Visualization of ULF waves in SuperDARN data

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Abstract. Measurements of ionospheric $\mathbf{E} \times \mathbf{B}$ drifts obtained with HF radars from the SuperDARN (Super Dual Auroral Radar) Network sometimes show signatures of ULF (few mHz) waves. We present a new data display technique that facilitates the detection of ULF waves in both ground and sea scatter returns. Statistical study of high time resolution data from the SuperDARN TIGER radar in Tasmania, Australia, revealed that ULF wave signatures occur on an everyday basis with ground scatter accounting for about 60% of wave events. About half of these events exhibit high coherence across large spatial distances and are associated with ULF pulsations recorded by a ground magnetometer. These results show that SuperDARN radars may be used to routinely monitor ULF waves in the high-latitude ionosphere.
1. Introduction

Propagating ultra-low frequency (ULF: ~1-100 mHz) magnetohydrodynamic (MHD) waves provide a convenient tool for remote sensing the magnetosphere and ionosphere. The waves are conventionally detected as geomagnetic field variations registered by ground-based magnetometers. This method is indirect because conversion of the ULF MHD mode into electromagnetic modes at the lower boundary of the ionosphere distorts the wave’s amplitude, phase, and polarization characteristics due to E-region Hall and Pedersen currents, and spatial integration effects. The latter also limits the spatial resolution of ground magnetometer measurements to $\delta r \approx 200$ km [Hughes and Southwood, 1976].

An alternative ULF wave diagnostic at ionospheric heights is provided by HF-VHF Doppler radars. ULF waves propagating in the ionosphere cause periodic variations in plasma motion due to $E \times B$ drift produced by the wave’s electric field and the background geomagnetic field. The resultant Doppler frequency shift of the scattered signals, $F_D$, is readily detected by radars. These can scan large regions (up to 1500-2000 km) of the ionosphere with $\delta r \approx 15$-45 km and have been successfully used for ULF studies for a few decades [e.g., Walker et al., 1979].

The Super Dual Auroral Radar Network (SuperDARN) was developed primarily for studies of large-scale ionospheric convection [Greenswald et al, 1995]. It comprises pairs of HF radars with overlapping fields of view (FOV) that typically scan through all 16 beams each 2 min, although special modes may provide higher temporal resolution in selected beams ($\geq 1$-3 s). An important parameter is the Doppler velocity $V_D = 2F_D/\lambda$, used for estimating the line-of-sight velocity of ionospheric plasma drift, $V_{LOS}$. Overlap-
ping FOVs permit measurement of the horizontal component of drift velocity, $V$. The radar echoes arrive from field-aligned electron density irregularities (denoted ionospheric scatter), when $F_D$ is affected mainly by horizontal plasma motions. SuperDARN radars also receive scatter from the sea or ground due to reflection of the radar signal from the ionosphere. This mode is sensitive to the vertical component of $V$ and is characterized by comparatively low background velocities and spectral widths [e.g. Menk et al., 2003]. Ground scatter echoes are usually excluded from radar data analysis.

Previous studies of ULF waves by SuperDARN radars have mostly been confined to case studies of the auroral, cusp and polar cap regions, due to the difficulty in identifying ULF wave signatures. The main problems are (i) the three-dimensional nature of the data (time-range-beam); (ii) the presence of multiple propagation modes; and (iii) the presence of fast background drifts with $V_0 \gtrsim 500-1000$ m/s that effectively obscure ULF wave signatures with typical amplitudes $V_{ULF} \sim 10 - 100$ m/s $\ll V_0$. Presently, the only reliable way to identify ULF waves in radar data is to visually inspect range-time plots for $V_{LOS}$, but this is a subjective and time-consuming procedure.

The waves observed around 70-80° MLAT have often been discussed in terms of Pc5 field-line resonances, including discrete, stable frequencies of 1.3, 1.9, 2.7, 3.1 mHz [Rouhoniemi et al., 1991; Samson et al., 1991]. The interpretation of these is still controversial. Another subject of intense study is high wavenumber Pc4-5 waves [Fenrich et al., 1995], which are believed to be generated by drift or drift-bounce wave-particle instabilities [Yeoman and Wright, 2001].
The present letter is focused on a new technique for visualization of wave-like processes in both ionospheric and ground (sea) scatter and its application for ULF wave studies using SuperDARN data.

2. Experimental facility and data processing procedures

The radar data discussed here are from the SuperDARN TIGER (Tasman International Geospace Environment) Radar. TIGER’s FOV covers lower magnetic and geographic latitudes than most other SuperDARN radars (Fig. 1), in particular the sub-auroral regions where a variety of ULF wave features may be observed.

The normal SuperDARN scan mode provides an effective Nyquist frequency \( F_N = 1/(2f_s) \approx 5 \text{ mHz} \) that is inadequate for studies of short periodicities such as Pc3-4 ULF waves \( (f \sim 10-100 \text{ mHz}) \). This may be overcome by decreasing the integration time or using a lesser number of beams. The first approach degrades the signal-to-noise ratio and the second restricts the radar’s FOV. This study focuses on special high time-resolution modes.

For our analysis we used range-time maps for \( V_D \) obtained by applying the FITACF procedure to radar autocorrelation functions [Baker et al., 1995]. An illustrative example of FITACF data for TIGER beam 14, 0600-1400 UT on February 21, 2000, is shown in the top panel of Fig. 2. During this day TIGER was operated in a special mode with beams 10, 12, and 14 sampled at \( t_s \approx 12 \text{ s} \). Most of the data (light gray) are characterized by a very low \( V_D \ll 500 \text{ m/s} \) and belong to ground scatter (actually scatter from the sea). There are also two regions of “standard” ionospheric scatter echoes with higher background velocities \( (\sim 0700-1030 \text{ UT}, \text{ range gates 40-60}, \text{ and 1100-1530 UT, gates 15-40}) \). This difference between ground and ionospheric scatter arises from the difference in their propagation mechanisms: for ionospheric scatter \( F_D \) is determined by...
$V_{LOS}$, which is essentially horizontal, while sea/ground scatter depends on the vertical component of $V$. Due to the transverse nature of the $\mathbf{E} \times \mathbf{B}$ drift and almost vertical orientation of the magnetic field lines within the radar’s FOV, the horizontal component of $V$ dominates the vertical one, leading to the observed difference in $F_D$.

Ground scatter signals are affected by ULF waves in the vicinity of the ionospheric reflection point [Menk et al., 2003]. A closer look at this component using a compressed dynamic range ($\pm 10 \text{ m/s}$ instead of $\pm 500 \text{ m/s}$) in the middle panel of Fig. 2 clearly shows wave-like features with periods $\approx 400-450 \text{ s}$ around 1000-1100 UT. These variations are very coherent over about 20 range gates, exhibiting high apparent phase velocity across the LOS. However, most of the data are still dominated by relatively high velocity background drifts. The next step is to extract the long-period trend from the time series. We have tried simple box-car, autoregressive, and median smoothing, all with very similar results, and by trial and error determined an optimum effective window size of $\Delta t_{sm} \approx 600-800 \text{ s}$.

The bottom panel in Fig. 2 shows the detrended data for $\Delta t_{sm} = 600 \text{ s}$. This process improved the visibility of the wave-like features, crucially revealing even low-amplitude waves in the ground scatter during 0730-1130 UT and clearly showing similar but larger amplitude waves in the ionospheric scatter around 1300-1400 UT. At times the waves are coherent in ionospheric and ground scatter across $\geq 30$ range gates.

To ensure that the observed oscillations are not artefacts of the detrending procedure we applied closely spaced but different values of $\Delta t_{sm}$ (say, 800 s and 1000 s) to the same time series. The observed $V_D$ variations retained the same periods regardless of the $\Delta t_{sm}$ value.
To demonstrate the relationship between the observed $V_D$ variations and ULF waves, in Fig. 3 we compare beam 14 radar data with the induction magnetometer records from Macquarie Island (MQI) just eastward of TIGER’s FOV (Fig. 2). For this purpose we arbitrarily choose a one-hour interval, 0900-1000 UT. The top panel in Fig. 3 shows the corresponding time series. The radar data were averaged over gates 24-35, justified by the high coherency of the observed oscillations, and the magnetometer records were integrated to compensate for the $\partial B/\partial t$ response. Note that the ground CGM NS magnetometer trace (thick black line) lags the radar time series (gray line) by about 90°. The bottom panel shows the corresponding frequency spectra. The spectra for $V_D$ and the NS magnetometer component are very similar, with a main peak at 2.22 mHz and a secondary peak at 3.16 mHz. There are no such variations in the CGM East-West (EW) component (thin black line), i.e., the observed wave is linearly polarized in the horizontal plane. Analysis of beams 10, 12 and 14 showed very similar results, with relatively small phase shifts ($\Delta \phi \ll \pi$) between the oscillations in different range-beam cells. This is indicative of a large-scale (low $m$-number) ULF wave.

To obtain further information on the nature of these waves we performed a statistical analysis using the above procedure for 43 days of TIGER special mode data from January-November 2000, when either beam 4 (28 days) or beam 14 (15 days) was sampled at $t_s \simeq 6$ s ($F_N \simeq 167$ mHz) or 12 s (84 mHz) respectively. As a result, 197 one-hour intervals (4-5 hrs/day) with ULF activity in the Pc4-5 band were identified. Ground scatter contributed to about 60% of these events. Event selection was based on the presence of a single dominant spectral peak in the radar data when averaged over 5 neighboring range gates. The detected variations were mostly in the 1-3 mHz range.
our FOV this is significantly below the local field line resonance frequency. Both low- and high-wavenumber Pc5 waves were observed. Altogether 54% of the radar oscillations were accompanied by similar spectral maxima in the MQI magnetometer data. This value was larger for beam 14 (61%) than for beam 4 (48%), probably because beam 14 is closer to the magnetometer (Fig. 2). However, the high percentage for both beams is indicative of low wavenumber events. These results suggest that most of the ionospheric oscillations are signatures of ULF waves, and not gravity or acoustic waves. In addition, some band-limited variations in the Pc3-4 range were detected in the ground scatter echoes, but were not included in the above statistics due to their multi-peak nature.

3. Discussion and conclusions

The above results prompt a cardinal re-evaluation of SuperDARN radar operations, since it is clear that these radars can be used to routinely monitor ULF waves in the ionosphere. The improved spatial resolution and extensive field of view of radars compared to magnetometers opens new opportunities for studying ULF wave behavior and the resultant effects on the ionospheric plasma.

The fact that the ULF waves are readily detected in ground scatter echoes is not surprising. This mode is sensitive to vertical ionospheric motions, which have a strong field-aligned component. The interaction of the ground scatter component with the ionosphere is identical to that for vertical Doppler sounding, used for ULF wave diagnostics [e.g., Wright et al, 1997; Marshall and Menk, 1999], while radars have the advantage of covering larger areas of ionosphere due to oblique propagation. It is important to remember that the indicated range of ground scatter signals is approximately twice larger than the real distance to the reflection point in the ionosphere.
Furthermore, in evaluating $F_D$, the SuperDARN FITACF procedure fits analytic functions to experimental ACFs. This process has advantage over conventional Fourier analysis only when the signal has a single dominant frequency component, and for signals with multi-peak or broad spectra its effectiveness decreases. Ground scatter fulfills these requirements much better than the ionospheric scatter. By its nature – oblique propagation to and from the vicinity of the skip zone – sea/ground scatter has narrow spectral width in contrast to the relatively broad spectra from ionospheric scatter. Also, ground scatter exhibits a regular daily appearance, associated with reflection from a regular ionospheric layer, compared to the more sporadic ionospheric component.

The range over which wave signatures are observed depends on the geometry of the HF path, the state of the ionosphere, e.g., presence of tilts or irregularities, aspect scatter conditions, and the spatial scale size of the ULF disturbance. Often identical wave features are observed in TIGER ground and ionospheric scatter $10^\circ$ or more apart in latitude (Fig. 2). These waves are unlikely to be local field line resonances. Conversely, it may be possible to observe both modes from overlapping regions of the ionosphere. This allows the full 3-component perturbation vector to be obtained.

We have observed 4 distinct types of ULF wave signatures. The most common is a low wavenumber Pc5 wave with high coherence over large distances. About 46% of the radar events have no ground magnetometer counterpart, indicating that many events may be high wavenumber Pc5 events with spatial coherence scale smaller than the separation between MQI and the ionospheric target region. We have also observed bandlimited daytime Pc3-4 pulsations, which most probably represent upstream waves, and narrowband
nighttime Pc4 oscillations that may be signatures of local field line resonances. Properties of these signals will be explored in further papers.

Importantly, the technique described in this paper has proven equally effective for identifying ULF waves in common mode ($t_s=120$ s) radar data as well.

In summary, this study has focused on the identification of ULF wave signatures in SuperDARN velocity data, with the following new results:

- The detection of low velocity wave-like variations in SuperDARN data is greatly improved by removing low-frequency trends and using a compressed dynamic range.

- Applying this technique to 43 days of data revealed an abundance of wave signatures in the mHz range. These are observed for 4-5 hrs/day on average.

- The sea/ground scatter component is particularly useful for monitoring these waves, accounting for about 60% of the observed events.

- Over half of all the waves were also observed by a ground magnetometer and were coherent over large areas.

- Other wave-like features observed in the ionosphere are likely associated with different types of ULF wave sources and modes.

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References


Figure 1. TIGER FOV in geographic coordinates. Triangle denotes Macquarie Island (MQI) magnetometer site.
Figure 2. Doppler velocity variations in beam 14 for 0600-1400 UT on February 21, 2000. Range-time cells with no valid data have diagonal shading. The top panel shows unmodified data obtained via FITACF procedure. The middle panel shows the same data but with an artificially saturated amplitude scale (±10 m/s). The bottom panel results from removing an autoregressive smoothing trend (window size 600 s) from the data and using the saturated amplitude scale.
Figure 3. Time series (top panel) and power spectra (bottom panel) for Doppler velocity variations in TIGER echoes (gray line) and Macquarie Island magnetometer (black lines) for 0900-1000 UT on February 21, 2000. Radar data for beam 14 were averaged over gates 24-35 (see Fig. 1).