Transition of Pi2 ULF wave polarization structure from the ionosphere to the ground

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[1] Trains of ultra low frequency (ULF) waves in the Pi2 range (40–150 s) are regularly detected in near-Earth space. While some Pi2 occur just before substorm onset, others do not show any casual relation to substorm activity so that the Pi2 generation and propagation mechanisms are still unclear. The bulk of information on Pi2 morphology is provided by ground-based magnetometers, subject to distortions due to transition through the highly conducting lower ionosphere. While space-borne magnetometers provide important in situ information, they cannot match the spatio-temporal continuity of ground-based instruments. In this paper, we devise a novel approach using co-located high-frequency ionospheric radars and ground magnetometers for the first direct observation of the Pi2 wave polarization transition between the ionosphere and the ground. Furthermore, application of the Hilbert transform enables us to reconstruct the transition dynamics, which resolves an apparent disagreement between the Pi2 spectra measured by the two instruments. **Citation:** Ponomarenko, P. V., and C. L. Waters (2013), Transition of Pi2 ULF wave polarization structure from the ionosphere to the ground, *Geophys. Res. Lett.*, 40, 1474–1478, doi:10.1002/grl.50271.

1. Introduction

[2] Ultra low frequency (ULF, $\simeq 1$ –100 mHz) variations of the geomagnetic field caused by plasma waves in the terrestrial magnetosphere have been categorized according to their regular (pulsations continuous, Pc) or irregular (pulsations irregular, Pi) temporal structure [Jacobs *et al.*, 1964]. Pi2 pulsations appear as damped sinusoidal variations in the 40–150 s period range, and some of them have been associated with substorm onset [Saito, 1969; Olson, 1999]. However, identical variations that are not related to substorms have also been reported [Liou *et al.*, 2000]. A recent review by Keiling and Takahashi [2011] summarized the current understanding of Pi2 generation and propagation in the context of seven models and analyzed the associated experimental evidence. While combined ground/satellite studies have distilled possible generation/propagation scenarios [e.g., Han *et al.*, 2004], they

have not covered effects from the highly conducting lower ionosphere. The ionosphere alters ULF wave properties by (1) acting as a spatial wave number filter [Hughes and Southwood, 1976; Ponomarenko *et al.*, 2001], (2) modifying the amplitude depending on the spatial and temporal scales of the disturbance [Hughes and Southwood, 1976; Yoshikawa *et al.*, 2002; Sciffer *et al.*, 2004] and (3) rotating the polarization ellipse [Nishida, 1964; Hughes, 1974; Southwood and Hughes, 1983; Sciffer *et al.*, 2005]. Therefore, comparison of spacecraft data with ground magnetometer records requires careful consideration of Pi2 propagation through the ionosphere.

[3] Information about ionospheric ULF wave signatures can be provided by HF/VHF radars. For example, Gjerloev *et al.*, [2007] and Frissell *et al.*, [2011] reported observations of ionospheric Pi2 signatures in the Doppler velocity variations from the Wallops Island HF radar. However, in both of these studies, the ionospheric data were limited to a single line-of-sight velocity component and, therefore, lacked important information on wave polarization. Vertical incidence HF Doppler sounders [e.g., Ikeda *et al.*, 2010] have similar problems because, in this case, Doppler shift is determined by an integral along the propagation path. Here, we make further progress by presenting (1) the first measurements of ULF wave polarization at ionospheric heights using crossed beams from a pair of HF radars and (2) the first direct observation of the ionosphere-ground transfer of a Pi2 wave polarization structure using co-located radar and magnetometer data. In addition, application of the Hilbert transform reveals the dynamics of the Pi2 evolution.

2. Experimental Setup

[4] The ionospheric properties of Pi2 waves were obtained through Doppler velocity measurements by two high-frequency (HF, 9–18 MHz) radars from the Super Dual Auroral Radar Network (SuperDARN) [Greenwald *et al.*, 1985; Ponomarenko and Waters, 2006; Chisham *et al.*, 2007]. SuperDARN radars measure Doppler shifts of HF signals backscattered by small-scale (~ 10 –15 m) ionospheric irregularities at F-region heights (~ 300 km). These shifts are generally caused by $\mathbf{E} \times \mathbf{B}_0$ plasma drifts, where $\mathbf{B}_0$ is the background magnetic field and $\mathbf{E}$ represents ionospheric electric fields of various origins. At high latitudes, the near-vertical orientation of $\mathbf{B}_0$ leads to near-horizontal drifts. ULF waves passing through the ionosphere possess an electric field component ~ 0.1 –1 mV/m that generates quasi-periodic variations in the drift velocity ~ 10 –100 m/s, which are regularly observed by SuperDARN radars [Ponomarenko *et al.*, 2003]. These radars normally operate with a 1 min scan period when all 16 beams are consecutively sampled using an integration time

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Figure 1. Radar beam configuration for the ULF scan mode. Range gates along each beam are separated by 45 km (mesh). Thick lines mark every 10th gate starting from gate 0. The red triangles mark the locations of the Macquarie Island (MQI) magnetometer site and the TIGER Bruny and Unwin radars.

of ≈ 3 s per beam (Nyquist frequency $F_N = 8.3$ mHz). This regime is not particularly suitable for detecting Pi2 waves (6.67–25 mHz). Therefore, a special “ULF” radar scan mode was designed and implemented in which the radar sampling rate was increased to ≈ 9 s ($F_N = 55.5$ mHz) by reducing the number of sampled beams to three, providing a satisfactory trade-off between F_N and spatial coverage. A single SuperDARN radar is only capable of measuring a single line-of-sight (LOS) component of the ionospheric drift velocity along each beam. In order to observe 2D ULF wave polarization properties in the ionosphere, it is necessary to use data from a common ionospheric volume observed simultaneously by two spatially separated radars. To achieve this, data from the pair of Tasman International Geospace Environment Radars (TIGER) radars with overlapping fields-of-view were combined. The location and beam patterns of the TIGER Bruny (Tasmania) and TIGER Unwin (New Zealand) radars are shown in Figure 1. Overlap with the magnetometer site on Macquarie Island (MQI, CGM $64^\circ 18'S$, $248^\circ 21'E$, $MLT \approx UT+12$) was achieved by rotation of the field-of-view of the Bruny radar by $\approx 7^\circ$ counter-clockwise using a specially designed phasing matrix (M. Parkinson, private communication). As a result, beam 14 from Bruny and beam 12 from Unwin intersected above MQI so that the ionospheric ULF wave characteristics could be directly compared with their ground magnetic signatures. The remaining beams (1 and 5 for Bruny and 0 and 15 for Unwin) provided supplementary information on the spatial extent of the observed ULF waves.

[5] The magnetic field vector data at ground level were sampled at a 1 s rate using fluxgate magnetometers operated by Geoscience Australia (Commonwealth of Australia (Geoscience Australia) 2012. This product is released under the Creative Commons Attribution 3.0 Australia Licence). The magnetic data components were aligned with magnetic (AACGM) coordinates, so that the North and East directions correspond to positive deviations. For ease of comparison,

the radar velocity vectors were converted to the same coordinate system, under the assumption that the LOS vectors for both radars are parallel to the ground.

3. Pi2 Data for 19 October 2006

[6] The data recorded over the 1 h interval preceding a moderate substorm observed on 19 October 2006 were analyzed. The top panel in Figure 2 shows the NS component of the geomagnetic field at MQI, which exhibits a persistent negative excursion starting at ≈ 10 UT (22 MLT) and lasting for several hours. The second panel of Figure 2 shows both horizontal components from the same data set, but zoomed to 09–10 UT (21–22 MLT) and with a 300 s boxcar moving average subtracted. The detrended data reveal several trains of Pi2-like oscillations. Similar variations in the LOS velocity with amplitudes reaching 100 m/s were also observed by both radars across range gates 10–30 (group range 900–1500 km), which is close to the average loca-

Figure 2. (Top panel) NS component of the geomagnetic field at MQI over 08–14 UT on 19 October 2006. A substorm onset is apparently near 10 UT. (Second panel) NS (black) and EW (red) magnetic field components at MQI zoomed to 09:00–10:00 UT and detrended by subtracting a 300 s boxcar moving average. Several isolated Pi2 trains are evident between 09:15 UT and the substorm onset. (Third panel) UT-range plot of Bruny beam 14 Doppler velocity data (09:00–10:00 UT, detrended). (Bottom panel) similar to the second panel but for the radar velocity data. Red arrows mark the 9:25–9:40 UT event analyzed in detail in this paper.

tion of the nighttime plasmopause. To illustrate the radar signatures, the third panel of Figure 2 shows velocity data for beam 14 of the Bruny radar. Following *Ponomarenko et al.*, [2003], these data were preprocessed by subtracting a 300 s moving average to remove the slow-varying ionosphere drifts. The velocity variations are plotted in saturated gray scale, while blue shading denotes missing data. The radar Pi2 signatures appear as vertical stripes of alternating shades of grey depicting synchronous velocity oscillations across a number of range gates. The bottom panel shows NS (black) and EW (red) components of the ionospheric drift velocity over MQI reconstructed from the crossed-beam radar data. The radar range cells located over MQI are gate 30 for Bruny and gate 22 for Unwin (Figure 1). While gate 22 on beam 12 of Unwin contains continuous data during the interval of interest, there is a small data gap in the Bruny data over gates 28–32. This was filled using the closest available gate containing valid data, gate 27, based on the high coherency of the velocity variations across at least 15 range gates. The selected radar records also contain a few outliers, which were identified and replaced by linear interpolation between neighboring valid data. Results from HF ray tracing for the given ionospheric conditions favor the interpretation of these echoes as 1/2-hop ionospheric backscatter. Similar Pi2 wave trains were observed nearly simultaneously across the whole 210° meridian magnetometer array (not shown) indicating the broad latitudinal extent of these events. For illustrative purposes, here, we focus on a pronounced ULF signature observed over 09:25–09:40 UT (21:25–21:40 MLT) as marked by red arrows in Figure 2. This event exhibited all the characteristic features of Pi2 waves, but occurred well before the substorm onset at ≈ 10 UT, so it does not represent a conventional precursor.

[7] Fourier analysis, supplemented by Hanning windowing, was applied to the unfiltered time series covering the 09:25–09:40 UT interval. Figure 3a shows normalized trace power (sum of spectral powers of the orthogonal components) for the radar (red) and magnetometer (black) data sets. The dominant peaks are located around 7–8 mHz, while significant spectral power is limited to frequencies below ≈ 20 mHz. In order to analyze ULF wave polarization, the equations for ellipticity and azimuth, based on Stokes parameters as described by, e.g., *Fowler et al.* [1967], were used. The respective spectra are plotted in Figures 3b and 3c. For the coordinates used, positive values of azimuth correspond to the angle measured clockwise from the magnetic North, and positive ellipticity values (sense of polarization) describe clockwise rotation of the polarization ellipse. Figure 3d represents the amplitude transition coefficient “ionosphere-ground” measured in nT/(m/s). The black vertical dashed lines in Figure 3a indicate the 3–30 mHz band used in complex decomposition analysis (see below).

[8] The Pi2 pulsations represent wave packets, which are confined in time. Therefore, important information on their temporal evolution can be missed when using conventional Fourier analysis. In order to observe the time history of the event, the complex decomposition technique was applied. This conventionally provides phases and amplitudes of the signal at the dominant spectral component sampled at the same rate as the signal itself. The major limitation of this technique is that it is applicable to narrow-band

signals, and Figure 3a indicates that this requirement is satisfied. In order to accommodate the Pi2 frequency range (6.67–25 mHz) and minimize contamination by the lower- and higher-frequency components, all data sets were bandpass-filtered to suppress spectral power outside the 3–30 mHz band. The complex signal, $S(t)$, was constructed using the recorded signal $s(t)$ as the real part and its Hilbert transform, $H(s(t))$, as the imaginary part, i.e., $S(t) = s(t) - iH(s(t)) = |S(t)|e^{i\phi}$, where $i = \sqrt{-1}$ and $|S(t)|$ and $\phi(t)$ are the time dependent amplitude and phase of the complex signal, respectively.

[9] In order to obtain time dependent polarization characteristics, the complex signals were processed using the same expressions from [Fowler et al., 1967], and the results are shown in the respective right-hand panels of Figure 3. For ease of comparison, the magnetic data, which were originally sampled at 1 s, are shown only at the times coinciding with the radar samples, i.e., every 9 s.

[10] To ensure that the polarization properties are calculated for the same periodicities, it was important to examine the temporal history of the signal frequency for both data sets. This was achieved in two steps. First, instantaneous phases for both orthogonal components, ϕ_x and ϕ_y , were differentiated in the time domain to obtain the respective frequencies, $f_{x,y}(t) = (1/2\pi)(\partial\phi_{x,y}(t)/\partial t)$. Second, the effective frequency of the polarized wave was calculated as a weighted average, $f = (f_x p_x + f_y p_y) / (p_x + p_y)$, where the weighting was based on the respective powers, p_x and p_y . This parameter is plotted in Figure 3h by black (ground) and red (ionosphere) diamonds using the right-hand Y axis.

4. Experimental Summary and Discussion

[11] The polarization spectra computed from the conventional Fourier analysis in Figures 3a–3d show a number of differences between the ionospheric and ground Pi2 signatures. While the trace power spectra overlap quite well in the frequency domain, they possess slightly different maximum frequencies, ≈ 7 mHz on the ground and ≈ 8 mHz in the ionosphere. More importantly, there is little resemblance in the respective ellipticity and azimuth spectra. There are two groups of factors that might lead to this: physical and instrumental.

[12] With respect to physical factors, one should expect some changes in the wave’s characteristics resulting from its transition between the ionosphere and the ground. The slight shift in the maximum frequency (Figure 3a) could be related to the screening of higher frequency/smaller scales, and this interpretation seems to be supported by the decrease of the transfer function with increasing frequency (Figure 3d). With respect to azimuth, early works [e.g., *Southwood and Hughes*, 1983] predicted a 90° rotation of the polarization ellipse on the ground with respect to its orientation above the ionosphere. If we assume that the measured radar velocity variations are caused by $\mathbf{E} \times \mathbf{B}$ drift of the fully magnetized plasma, then the wave magnetic field oscillations are aligned with those in the plasma drift. This means that the observed azimuth change (Figure 3c) is smaller than expected in magnitude and rather complex in nature. The reduced amount of rotation can be explained by more realistic models, which account for a non-vertical geomagnetic field, wave mode conversion coefficients and horizontal non-uniformity of the E-layer conductivity. For example, *Sciffer*

Figure 3. Comparison of polarization characteristics of the radar (red) and magnetometer (black) data for 9:25–9:40 UT, 19 October 2006, obtained using (a–d) the Fourier transform and (e–h) the complex decomposition based on the Hilbert transform. The vertical dash-dot lines correspond to the maximum power in the respective data sets. The vertical dashed lines in Figure 3a show the frequency band used for the complex decomposition analysis (right column). The horizontal dashed lines in Figures 3a and 3f indicate a 5% power cutoff used for plotting the polarization characteristics in the lower panels. The black and red diamonds in Figure 3h correspond to the right Y axis and represent instant frequencies, while the blue symbols depict the transfer function (left Y axis, see text for more details).

et al. [2005] showed that the azimuth rotation depends on the relative contributions from fast and shear Alfvén modes in the topside ionosphere, so it is altitude dependent. However, our spectral data also show opposite rotation signs at the ionospheric and ground spectral maxima, while the respective ellipticity values exhibit opposite signs and differing magnitudes. While these observational details appear to be unexplainable within our current understanding of the ULF wave transfer through the ionosphere, they can be reconciled with theory by analyzing the temporal evolution of the ULF wave.

[13] At first glance, the instantaneous Pi2 characteristics in Figures 3e–3h also show little resemblance between the ionosphere and the ground. The trace power in the ionosphere shows a single peak at 09:30:30 UT, while the ground power peaks at $\approx 9:32:30$ UT showing only a secondary enhancement coinciding with the ionospheric maximum. The respective ellipticity and azimuth time series also change in apparently independent ways. However, a

closer look at the polarization characteristics near the coincident peaks at $\approx 9:30:30$ UT indicates that these peaks have a common origin. These indicators include (1) nearly linear polarizations (Figure 3f), (2) consistent azimuth shift of $\approx 40^\circ$ (Figure 3g), (3) constant transfer function at ≈ 0.025 nT/(m/s) (Figure 3h, blue), and (4) close instantaneous frequencies at ≈ 7.5 mHz (red and black diamonds in Figure 3h).

[14] The existence of the second (major) temporal power peak in the ground record might be related to instrumental effects arising from the different spatial coverage of the diagnostic tools used to analyze ULF wave signatures in the ionosphere and on the ground. Above MQI, the radars provide a significantly better spatial resolution determined by the 45 km range gate cell along LOS and 50–100 km across it. In contrast, the ground magnetometers integrate the signal from a much larger area of the ionosphere. Therefore, the second ground maximum may originate from an active ionospheric region, which lies away from the zenith

direction at MQI, so it is unseen by the radar, but makes a major contribution to the ground data. As a result, the spectral characteristics of the ionospheric and ground data may be dominated by different spatio-temporal components, thus explaining the observed differences in the Fourier spectra. The currently available information is insufficient to clarify the nature of this additional component. Finally, assuming that the observed Pi2 event preserves its linear polarization over the field-of-view of the radars, we estimated the azimuthal wave number using data from additional beams of the Bruny radar, $m \simeq -(5-6)$ with the minus sign indicating westward phase propagation.

5. Conclusions

[15] In this paper, we have reported the first direct observation of the ionosphere-ground transition of the polarization characteristics for a Pi2 wave in the vicinity of the nightside plasmopause using Doppler velocity records from a pair of SuperDARN HF radars and co-located ground magnetometer data. Application of the Hilbert transform reveals the temporal evolution of the event and resolves the discrepancy between the average pulsation characteristics in the ionosphere and on the ground, which apparently arises from the difference in the spatial resolution of the instruments.

[16] For this particular event, the approximate linear polarization of the Pi2 wave was transferred from the ionosphere to the ground, accompanied by an $\simeq 40^\circ$ rotation of the polarization ellipse. The amplitude transfer ratio was nearly constant at 0.025 nT/(m/s), and the azimuthal wave number was $\simeq 5-6$ westward. This information is vital for understanding the ionosphere-ground transition of Pi2 waves and how spacecraft measurements are related to ground magnetometer signatures of Pi2 signals.

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