# ULF Waves in the Ionosphere: Recent Observations and Modelling

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## Background

Our purpose is to examine the effects of ULF (~1 mHz – 1 Hz) magnetohydrodynamic waves on the ionospheric plasma. To this end we combine observational data from low and middle latitude radio sounders and ground-based magnetometers, and investigate relevant mathematical models of ULF wave propagation in the ionosphere. The TIGER SuperDARN radar scans the region mapped by the plasmapause, and we have commenced a program to study the ionospheric signature of ULF waves in this region.

## Previous observations of ULF waves in the ionosphere

Ionospheric oscillations and perturbations driven by downgoing ULF waves have been previously observed using HF radars and Doppler sounders. It is generally believed that solar wind perturbations drive ULF energy that propagates in the fast wave mode through the outer magnetosphere and across the plasmapause into the plasmasphere. The fast mode waves couple to localised shear Alfvén mode resonances on closed field lines where the frequencies match. Since at a given latitude the resonance occupies a discrete frequency, while a broad spectrum may be observed on the ground, a mixture of both fast and shear Alfvén modes is incident on the ionosphere.

*High latitudes*

Field line resonances (FLRs) with frequencies of a few milliHertz have been recorded in the F-region by high latitude HF radars (e.g. Walker et al., 1992). The waves sometimes appear to exhibit quantized frequencies and have therefore been discussed in terms of magnetospheric cavity or waveguide modes (Ruohoniemi et al., 1991; Samson et al., 1992), although this conclusion is still controversial (Ziesolleck and McDiarmid, 1994). Nevertheless, the radars clearly reveal the variation in amplitude and phase with latitude, and the diurnal variation in frequency, expected for FLRs. The radars detect echoes that are backscattered from field-aligned plasma density irregularities when the radio beam is close orthogonal to the **B** field. The ULF wave-related Doppler velocity features are believed to be due to **E** x **B** motions driven by the downgoing wave field.

*Low latitudes*

At low latitudes HF Doppler sounders provide measurements of ULF wave effects in the ionosphere. Field line resonances provide only a minor contribution to the ULF spectrum on the ground at these latitudes, and downgoing fast mode waves are more important. However, discussions of related theory are usually couched in terms of downgoing shear Alfvén mode waves.

A recent study by the University of Newcastle used HF Doppler receivers and magnetometers to examine ULF oscillations in the F-region between L=1.7 and L=2.2 (see map in Appendix for details). Data analysis took two forms:

(a) Comparison of the magnetic pulsation spectrum on the ground (NEWX and NEWY in the plot for 16 April 1993 shown in the Appendix) with the corresponding Doppler spectrum in the ionosphere (NWIX).
(b) Examination of the ionosphere-ground amplitude and phase relationship as a function of pulsation frequency and latitude.

Accordingly it was found that

(a) the spectrum of ULF irregularities in the ionosphere is similar to the pulsation spectrum on the ground; and
(b) the amplitude of the Doppler shifts (Hz/nT) and the ionosphere-ground cross-phase is almost constant with pulsation frequency at different latitudes *except* at the resonant frequency and its harmonics, where the amplitude peaks and there is a sharp dip in the phase. Both of the latter results are remarkable. For example, resonance harmonics are not seen on the ground at low latitudes but can be clearly identified in the ionosphere-ground cross-phase plots. These results suggest a transition from almost pure incident fast mode waves off resonance to mixed and shear Alfvén mode waves near and at resonance.

*Ground scatter observations*

Recent results from the CUTLASS radar have suggested that at high latitudes ground scatter may provide an important new mode for observing ULF wave effects in the ionosphere. Detailed examination of a solar wind negative pressure pulse event (23 February, 1996; see Appendix) has revealed small Doppler velocity oscillations in ground scatter recorded by both the Iceland East and Finland HF radars. The oscillations were also seen with a co-located HF Doppler sounder and with magnetometers of the IMAGE array.

The magnetometer data show 1.6 mHz pulsations, lasting for some hours and with remarkably similar structure over 20$^{o}$ in latitude. There is a FLR near 72$^{o}$ latitude, but the most likely explanation of the signals elsewhere is that they are global mode oscillations. CUTLASS observes the pulsations mostly equatorward of the resonance latitude. Accordingly, we believe the radar oscillations are due to Doppler shifts of the ground scatter signal during its traversal through the F-region. This suggests that radar observations of ground scatter may provide high resolution measurements of ULF wave effects in the F-region.

**Modelling ULF wave propagation in the ionosphere**

*Previous models*

The simplest assumption is that the oscillating **E** field of downgoing ULF waves drives **E** x **B** drifts in the ionosphere (e.g. Rishbeth and Garriott, 1964). However, the effect of the ionosphere and atmosphere on the incident wave also needs to be considered (Hughes, 1974; Hughes and Southwood, 1976). Poole et al. (1988) and Sutcliffe and Poole (1989) showed that three separate mechanisms might lead to Doppler shifts in HF signals. They developed a model predicting the Doppler shift in each case, using realistic values for electron density and other parameters.

An important limitation of this modelling is that it only considers Alfvén waves incident on the ionosphere. In order to determine the HF Doppler shifts it is necessary to specify the ULF wave fields as a function of height from the ground up to the radio signal reflection point. Poole et al. (1988) used the Hughes (1974) model for this purpose. However, this restricts the Doppler shift predictions to the case of FLRs.

*One-dimensional modelling*
We have recast the Poole et al. (1988) model to include fast mode and a mixture of wave modes incident on the ionosphere, as well as off-vertical magnetic field angles. This was achieved using a boundary value approach, following Zhang and Cole (1994, 1995), allowing us to specify the polarization and wave mode state of the incident wave. The bottom side boundary is at the ground and is assumed to have isotropic, finite conductivity. We assume the incident waves vary as $\exp[i(\omega t-k_x x-k_y y)]$ and make reasonable assumptions about the spatial character (wavenumber) of the waves in two dimensions. We then calculate the resultant electric and magnetic ULF wave fields in the ionosphere and use atmospheric and ionospheric data from the MSIS and IRI models to determine the conductivity and particle density profiles. Finally, we use the Appleton-Hartree equations for HF wave propagation in the ionosphere to calculate the Doppler shift for the three mechanisms discussed by Poole et al. (1988).

The model predictions are in good agreement with the observed ionosphere-ground amplitude and phase properties (shown in the figure by the solid curve superimposed on the observational data). We assumed pure fast mode incident ULF waves at all frequencies except at the resonance (pure shear Alfvén mode) and used a field inclination appropriate to our latitude. The main contribution to the fast mode Doppler shift is from the $V_3$ mechanism (Sutcliffe and Poole, 1989), which describes changes in refractive index due to the divergence of the electron velocity.

*Two-dimensional modelling*
This is presently under way. We consider the time-independent case and only need to provide information on the wave's spatial character in one dimension. Ray tracing techniques are used to determine the ray path of a radio signal. This is suited to modelling ULF-driven HF Doppler shifts along a ray path or across radar beams. In addition, it will be possible to determine the individual effect of the three mechanisms causing these Doppler shifts.

A further extension of this modelling is to consider the time-dependent case. This will allow impulsive signals such as flow bursts and pressure pulses to be examined.

**ULF wave studies using TIGER**
TIGER's field of view extends from equatorward of the plasmapause to very high latitudes, and its easternmost beam passes near Macquarie Island, where a pulsation magnetometer and ionosonde are operated. We are operating experimental campaigns using discretionary mode time to give high spatial and time resolution coverage near Macquarie's longitude. These campaigns include study of ground scatter signals for signatures of low velocity features.

Theoretical studies of ULF wave propagation in the magnetosphere predict the existence of reflection points so that the fast mode wave is resonant in the magnetospheric cavity. These cavity/waveguide modes couple to localized field line resonances in the milliHertz range and have previously been observed with high latitude radars. At the other end of the ULF spectrum, modelling by André et al. (1999) has demonstrated that the electric field of downgoing electrostatic Pc1-2 waves may give rise to the spectral width enhancement usually associated with the cusp. This has not yet been investigated experimentally.

We will use TIGER to study the signatures of
(a) field line resonances in the vicinity of the plasmapause,
(b) global cavity modes, and
(c) broadband unstructured Pc1-2 recorded near the cusp and boundary layer.

Topic (a) includes studies of the dynamics of the establishment of a new plasmapause boundary after substorm activity and the evolution of the global plasmapause shape during plasma erosion. The ULF wave signature of the plasmapause during these processes is of particular interest. This includes studies of the field resonance mode with plasmapause dynamics and the investigation of plasmapause surface waves.

We have already observed signatures in ground scatter data of equatorward propagating gravity waves and TIDs. We have also found several intervals of sustained oscillations extending over large distances in the F-region, occurring at the same time and with similar period to Pc5 ULF pulsations recorded on the ground at Macquarie Island.

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