence rate peak becomes most prominent during equinox also supports this idea (Russell & McPherron, 1973). Multiple frequency peaks in the frequency histogram shown in Figure 5 and no obvious frequency variation at midlatitudes from 54° to 62° MLAT suggest that they might be associated with plasmaspheric cavity mode/virtual resonances as reported by Teramoto et al. (2016) and Shi et al. (2017).

Finally, it is possible that some of the identified Pc3-5 events in this study are ionospheric plasma drift fluctuations (Cousins & Shepherd, 2012), which are not related to MHD waves, because our algorithm cannot differentiate between them. To definitely determine whether these events are MHD waves, we would need nearby ground magnetometer and/or conjugate spacecraft measurements, which is beyond the scope of this study and will be explored in future studies.

5. Summary and Conclusions

In this study, ionospheric ULF wave signatures in the Pc3-5 band (1.7–40.0 mHz) were surveyed in the SuperDARN THEMIS mode data from 2010 to 2016 by means of the Lomb-Scargle periodogram. Empirical relationships between the Lomb-Scargle periodogram NPP and associated wave period are derived based on a series of numerical experiments to guide automated detection of ULF signatures. Statistics regarding the occurrence and frequency distributions, seasonal effects, solar wind condition, and geomagnetic activity level dependence have been studied. The main results are summarized as follows: (1) Pc5 events occur predominantly at high and polar latitudes while Pc3-4 are relatively more common at midlatitudes on the nightside; (2) the most probable Pc5 (Pc3-4) frequency is ~2 (11) mHz; (3) at high latitudes, Pc4-5 occurrence probability peaks in the dusk sector and in winter and is elevated during northward IMF and quiet geomagnetic intervals with decreasing geomagnetic activity; (4) at midlatitudes, Pc3-4 occurrence probability peaks at premidnight and becomes most prominent at equinox with a preference for southward IMF conditions and increasing geomagnetic disturbance level. An internal wave-particle interaction source is suggested for Pc4 events at high latitudes in the duskside ionosphere and a source associated with the magnetotail dynamics during active geomagnetic times for Pc3-4/Pi2 events at midlatitudes in the nightside ionosphere. Our results also emphasize the role of ionospheric conductivity in controlling ULF wave occurrence.

Appendix A: Methodology: Lomb-Scargle Periodogram

The Lomb-Scargle periodogram is a spectrum analysis technique especially advantageous for unevenly sampled data (Lomb, 1976; Scargle, 1982). It has recently been used to search Pc5 ultralow frequency oscillations from the SuperDARN common mode data (Bland et al., 2014). The periodogram at angular frequency ω is defined as

$$P(\omega) = \frac{1}{2\sigma^2} \left(\frac{[\sum_i x_i \cos \omega(t_i - \tau)]^2}{\sum_i \cos^2 \omega(t_i - \tau)} + \frac{[\sum_i x_i \sin \omega(t_i - \tau)]^2}{\sum_i \sin^2 \omega(t_i - \tau)} \right), \quad (A1)$$

where x_i is the sampled signal at sampling time t_i , σ is the standard deviation of the data, and the constant τ is defined such that $\tan(2\omega\tau) = \frac{\sum_i \sin 2\omega t_i}{\sum_i \cos 2\omega t_i}$ and $P(\omega)$ is invariant under a constant shift applied to all the time stamps. The power spectrum is normalized by the variance of the signal (σ^2). A sufficiently high value of normalized peak power (NPP) indicates the existence of a wave signature at the associated frequency. The significance of this prediction used to be evaluated by the false alarm probability, namely, the probability that the peak was produced by white Gaussian noise:

$$p = 1 - (1 - e^{-z})^M \approx M \cdot e^{-z} \quad (A2)$$

Here M is the number of independent frequencies, which is roughly the number of signal points, and z is the NPP. However, this evaluation is frequency independent and may become unevenly fair when the target frequency has a broad range. The ultralow frequency wave frequency range is typically from 1.0 to 1,000 mHz, which covers 3 orders of magnitude. Assuming the observed wave signatures have a comparable number of cycles, the NPP of a high-frequency wave should be lower than that of a low-frequency wave due to lower duty cycle, as verified in the numerical experiments below.

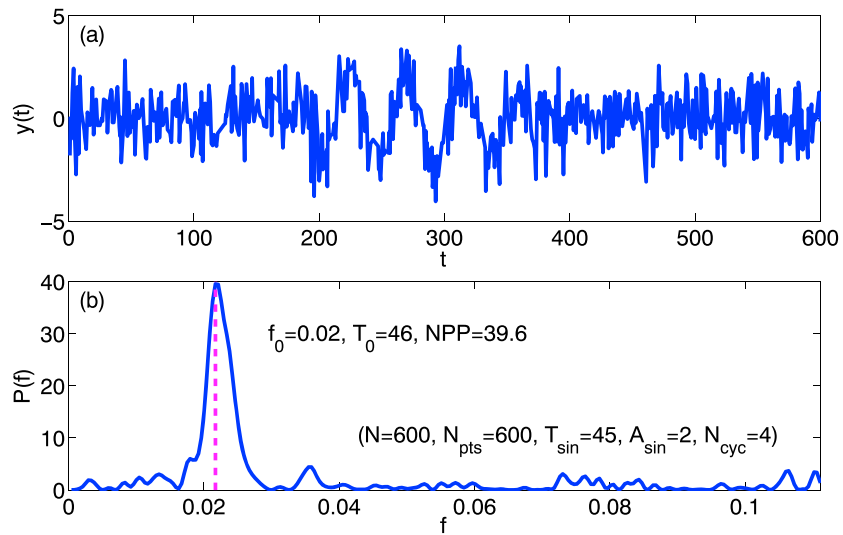


Figure A1. Example Lomb-Scargle periodogram analysis: (a) A simulated signal with length of 600 points, wave period of 45 points, wave amplitude of 2, and 4 sinusoidal cycles; (b) Lomb-Scargle periodogram of the simulated signal. The magenta dashed line indicates that the NPP is 37.6, the wave frequency is 0.02, and the wave period is 46. NPP = normalized peak power.

In order to determine thresholds of NPP that account for wave periods, numerical experiments were conducted to explore the statistically expected NPP of signals with different wave periods. SuperDARN measurements are simulated by assuming the signal as a mixture of a sinusoidal component and a Gaussian background noise. It should be pointed out that besides the wave period, NPP also depends on signal parameters including the number of data points, duty cycle of the sinusoidal component, and the signal-to-noise ratio. The duty cycle is defined as $N_{\text{CYC}} \cdot T_{\text{sin}}/N$, where N_{CYC} is the number of sinusoidal cycles, T_{sin} is the wave period, and N is the signal length. The signal-to-noise ratio is determined by the wave amplitude A_{sin} normalized by the standard deviation of Gaussian noise. In the simulations presented in this paper, A_{sin} and T_{sin} are

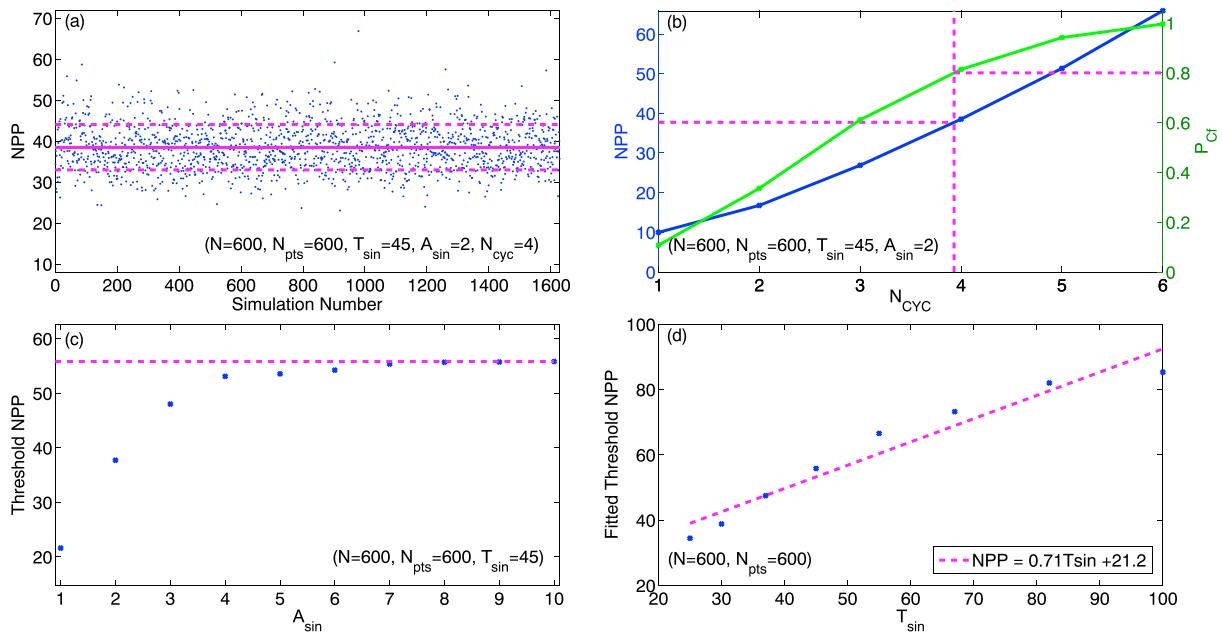


Figure A2. Procedure to derive wave period-dependent threshold NPP. (a) NPP distribution for ($N = 600$, $T_{\text{sin}} = 45$, $A_{\text{sin}} = 2$, $N_{\text{CYC}} = 4$); (b) P_{Cf} (green) and mean NPP (blue) for $N_{\text{CYC}} = 1 - 6$ with ($N = 600$, $T_{\text{sin}} = 45$, $A_{\text{sin}} = 2$); (c) threshold NPP for $A_{\text{sin}} = 1 - 10$ with ($N = 600$, $T_{\text{sin}} = 45$); and (d) asymptotic threshold NPP for $T_{\text{sin}} = 25 - 100$ with ($N = 600$). See text for details. NPP = normalized peak power.

both assumed to be constant within one signal. Figure A1a shows a sample simulation with a signal length of $N = 600$. This length is equivalent to 1 hr given 6-s sampling rate of the SuperDARN THEMIS mode data. The length is chosen so as to cover a few Pc5 wave cycles. The sinusoidal signal component has a period of 45 6-s steps in time (i.e., 270 s) and an amplitude of 2. The signal consists of four cycles. Figure A1b shows the Lomb-Scargle periodogram of the sample simulation. The NPP is found to be 37.6 at a period of 46 time steps, which is within 5% of the designed value.

Figure A2 illustrates the procedures to derive a wave period-dependent threshold NPP for signals with length of $N = 600$. The 2,000 simulations were performed to be statistically significant for the same parameter set as in Figure A1 ($N = 600$, $T_{\text{sin}} = 45$, $A_{\text{sin}} = 2$, $N_{\text{CYC}} = 4$). The effectiveness of Lomb-Scargle periodogram for this parameter set is evaluated by the correct-period probability P_{CF} , which is defined as the ratio between the number of simulations for which the wave period is consistently identified by Lomb-Scargle periodogram and the total number of simulations. Figure A2a shows the distribution of NPPs with consistently identified wave period. The P_{CF} of this parameter set is $1658/2000 = 0.83$. The mean value of the period-consistent NPPs is 38.2 and the standard deviation is 5.0. Figure A2b shows the mean NPP (blue) and P_{CF} (green) for N_{CYC} from 1 to 6 with ($N = 600$, $T_{\text{sin}} = 45$, $A_{\text{sin}} = 2$). It is visible that Lomb-Scargle periodogram has a better performance in identifying wave period correctly with more cycles. The NPP also increases with cycle number monotonically. Defining a threshold P_{CF} of 80%, the threshold NPP corresponding to this probability can be calculated via linear interpolation as shown by the magenta dashed lines. The threshold NPP for ($N = 600$, $T_{\text{sin}} = 45$, $A_{\text{sin}} = 2$) is 36.8. Figure A2c shows the threshold NPP for A_{sin} from 1 to 10 with ($N = 600$, $T_{\text{sin}} = 45$). The threshold NPP increases with the wave amplitude and approaches a stable level of ~ 54.3 when A_{sin} is above 4. The asymptotic level represents the threshold NPP of the given signal length and wave period. Figure A2d shows the threshold NPPs of 8 wave periods in the Pc5 range (150–600 s): 25, 30, 37, 45, 55, 67, 82, and 100. These threshold NPPs are linearly fitted by $\text{NPP} = 0.71T_{\text{sin}} + 21.2$. NPP above the value specified by this equation indicates the existence of a wave signature at the associated period with a probability of more than 80%.

It should be noted that the empirical equation obtained by fitting values of NPP depends on two observables of Lomb-Scargle periodogram: T_{sin} and NPP. The threshold NPP for a high-frequency wave signature is lower than for a lower-frequency wave, which is reasonable considering that more cycles of high-frequency waves are needed to achieve the same duty cycle. The classical false alarm probability uniquely dependent on NPP is overly strict for high-frequency wave signatures and not strict enough for low-frequency wave signatures. In Figure A2c, the asymptotic level may raise the threshold for small amplitude wave signatures. However, this could exclude weak signals relative to the background noise, thus increasing the reliability of wave signature identification. In real SuperDARN data, the number of data points available in a 1-hr interval could deviate from 600 due to gaps or oversampling. Gaps and oversampling effects were simulated and analyzed with the same method introduced above. The threshold NPP equations for different numbers of points (N_{pts}) are listed in Table 1. The threshold equations for Pc3–4 wave identification are based on a basic length of 30 min.

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