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- Technique for automatic detection of ULF oscillations in SuperDARN data
- Rapid visualization of the presence and spatial extent of Pc5 pulsation activity
- Pc5 ULF oscillations observed most often on the nightside of the magnetosphere

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Multipoint visualization of ULF oscillations using the Super Dual Auroral Radar Network

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Abstract We present a technique for the automatic detection of Pc5 (150 s to 600 s period) ultralow frequency (ULF) pulsations in ground and ionospheric backscatter from the Super Dual Auroral Radar Network (SuperDARN). This new technique enables rapid identification and visualization of ULF oscillations over the very wide geographical coverage of SuperDARN. The technique detects ULF oscillations using the Lomb-Scargle periodogram method, which provides a natural test for periodic behavior against the null hypothesis of a pure noise distribution. This does not require any interpolation across data gaps and is thus appropriate for SuperDARN data. We demonstrate the application of the technique to SuperDARN data for March 2014 and find that Pc5 pulsations are frequently observed by multiple radars simultaneously. A preliminary investigation using data from all Northern Hemisphere SuperDARN radars indicates that Pc5 pulsation activity occurs most often on the nightside of the magnetosphere, with a mean frequency of about 2 mHz.

1. Introduction

Signatures of Pc5 (150–600 s period) ultralow frequency (ULF) waves are often present in ionospheric and ground backscatter returns from the Super Dual Auroral Radar Network (SuperDARN). These waves manifest in SuperDARN data as periodic oscillations in the Doppler velocity, which arise due to the $\vec{E} \times \vec{B}$ drift velocity $\vec{V}$ generated in the ionosphere by the ULF wave electric field $\vec{E}$ and background geomagnetic field $\vec{B}$. In ionospheric backscatter, these oscillations arise mostly from the horizontal component of $\vec{V}$ and have amplitudes up to about 100 m s^{−1}. In ground backscatter, the measured Doppler velocity is determined mostly by the vertical component of $\vec{V}$ and yields velocity amplitudes of about 10–20 m s^{−1}. At times these oscillations may be coherent over more than 10° of magnetic latitude and may last for several hours [Ponomarenko *et al.*, 2003].

ULF pulsations have conventionally been studied using arrays of ground-based magnetometers. Magnetometer studies of the amplitude, polarization, and phase properties of Pc5 pulsations suggest that they are generated by sources external to the magnetosphere, such as the Kelvin-Helmholtz instability at the magnetopause [e.g., Samson *et al.*, 1971; Ziesolleck and McDiarmid, 1994; Chisham and Orr, 1997] or density perturbations in the solar wind [e.g., Viall *et al.*, 2009]. However, since ground magnetometers measure the magnetic field due to ionospheric currents integrated over a radius of about 100 km, they are limited to the study of ULF pulsations with relatively large azimuthal scale size only. Pc5 pulsations with small azimuthal scale size are thought to be generated by drift and drift-bounce resonance interactions of particles trapped in the magnetosphere [e.g., Wright and Yeoman, 1999; Baddeley *et al.*, 2005]. High-frequency (HF) radars provide a more direct means of observing ULF waves and are capable of detecting pulsations of either large- or small-scale size [Fenrich *et al.*, 1995]. They also have the advantage of a very wide geographical coverage, including over the oceans where the use of other ground-based instruments is not possible.

SuperDARN is a global network of HF coherent scatter radars designed primarily for studying plasma convection in the auroral ionosphere [Greenwald *et al.*, 1995; Chisham *et al.*, 2007]. The network presently consists of 21 radars in the Northern Hemisphere and 11 radars in the Southern Hemisphere. The combined geographical coverage of the network represents a significant portion of the mid-latitude, high-latitude, and polar regions of the ionosphere. A map showing the locations and fields of view of all SuperDARN radars is available at <http://vt.superdarn.org/>.

Despite the extensive geographical coverage of the network, most SuperDARN studies of Pc5 pulsations have utilized data from only a small number of radars [e.g., *Fenrich et al.*, 1995; *Sakaguchi et al.*, 2012]. Signatures of ULF waves can be enhanced in SuperDARN data using a technique developed by *Ponomarenko et al.* [2003]. This involves subtracting the long-period background drift velocity using a median or boxcar filter, then generating range-time plots of the detrended velocity with an artificially saturated amplitude scale, accentuating periodic changes in the sign of the velocity. This requires manual inspection of range-time plots for individual radar beams, limiting its application in large-scale studies over many radars. In this letter we present an automated algorithm for identifying ULF pulsation activity over the total geographical area covered by SuperDARN, enabling rapid visualization of the presence and spatial extent of Pc5 pulsation activity.

2. Instrumentation

SuperDARN radars operate in the frequency range 8–20 MHz, employing a linear array of 16 antennas to create a narrow, steerable beam. In the standard SuperDARN design, this beam is approximately 3.25° wide in azimuth and can be electronically steered in 16 different azimuthal directions. The total field of view of each radar thus covers a $\sim 52^\circ$ azimuthal sector and extends out to about 3500 km in range. Some newer radars in the network operate with more beams covering a wider azimuthal sector ($\sim 70^\circ$) and can detect backscatter from longer ranges (~ 4500 km).

The primary data products of SuperDARN are power (signal-to-noise ratio), line-of-sight Doppler velocity, and Doppler spectral width of the received backscatter. These parameters are determined by fitting the complex autocorrelation function (ACF) for each range gate to time lags generated using a multipulse sequence [*Greenwald et al.*, 1985]. In the standard mode of operation, called “common mode,” this procedure is performed with a range resolution of 45 km and an integration time of ~ 3 s per beam, which results in a total scan time of 1 min to sample all azimuthal directions. This produces a Nyquist frequency of about 8 mHz, limiting ULF wave observations using SuperDARN common mode data to the Pc5 band (1.7–6.7 mHz). With the use of high time resolution modes, achieved by scanning a reduced number of beams or by decreasing the integration time for each beam, higher-frequency ULF waves are also observable [e.g., *Ponomarenko et al.*, 2003, 2005]. In this work we focus on the automated detection of Pc5 pulsations in SuperDARN common mode data, as the coordinated use of this mode by all radars maximizes the geographical area over which ULF pulsations may be detected.

3. Automated Search Algorithm

We demonstrate the application of our algorithm to all Northern Hemisphere SuperDARN radars for the month of March 2014. We begin by separating ground backscatter from ionospheric backscatter, since echoes from these two propagation modes at a fixed range correspond to interaction with different locations in the ionosphere. In this work we identify ground backscatter by its low Doppler velocity ($|V| < 50 \text{ m s}^{-1}$) and low spectral width ($W < 50 \text{ m s}^{-1}$), and also using the standard SuperDARN ground scatter condition [see *Ribeiro et al.*, 2011]; data which do not meet these criteria are classified as ionospheric scatter. We then divide the available data for March 2014 into 1 h intervals, incremented by 15 min such that 1 h intervals commence at 00:00 UT, 00:15 UT, 00:30 UT, and so on. Overlapping the time intervals in this way allows ULF oscillations to be detected regardless of the event onset time. We then consider each range/azimuth cell separately and assemble a list of 1 h intervals which contain significant amounts of ionospheric or ground backscatter in a given cell. For an interval to be accepted for further analysis, we require that at least 75% of the data in that interval and cell satisfy the following criteria: (1) the signal-to-noise ratio is at least 3 dB and (2) the errors in the Doppler velocity V and spectral width W are small ($|V_{\text{err}}| < 100 \text{ m s}^{-1}$ and $|W_{\text{err}}| < 100 \text{ m s}^{-1}$). Echoes may fail to satisfy these criteria if there was no suitable ionospheric or ground scattering target present or if a mixture of ionospheric and ground backscatter was detected in the same range/azimuth cell simultaneously [see *Ponomarenko et al.*, 2008].

We then proceed to test each 1 h interval for periodic behavior in the Doppler velocity, which might indicate that a Pc5 pulsation has been detected. The data in each range/azimuth cell are first detrended to remove the background drift velocities using the method of *Ponomarenko et al.* [2003] described in section 1, using an effective window size of 600 s. Since we have discarded any data with low ACF power or with large errors in V or W , we are working with a data set which has been sampled at regular intervals but

which may contain data gaps. In SuperDARN studies of ULF waves, it is common to interpolate across small data gaps and then use a Fourier transform to determine the spectral content [e.g., Ruohoniemi *et al.*, 1991; Fenrich *et al.*, 1995; Mthembu *et al.*, 2009]. One side effect of this kind of interpolation is that additional peaks may be introduced into the spectrum, particularly at frequencies that correspond to periods of comparable size to the data gaps [e.g., Press *et al.*, 2002]. Since the time resolution of SuperDARN common-mode data is quite poor relative to the period of Pc5 pulsations, it is likely that spurious peaks in the Pc5 range will sometimes appear in the Fourier spectrum following interpolation. Therefore, we have adopted the Lomb-Scargle method [Lomb, 1976; Scargle, 1982] to generate periodograms of the velocity time series data for each range/azimuth cell, which does not require interpolation across data gaps. Lomb normalized periodogram (LNP) $P(\omega)$ is given by

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

where x_i is the velocity measured at time t_i and ω is the angular frequency. The factor σ^2 is the variance of the data x_i , which is used to normalize $P(\omega)$. The constant τ ensures that $P(\omega)$ is invariant under a constant shift in all the t_i 's. Calculating $P(\omega)$ is mathematically equivalent to performing a least squares fit of sinusoidal functions to the velocity time series data. Importantly, only the available data x_i are used in the calculation of $P(\omega)$, so no interpolation is required. The Lomb normalized periodogram method has been widely used in astronomy, where it is common for data sets to be unevenly sampled or incomplete. The method has also been extended to allow calculation of the phase [Hocke, 1998; Mathias *et al.*, 2004] and for application to data sets with nonsinusoidal periodicities [Bretthorst, 2001].

In our ULF wave search algorithm, we calculate $P(\omega)$ in IDL (Interactive Data Language) using the native LNP_TEST routine. We have adopted the standard implementation of this routine [Press and Teukolsky, 1988], in which the frequency range is oversampled by a factor of 4 between 0 and the Nyquist frequency.

Large peaks in $P(\omega)$ indicate the possible existence of a periodic signal in the velocity time series. However, Gaussian noise also produces peaks in $P(\omega)$. Therefore, we seek to test each peak against the null hypothesis that it was produced by random fluctuations. The probability p that a peak in $P(\omega)$ of height z was produced by white Gaussian noise is [Scargle, 1982]

$$p = 1 - (1 - e^{-z})^M \quad (2)$$

where M is the number of independent frequencies sampled in the calculation of $P(\omega)$, which has been shown through Monte Carlo simulations to be approximately equal to the number of data values N in the time series [Horne and Baliunas, 1986]. As a result, M is set equal to N in the standard implementation of LNP_TEST. If a peak of power z is present in $P(\omega)$ with $p \ll 1$, then it is likely that the data set contains a strong periodic component. We identify a ULF oscillation when the value of p corresponding to $z = \max[P(\omega)]$ falls below a threshold value p_0 . It is desired that this threshold will identify most true periodic signals present in the data but will also reject as many null events as possible. Signals that are most likely to be detected are expected to have the following properties: the velocity oscillation has a large amplitude relative to the background noise; the oscillation lasts for most or all of the 1 h interval, executing several wave cycles; and the wave frequency is stable.

We have conducted simulations to determine the extent to which the above properties affect the height z of a peak in $P(\omega)$. We generated 1 h samples of simulated SuperDARN common-mode data ($N = 60$ points), which initially consisted of white Gaussian noise. We then introduced a periodic component to the velocity time series by adding an integer number of sinusoidal wave cycles to the underlying noise component. For each sample we recorded the maximum height z of $P(\omega)$. To investigate the effects of the signal amplitude, frequency, and frequency stability on the periodogram, we varied the wave amplitude relative to the noise level, the wave frequency, and allowed a $\pm 5\%$ variation in the wave period about the central value. A sample of our results is shown in Figure 1. In this example, the wave period was 600 ± 30 s, and the wave amplitude was 3 times the background noise level. The panels on the left show histograms of the maximum Lomb normalized power, each generated from 2000 simulated events, and the panels on the right show a sample velocity time series of the events used to generate each histogram. The blue vertical lines indicate, from

Figure 1. Results from simulated experiment for detecting Pc5 pulsations in SuperDARN data. (left) Histograms of the maximum power of the periodogram $P(\omega)$ generated from 2000 60-point time series samples, each containing 1–4 cycles of a 600 ± 30 s sinusoidal signal superposed on a Gaussian noise distribution. (right) A sample time series used to generate each histogram.

left to right, the 0.5, 0.1 and 0.01 confidence limits calculated using equation (2) with $M = N = 60$. In this example, over 50% of events with 4 wave cycles exceeded the 0.01 confidence limit, and almost all such events exceeded the 0.1 limit. Setting the probability threshold to 0.1 would also detect some pulsation events of only 2 cycles, but would rarely detect a pulsation of one cycle. For the results shown in Figure 1, the 5% variation in the wave period led to a substantial reduction in the power of the maximum peak. In other simulations where the frequency was kept fixed (not shown), even small-amplitude signals could be readily detected with a confidence above 0.01, provided that the event lasted for most of the 1 h interval.

Figure 2 shows a typical output from our ULF wave search algorithm, for the interval 08:30–09:30 UT on 21 March 2014. Solar wind and geomagnetic conditions for this day and preceding days were quiet, with relatively low solar wind speed ($V_{sw} = 300\text{--}350$ km s^{−1}), and $K_p = 2+$ at the event onset time. Each colored arc segment in Figure 2 indicates a range/azimuth cell for which Pc5 pulsation activity was identified; the color scale indicates the frequency of the velocity oscillation in millihertz. The probability threshold used to identify the events shown in this plot was $p_0 = 0.1$. The locations of the radars are indicated by asterisks, and dashed lines indicate corrected geomagnetic (CGM) latitude contours. During this time interval, ULF oscillations were observed in multiple range/azimuth cells of the Christmas Valley West (cvw), Christmas Valley

Figure 2. Azimuthal plot of Pc5 pulsation activity in the Northern Hemisphere during the interval 08:30–09:30 UT on 21 March 2014. Each colored arc segment shows a pulsation event found in a single range/azimuth cell of a particular radar; the color scale indicates the pulsation frequency. Grey shading denotes local nighttime.

East (cve), and Adak East (ade) SuperDARN radars at about 60–65° magnetic latitude. ULF oscillations were also detected by the Stokkseyri (sto), Pykkvibaer (pyk), and Rankin Inlet (rkn) radars; however, the results are sparse due to data gaps.

4. Discussion

For the month of March 2014, we identified 11 days for which Pc5 ULF oscillations were present in the fields of view of at least 3 SuperDARN radars simultaneously. Some events occurring in a particular magnetic local time (MLT) sector were observed again a short time later by a different radar when its field of view had moved into that MLT sector.

Our algorithm imposes the strict criterion that no more than 25% of the data in a 1 h interval can be missing. In Figure 2, there is some evidence of ULF oscillations in the fields of view of the Stokkseyri (sto), Pykkvibaer (pyk), and Rankin Inlet (rkn) radars. In an attempt to reveal more range/azimuth cells showing ULF oscillations for these radars, we

tried relaxing the missing data criterion from 25% to 50%. This did reveal additional cells with ULF oscillations; however, the frequencies measured in neighboring cells were inconsistent. This highlights the importance of having sufficient data available for the Lomb-Scargle method to reliably identify periodic features. For cases where the missing data are grouped together at one end of a 1 h interval, reducing the interval length to 45 min, for example, may improve the detection efficiency of the algorithm.

Figure 3a is a two-dimensional histogram plot showing the ULF oscillation occurrence for March 2014, as a function of magnetic local time and magnetic latitude. The histogram was generated using approximately

Figure 3. ULF wave search algorithm statistics for March 2014: (a) Histogram plot showing the percentage of 1 h intervals in which ULF oscillations were detected in each latitude/MLT bin. (b) Frequency occurrence distribution as a function of magnetic latitude. (c) Frequency occurrence distribution as a function of magnetic local time. Grey shading in Figure 3a indicates bins excluded from the histogram due to sparse echo occurrence.

115,000 ULF oscillations recorded in individual range/azimuth cells of Northern Hemisphere SuperDARN radars. Since an ionospheric or ground scattering target must be present for a ULF oscillation to be observable by radar, the histogram has been scaled to represent the *percentage* of 1 h intervals that were found to exhibit ULF oscillations in a particular MLT/latitude bin. Grey shading indicates bins which have been excluded from the histogram due to sparse echo occurrence in those bins. The ULF oscillations observed below 70° magnetic latitude from approximately 05:00 to 20:00 MLT were detected mostly in the ground backscatter, and the remaining oscillations were observed mostly in the ionospheric backscatter. ULF oscillations at these latitudes were observed at all magnetic local times; however, they were observed more frequently on the nightside of the magnetosphere, with occurrence peaking at 40% between 4:00 and 06:00 MLT at 70–75° magnetic latitude. This result is consistent with a recent study by *Sakaguchi et al.* [2012] using the King Salmon SuperDARN radar.

The oscillations above 75° magnetic latitude were detected using the three SuperDARN radars located within the polar cap—Rankin Inlet (rkn), Inuvik (inv), and Clyde River (cly). We identify these as a distinct class of ULF oscillations, since the magnetic field lines at these polar latitudes are expected to be open. The observed oscillations may be of a similar nature to those reported recently by *Scoular et al.* [2013], who suggested that particle precipitation into the auroral ionosphere may produce periodic features in the Doppler velocity measured by SuperDARN radars.

ULF oscillations on the nightside of the magnetosphere were generally not accompanied by a ground magnetometer signature. For oscillations with small azimuthal scale size (large azimuthal wave number m), no ground magnetic signature is expected due to the ionospheric screening effect [e.g., *Ponomarenko et al.*, 2001]. If the oscillations were due to large-scale toroidal mode ULF waves with small azimuthal wave number, a corresponding signature in the ground magnetometer data would generally be expected. However, the amplitudes of these ground magnetic signatures depend strongly on the ionospheric conditions, in particular the height-integrated Hall conductivity [*Sakaguchi et al.*, 2012]. *Pilipenko et al.* [2012] describe a method for estimating the amplitude of the ground magnetic response due to electric field oscillations in the ionosphere. They show that the reduced ionospheric conductivity at night tends to reduce the amplitudes of large-scale toroidal magnetic field oscillations on the ground, and so they may not present as a clear signature in the ground magnetometer record.

Figures 3b and 3c show the frequency distribution of the ULF oscillations identified by our algorithm, as a function of magnetic latitude and magnetic local time, respectively. The oscillations have a mean frequency of about 2 mHz and exhibit no clear latitudinal variation. A slight increase in frequency may be apparent near magnetic noon. We suggest that the majority of these oscillations are not field line resonances and instead might be signatures of a more global process on the nightside of the magnetosphere. It is possible that the oscillations observed at polar latitudes may have a different source mechanism to those observed at lower latitudes; however, we note that both distributions exhibit similar frequency characteristics. Work is ongoing to characterize these polar cap oscillations in more detail.

5. Conclusion

We have developed a technique for the automatic detection of Pc5 ULF oscillations in ionospheric and ground backscatter from SuperDARN radars. When applied simultaneously over the entire SuperDARN network, this provides an effective tool for visualizing ULF oscillations in the mid-latitude, high-latitude, and polar ionosphere. Application of our algorithm to 1 month of SuperDARN data indicates that ULF oscillations in the Pc5 range are often observed over a large spatial extent in the nighttime ionosphere, especially at high latitudes, but they are generally not accompanied by a ground magnetometer signature.

The Lomb-Scargle periodogram method has two significant advantages over the traditional Fourier methods used in many other SuperDARN studies of ULF waves: (1) interpolation across data gaps, which sometimes causes spurious peaks in Fourier spectra, is not required and (2) the periodogram has a simple statistical behavior which provides a natural test for identifying periodic velocity features.

Our technique has been developed for use with SuperDARN common-mode data in order to maximize the geographical area over which ULF oscillations may be detected. This limits ULF wave observations to the Pc5 band due to the time resolution produced by the SuperDARN common mode. With the use of high time

resolution modes, it is likely that higher-frequency pulsations such as Pc3–4 could also be detected using a similar method.

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