
HF Doppler Observations of ULF Waves:
System Development and High Latitude Results

Thesis submitted for the degree of
Doctor of Philosophy
at the University of Leicester

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August 1996

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Darren Mark Wright

Abstract

This thesis describes a study of ultra low frequency (ULF) waves in the high latitude ionosphere. These waves have been observed by means of a high frequency (HF) Doppler sounder known as the Doppler Pulsation Experiment (DOPE). The ULF waves perturb the phase path which produces a small Doppler frequency shift in the received radio signal. These Doppler signatures can be related to the ULF wave characteristics. The receiver is computer controlled and dedicated software enables the system to run unattended for several weeks. The archived data are returned to Leicester for analysis. The sounder is located in northern Norway near the EISCAT radar installation.

A statistical study of an earlier data set collected at the same location has established the diurnal, seasonal, solar cycle and geomagnetic activity variations of the ULF wave signatures. The effectiveness of the technique for observing ULF waves has also been investigated and this has allowed the optimisation of DOPE for studies of ULF waves.

The first results from DOPE indicate that two distinct types of waves are present; those which have a correlated ground magnetic signature and those which do not. The "correlated" events are associated with field line resonances in the Earth's magnetosphere. The "uncorrelated" signatures are divided into events which occur in the morning and afternoon sectors. The morning events are reminiscent of giant pulsations which occur under quiet geomagnetic conditions. Afternoon waves coincide with depressions of the D_{st} index and are consistent with observations of storm time ULF waves. The "uncorrelated" waves are not observed by ground based magnetometers because of their high azimuthal wave numbers.

The Doppler technique has proved to be a powerful tool for ULF wave studies and a number of ULF wave features have been identified for the first time.

*For my Grandfathers,
John Harry Wright and John Bradbury*

Acknowledgements

I am very grateful to the following people for their involvement leading to the completion of this thesis:

Professor Tudor Jones for offering me the opportunity to join the Radio and Space Plasma Physics group and for his comments on this manuscript.

Dr. Tim Yeoman, who made the DOPE project possible, for many enlightening discussions, his continuous encouragement and for the use of the bin in his office.

The staff at the EISCAT site in Ramfjordmoen, Norway for looking after the Doppler system and returning data tapes to Leicester. Furthermore, for providing other data employed in this thesis I would like to thank: Matthew Wild and Chris Davis at the World Data Centre C1 for providing ionosonde and dynasonde data; The Sodankylä Geophysical Observatory and Børre Holmeslet at the Tromsø Auroral Observatory for magnetometer data.

Kinky Peter Chapman, Stuart Crooks and Mick Parsons for creating the DOPE transmitter and receiver and for educating me in the school of life.

The Particle Physics and Astronomy Research Council (PPARC) for funding my PhD and to the Royal Society for awarding a grant for the DOPE project.

Dr. Terry Robinson and members of the Heating team who allowed me time to finish this thesis.

All of the members of the group, past and present, including Brian Shand, Steve Milan, Jackie Davies, Alan Stocker, big Giles Bond, Paul "Eggman" Eglitis, Jon Angell, Eric Bradshaw, Andrew "Grit" Stone, Paul Hamadyk, my great Uncle Mark Lester, Paul Rylah and Craig Foster for their friendship, drinking partnership and fun times.

Mum and Dad for their support throughout my education and interest in my work. In addition, all my friends and family for their encouragement.

A special thank you to Helena who has made life truly wonderful. Her love, and when I had to work late, her understanding have kept me motivated.

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Glossary

Abbreviations, Acronyms and Important Terms

AGC	Automatic Gain Controller
AGW	Acoustic Gravity Wave
AMPTE-CCE	Active Magnetospheric Particle Tracer Explorer - Charge Composition Explorer
CANOPUS	Canadian Auroral Network for the Open Program Unified Study
CCM	Coupled Cavity Mode
CW	Continuous Wave
DAT	Digital Audio Tape
DOPE	Doppler Pulsation Experiment
D_{st}	Disturbance storm time index
EISCAT	European Incoherent Scatter
FFT	Fast Fourier Transform
FLR	Field Line Resonance
f_{min}	Minimum frequency occurring on an ionogram
foE	O-mode critical frequency of the E-region
$foF2$	O-mode critical frequency of the (daytime) F-region
$fxF2$	X-mode critical frequency of the (daytime) F-region
GOES2/3	Geostationary Operational Environmanetal Satellites
GPS	Global Positioning Satellite
GUI	Graphical User Interface
HF	High Frequency
hmE	Height corresponding to the maximum electron density of the E-region
$hmF2$	Height corresponding to the maximum electron density of the (daytime) F-region
IF	Intermediate Frequency
IMAGE	International Monitor for Auroral Geomagnetic Effects
IMF	Interplanetary Magnetic Field
IPC	Interprocess Communication
IRI	International Reference Ionosphere
L	The distance, in R_E , to the point in the where a field line crosses the geomagnetic equatorial plane.

Glossary

LANL	Los Alamos National Laboratory
LO	Local Oscillator
LT	Local Time
LUF	Lowest Usable Frequency
m	Azimuthal Wave Number
MHD	Magnetohydrodynamic
MLT	Magnetic Local Time
MUF	Maximum Usable Frequency
NmE	Maximum electron density of the E-region
NmF2	Maximum electron density of the (daytime) F-region
O-mode	The ordinary mode of a HF radio wave
PC	Personal Computer
Pc	Continuous (Regular) Pulsation
Pg	Giant Pulsation
Pi	Irregular Pulsation
R_E	Radius of the Earth
RF	Radio Frequency
RTM	Real Time Monitor
SABRE	Sweden And Britain Radar Experiment
SAMNET	Sub-Auroral Magnetometer Network
SOD	Sodankylä IMAGE station ID
SP-UK-DOPE	United Kingdom EISCAT Special Program
STARE	Scandinavian Twin Auroral Radar Experiment
TID	Travelling Ionospheric Disturbance
TRO	Tromsø IMAGE station ID
TTL	Transistor-Transistor Logic
ULF	Ultra Low Frequency
UPS	Uninterruptible Power Supply
UT	Universal Time
VHF	Very High Frequency
X-mode	The extraordinary mode HF radio wave

Chapter 1

Introduction

1.1 Introduction

The sun continuously emits a stream of ionised matter, known as plasma, which forms the so called solar wind. This flows supersonically through space and interacts with the Earth's magnetic field to form the magnetosphere, a cavity into which the entry of solar wind plasma is restricted. The solar wind carries with it a magnetic field which can, under appropriate conditions, couple to that of the Earth and allow plasma to enter the cavity. Changes in the flow of the solar wind and the viscous interaction with the magnetosphere can cause magnetohydrodynamic (MHD) oscillations of the field inside this cavity.

The ionosphere is a region of the upper atmosphere, surrounding the Earth, where gaseous neutral atoms and molecules have been ionised by energetic photons provided by the solar illumination. The Earth's magnetic field lines penetrate this region and any field perturbations, originating in the magnetosphere, interact with the ionospheric plasma and cause characteristic signatures in the form of density changes, variations in the electric and magnetic fields and in the bulk velocity of the medium. Such signatures may be detected by means of radio wave diagnostic instrumentation such as radars or Doppler sounders. The subsequent sections of this chapter describe the solar wind, the Earth's magnetosphere and ionosphere. Finally, an introduction to the present study and the motivations behind it is presented.

1.2 The Solar Wind - Magnetosphere System

In addition to a broad spectrum of electromagnetic radiation, the sun emits a stream of energetic high velocity (typically $300\text{-}500\text{ km s}^{-1}$) plasma known as the solar wind. It consists mainly of protons and electrons which are ejected from the solar corona and has associated with it a magnetic field, commonly called the interplanetary magnetic field or IMF. This field interacts in a complicated manner with the Earth's own magnetic field. This interaction can allow the solar wind plasma to gain entry into the magnetosphere and also into the ionosphere itself.

In its simplest form, the Earth's magnetic field can be represented by a dipole configuration inclined at approximately 12° to the geographic spin axis. However, the field becomes less dipolar as the distance away from the Earth increases. The

influence of the solar wind distorts the dipole pattern, compressing the sunward side of the field and elongating the downstream magnetosphere into a “tail” which extends to about 1000 Earth radii (R_E) long (figure 1.1a). Where the supersonic solar wind stream meets the magnetosphere a bow shock forms (figure 1.1b) which rapidly slows the flow at its apex, created about $13 R_E$ from the centre of the Earth. The solar wind flow moves turbulently around the flanks of the magnetosphere forming what is known as the magnetosheath. The magnetopause is the boundary which separates the magnetic fields of the solar wind and the Earth.

When discussing magnetospheric regions it is useful also to define the concept of an L -shell. Consider the set of closed field lines, in a perfect dipolar field, which all cross the geomagnetic equatorial plane at the same distance from the centre of the Earth. This distance, in Earth radii, is called the “ L ” value of that shell. Each of the field lines constituting the “shell”, ideally, would connect to the Earth at the same geomagnetic latitude in a given hemisphere. Higher latitude field lines tend to be on higher numbered L -shells. This concept allows effects associated with magnetospheric phenomena to be mapped back out into the magnetosphere. For example the Norwegian city of Tromsø, which is relevant to this work, corresponds to L of about 6.5. However, as already mentioned, the Earth’s field is not dipolar and so more representative field models are necessary to evaluate L accurately. In the region of closed field lines around the Earth the field is approximately dipolar and so the concept of an L -shell is a useful one.

If the Interplanetary Magnetic Field (IMF) has a southward component, then it may reconnect with the Earth’s field at positions where it is oppositely directed (figure 1.2). This “reconnection” process [Dungey (1961)] means the two fields are coupled which allows the solar wind plasma direct access into the Earth’s inner magnetosphere by flowing along these open field lines. The reconnected field lines are dragged along by the IMF, which is “frozen” into the solar wind stream, and stretched down the magnetotail. A second reconnection site becomes possible at this location and open field lines from the northern and southern magnetotail lobes pinch off to reform closed field lines. These field lines, having been stretched downtail, have a great deal of energy stored as magnetic tension and restore themselves to a more stable state by moving in closer to the Earth thus releasing the tension (figure 1.2). Solar wind plasma, trapped by the field line-at pinch off, is accelerated by this motion towards the Earth. This results in the injection of energetic plasma into the nightside [e.g. Reeves *et al.* (1990)] where, under the influence of gradient-curvature drift, protons and electrons move around

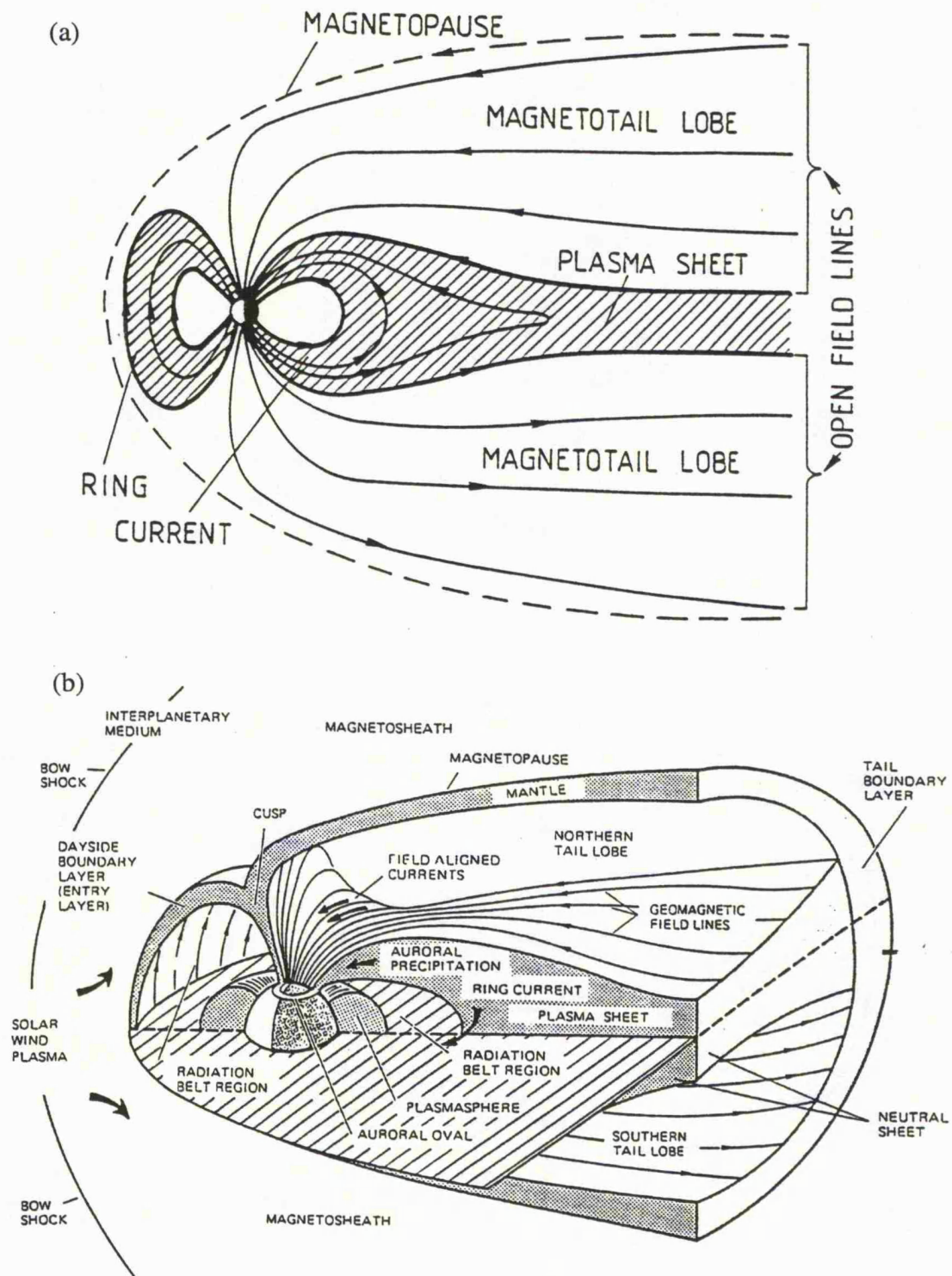


Figure 1.1: Two and three dimensional representations of the magnetosphere. (a) an illustration of the distortion of the Earth's magnetic field from a simple dipole field; (b) the magnetospheric cavity and some of the important regions that occur there. The bow shock is formed as a result of the interaction between the supersonic solar wind and the Earth's field. [after Milan (1994)]

the Earth in opposite directions constituting part of the global ring current (see section 2.2.3). Such an injection may be a result of a substorm onset and the particle populations which drift around the Earth may drive oscillations, via wave-particle interactions, of the Earth's magnetic field called geomagnetic pulsations. An in-depth study of substorms is beyond the scope of this thesis but the pulsation generation mechanism will be discussed in chapter 2.

The plasmasphere is a region of relatively dense (10^8 m^{-3}) "cold" plasma - so called because it does not possess the energy to move perpendicular to the field. It is thus frozen onto the closed field lines (figure 1.1) and is unable to escape from this region. The plasma, which originates mostly from the ionosphere, co-rotates with the Earth. The plasmapause is the outer boundary of this region, located at around $4 R_E$ from the Earth, at which a large density gradient exists.

1.3 The Ionosphere

The sun emits radiation and particles which can ionise the atoms and molecules of the Earth's atmosphere. The production processes for the free electrons are balanced by a number of loss processes, such as recombination and attachment. Because of the higher atmospheric gas densities in the lower atmosphere, below 60 km altitude, the loss processes dominate. Above 60 km free electrons can exist for considerable periods of time. The ionosphere is that part of the atmosphere extending from 60 km to over 1000 km, which consists of a weakly ionised, quasi-neutral plasma. It is a region where the ionisation is sufficient to affect the propagation of radio waves [*e.g.* Davies (1969)]. At night the ionising photon flux is no longer present and loss processes dominate, resulting in a depletion of the ionospheric electron density.

As a consequence of the stratification of atmospheric constituents by gravity and the variation in ionisation cross-section between these constituents, the electron density of the ionosphere varies with height and exhibits several distinct ionospheric regions - the D, E, and F regions. Typical mid-latitude electron density profiles are illustrated in figure 1.3. The D-region extends from 60 km to 90 km, with an approximate daytime electron density of 10^{10} m^{-3} . During the night the D-region completely recombines. The E-region extends from 90 km to 120 km, and has a typical daytime electron density of 10^{11} m^{-3} . The electron density of the E-region varies regularly with the level of solar illumination. In the E-region, where the recombination rate is sufficiently high that production and loss processes reach quasi-equilibrium, the electron density, N_e , is a function of the

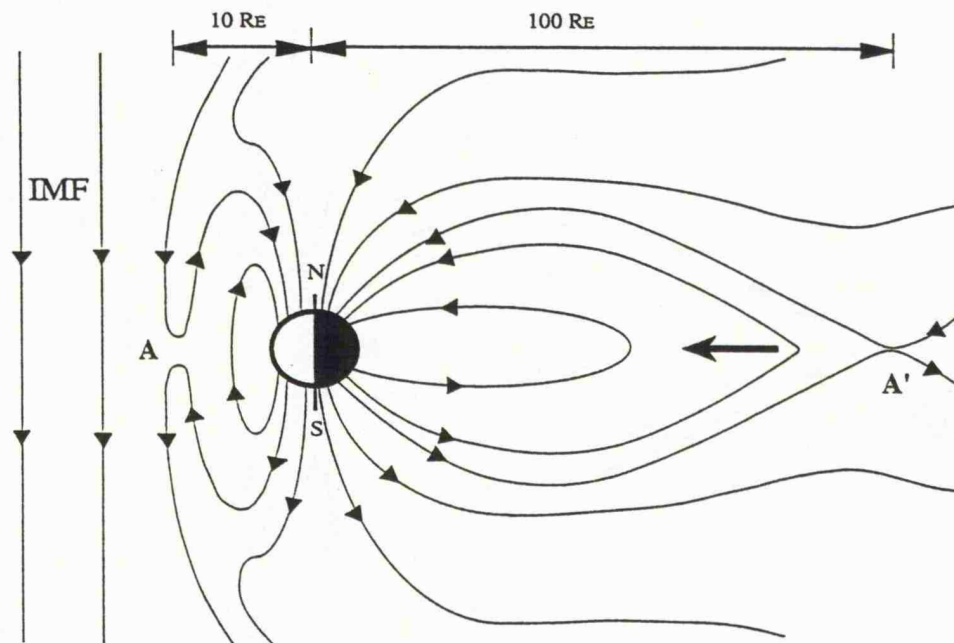


Figure 1.2: Reconnection occurrence between the Earth's magnetic field and the interplanetary magnetic field (IMF). The process may occur where the two field directions are opposite. A and A' represent two reconnection sites. The magnetotail site A' occurs where 'open' field lines pinch off. The resulting closed field line releases its magnetic tension and accelerates trapped plasma towards the Earth. [After Taylor (1994)]

intensity of ionising flux falling per unit area [Chapman (1931)] and can be written as:

$$N_e \propto \cos^n \chi, \quad (1.1)$$

where χ is the solar zenith angle and $0.2 < n < 0.9$ [Davies (1990)]. These characteristics describe a so called Chapman layer. Finally the F-region, in which the maximum electron density generally occurs, extends above 120 km. During the day in summer the F-region is sometimes composed of two parts, the F1 and F2 regions. The electron density in the F-region increases rapidly after sunrise, but decreases slowly after sunset. In contrast to the expected solar control, the electron density of the F-region is greater in winter than in summer. This feature is known as the seasonal anomaly and is a consequence of a seasonal variation in chemical composition, with lower winter temperatures retarding recombination processes. Because of this the F-region does not exhibit Chapman-like behaviour.

The solar flux, and consequently the electron density of the ionosphere, varies with an 11 year period, the solar cycle. The peak ionospheric electron density can vary by over a factor of 2 between solar minimum and solar maximum. The principal features of the electron density profile of the ionosphere are described by the maximum electron densities in the E and F regions, N_mE and N_mF2 , and the heights of these maxima, h_mE and h_mF2 . Associated with these electron densities are plasma frequencies or critical layer frequencies, f_oE and f_oF2 , the maximum frequencies of vertically propagating radio waves that are reflected by the ionospheric regions (see section 3.2.1). A more detailed discussion on the ionosphere and its structure may be found in texts such as Rishbeth and Garriot (1964) and Davies (1990).

1.4 The Present Study

This thesis is concerned with the investigation of the ionospheric signatures of magnetospheric ultra low frequency (ULF) waves. ULF waves are important in the coupling mechanism between the magnetosphere and the ionosphere since they can transfer energy and momentum. These processes are most significant in the high latitude ionosphere, where the magnetosphere - ionosphere interaction is strongest. The waves also act as an important diagnostic of magnetospheric morphology and dynamics. The ionosphere determines the boundary conditions for magnetospheric MHD wave modes and hence controls the transfer of energy and momentum. It also modifies the magnetospheric wave signature, leading to rotation and attenuation of the wave magnetic signature detected on the ground.

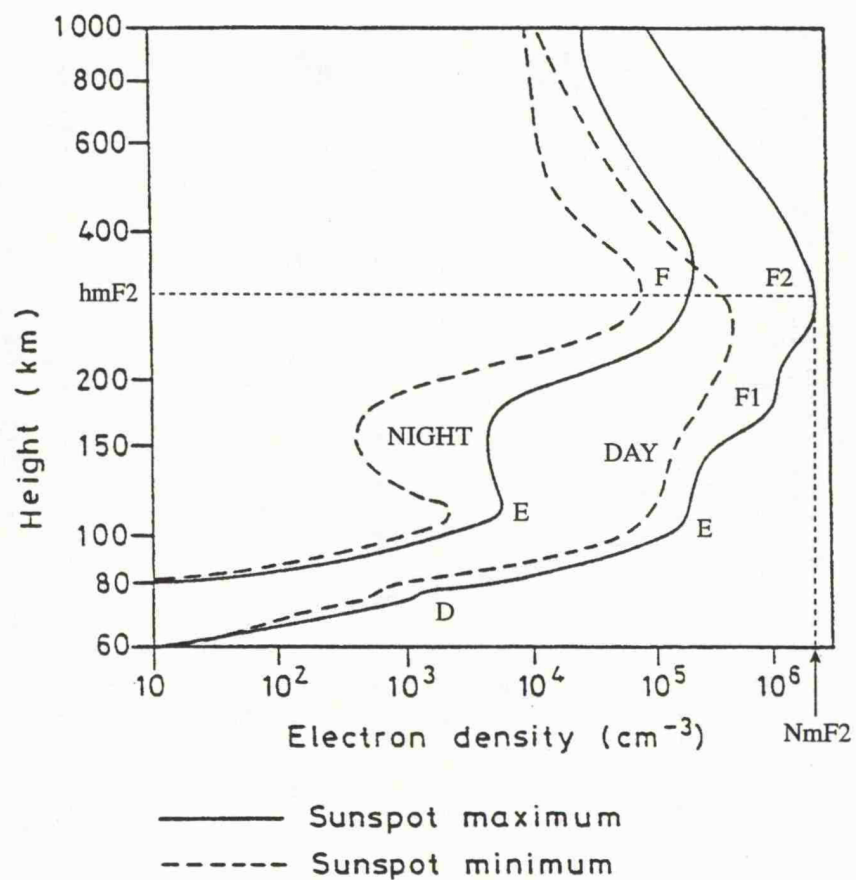


Figure 1.3: Typical mid latitude profiles of ionospheric electron density illustrating the distinct regions. NmF2 and hmF2 are, respectively, the electron density and the height corresponding to the F2 peak [After Hargreaves (1979)].

Radio wave techniques are a well established method of probing the ionosphere. Some of these methods are better suited for observing changes in the ionosphere than others and can therefore detect the transient effects produced by ULF waves originating in the magnetosphere. For this investigation an instrument known as a high frequency (HF) Doppler sounder has been deployed at high latitude (Tromsø: 69.6°N 19.2°E). It consists of a frequency stable transmitter and a receiver which are separated, in the present case, by about 50 km. A fixed frequency continuous wave signal is radiated and after reflection by the ionosphere is received at the ground. Variations in the refractive index or bulk motion of the plasma along the path of the radio wave cause small shifts in the received frequency, due to changes in the phase path of the wave. The measured Doppler shifts can thus indicate the characteristics of waves affecting the ionospheric plasma in the region being sounded.

The Doppler Pulsation Experiment (DOPE) is a new sounder developed and deployed specifically to undertake a study of ULF wave characteristics in the ionosphere. It forms part of a multi-instrument experiment operating in northern Scandinavia, where measurements are simultaneously made with DOPE, the European Incoherent Scatter (EISCAT) radar facility and a network of ground magnetometers. These instruments record a range of parameters such as (a) the magnetic perturbation field of the ULF wave on the ground, (b) the ionospheric conductivity, (c) the plasma flow velocity (and hence electric field in the ionosphere) and (d) height profiles of electron density. This new experiment has, for the first time, allowed routine observations of the ionospheric signatures of high latitude ULF waves at a very high spatial resolution (including waves with small spatial scales). The information gathered provides a means of testing new theories of the ionospheric response to these waves and measuring the evolution of the waves as they travel through the ionosphere.

Subsequent chapters will provide an overview of existing knowledge of HF radio wave propagation and ULF wave observations. The development and deployment of the DOPE sounder is described, followed by a discussion of a statistical study performed on an earlier high latitude Doppler sounder data set in order to optimise the new DOPE experiment. Finally, the first results from this new experiment are presented. The data demonstrate the sensitivity and high spatial resolution of the DOPE sounder for observing the ionospheric effects of ULF waves. The results are compared with those of previous studies and the conclusions drawn indicate that Doppler sounders have the potential to provide a wealth of new information on ULF wave coupling between the ionosphere and the magnetosphere.

Chapter 2

Magnetospheric ULF Waves

2.1 Introduction

The mechanisms of generation and propagation of magnetospheric ultra low frequency (ULF) waves and their identification by ground and space based instruments are reviewed in this chapter. Such magnetohydrodynamic (MHD) waves are excited in the magnetosphere by internal and external mechanisms, such as particle driven and solar wind processes respectively. The ionosphere plays a critical role in controlling the detection of the waves in this region and their signatures observed at the ground. The variation of high latitude ULF wave occurrence with local time, season, solar cycle and geomagnetic activity has previously been investigated by a number of authors and these studies are briefly reviewed here.

2.2 ULF Waves

A large variety of magnetic disturbances are observed on the Earth's surface and on board satellites by sensitive magnetometers which normally record the strength of the magnetic field in three orthogonal directions. Many of these events are quasi-sinusoidal in appearance and can be regarded as oscillations of the Earth's magnetic field, hence, they are often called geomagnetic pulsations. The terms "pulsation" and "ULF wave" are also common names for these phenomena and are the ones which will be adopted in this thesis. Pulsation signatures or periodic structures in the ULF frequency range, have been observed by a wide variety of instruments. The most well known are those which occur in ground based magnetograms and were first reported by Stewart (1861) at Kew observatory. They occur at all times of day and at all latitudes and exhibit all periods up to about 600 seconds, as characterised (table 2.1) by Jacobs *et al.* (1964). This study is, however, restricted to high latitude observations of waves in the Pc4 and Pc5 range. There have been many studies of the occurrence and the characteristics of these waves, including observations on the ground, in the ionosphere and *in situ* in the Earth's magnetosphere.

2.2.1 MHD Wave Modes

The first detailed discussion on how ULF waves are associated with magnetohydrodynamic (MHD) wave modes was presented by Dungey (1958). Earlier

Dungey (1954) derived the coupled differential MHD equations for non-uniform magnetic fields permeating plasma populations. There are three wave modes described by MHD theory, the Alfvén, fast and slow modes.

Pulsation Type	Period Range (seconds)
Pc1	0.2 - 5
Pc2	5 - 10
Pc3	10- 45
Pc4	45 - 150
Pc5	150 - 600
Pi1	1 - 40
Pi2	40 - 150
Pi3	>150

Table 2.1: The classification of geomagnetic micropulsations as given by Jacobs *et al.* (1964). Pc refers to regular, continuous pulsations whereas Pi denotes irregular damped pulsations.

The Alfvén mode wave is transverse and guided along the field lines (figure 2.1). In a simple three dimensional box model of the magnetosphere [Southwood (1974)], in a Cartesian coordinate system, the dispersion relation is given by

$$\omega^2 = V_A^2 k_z^2, \quad (2.1)$$

where

$$V_A = \frac{B_0}{\sqrt{\mu_0 \rho}} \quad (2.2)$$

is the Alfvén velocity of the wave. The magnetic field strength, $\mathbf{B} = (0, 0, B_0)$, ρ is the plasma density, μ_0 is the permittivity of free space, k_z is the vertical component of the wave number and ω is the wave angular frequency. Here the y dimension is azimuthal (east-west) and the x axis is radial. In this model it is useful to assume that $\rho = \rho(x)$ only and, thus, the Alfvén speed varies in x also. This wave is a shear wave, that is, there is no compression of the magnetic field. In a dipole geometry, such as the Earth's magnetic field, two types of field guided Alfvén waves are possible [e.g. Hughes (1983)] - one is known as the toroidal mode, where the magnetic field perturbation is azimuthal and the azimuthal wave number, m (see section 2.2.3) is low. The other is known as the poloidal mode, where the magnetic field perturbation is in the meridian plane, and m is high.

In contrast, the fast mode wave is longitudinal and compressional in nature (figure 2.1). It is not guided by magnetic field lines and hence is isotropic. For this mode:

$$\omega^2 = (C_s^2 + V_A^2)k^2, \quad (2.3)$$

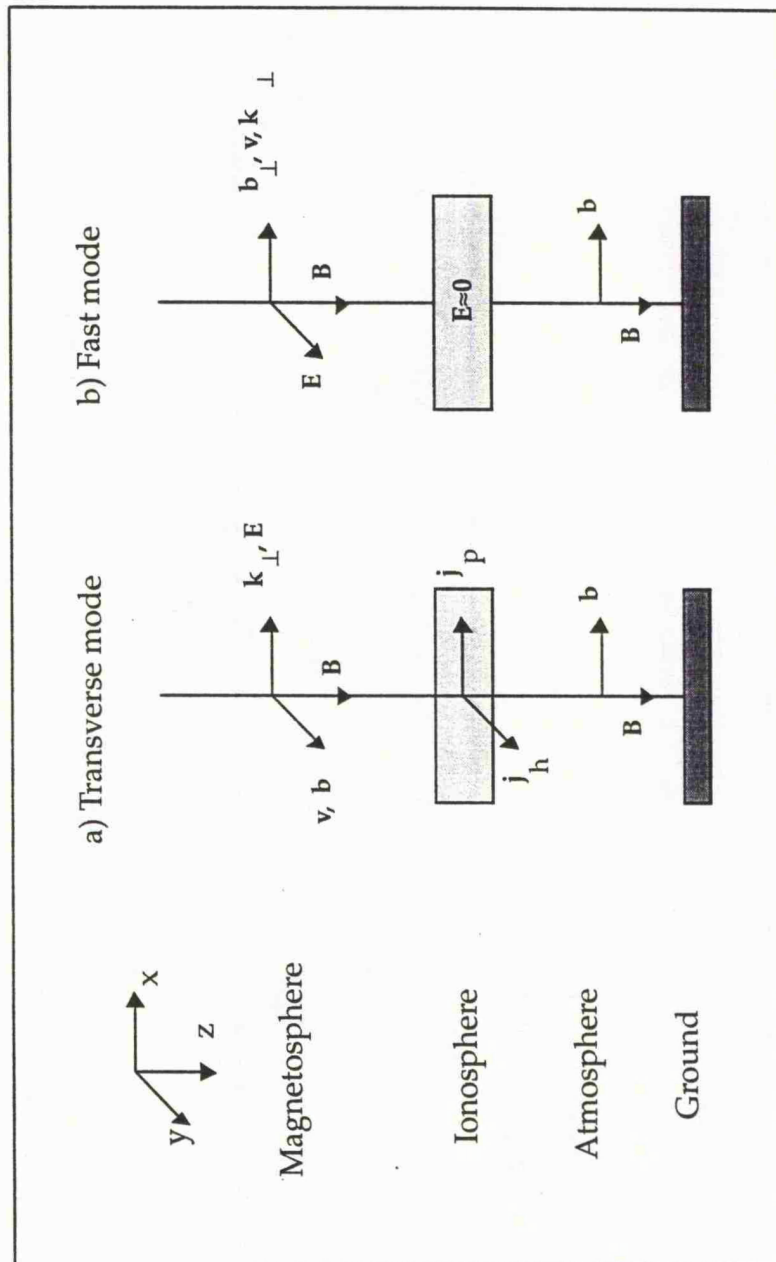


Figure 2.1: A schematic illustration of the characteristics of the (a) Alfvén and (b) fast MHD wave modes between the magnetosphere and the ground. The Alfvén mode is transverse and field guided. It is incompressible and carries a field parallel current, which drives Pedersen (j_p) and, consequently, Hall (j_h) currents in the ionosphere. The fast mode is isotropic, compressible and carries no parallel current. It has a small electric field in the ionosphere. [Courtesy of T. K. Yeoman (1996)].

where now $k = (k_x, k_y, k_z)$ and C_s is the sound speed. As will be discussed later, the two modes may couple together when conditions are appropriate. The plasma and magnetic pressure vary in phase in the fast mode which means that the isotropic wave travels fastest across the field.

There is one other wave mode possible in MHD - the slow mode. This is also a compressional wave but in contrast to the fast mode, the plasma and magnetic pressure vary out of phase, hence, this mode cannot propagate across the field. In a cold plasma, where the plasma pressure is low, this mode is indistinguishable from the fast mode and, therefore, is insignificant under these conditions. Slow mode waves are significant in hot ring current plasma and are relevant to particle driven waves such as the storm time Pc5s discussed in section 2.2.4. They have the slowest phase velocity of the three modes and, since they cannot propagate perpendicular to the field, have a substantial field guided component.

Resonant Field Lines and Cavity Resonances

The Alfvén mode, being field guided, travels along a field line in a way analogous to a wave on a string in a one dimensional cavity. When the frequency of the MHD mode matches the fundamental eigenfrequency or a related harmonic of the field line the oscillation becomes resonant. Fast mode waves, on the other hand, may occur in the form of cavity resonances. In this situation the entire magnetospheric cavity oscillates and a fast mode standing wave is set up between the magnetopause and the Earth's atmosphere. Cavity mode waves can couple to field line resonances (FLR) inside the magnetosphere where the frequency of the fast mode wave matches the resonant frequency of a field line. These wave modes will be discussed further in section 2.2.3.

2.2.2 The Ionospheric Response to ULF Waves

Fast mode compressional waves incident on the Earth's ionosphere do not drive appreciable currents in the ionosphere (figure 2.1) and are reflected by the neutral atmosphere which acts as an insulating boundary [Kivelson and Southwood (1988)]. However, Alfvén modes may drive ionospheric currents as the ionosphere is not a perfect conductor. Because of this fact, a field guided mode will be reflected from the ionosphere. The reflection coefficient [Southwood and Hughes (1983)] is related to the height integrated Pedersen conductivity, Σ_p , by

$$\frac{E_r}{E_i} = \frac{1 - \mu_0 \Sigma_p V_A}{1 + \mu_0 \Sigma_p V_A}, \quad (2.4)$$

where E_r and E_i are, respectively, the reflected and incident electric field amplitudes of the Alfvén wave. At the equinox, the ionospheres in both

hemispheres are the most similar since the solar illumination of each is roughly equal. This condition optimises the bounce duration of the wave along the field line. At other times of year the ionosphere with lowest conductivity causes more damping, via Joule heating, and so the wave has a more limited lifetime in Summer and Winter.

The Screening Effect of the Ionosphere

The ionosphere acts as a shield between the ground and incident Alfvén waves. The pulsation electric field drives Pedersen currents in the ionosphere (figures 2.2, 2.3) which provide current continuity with the field aligned currents associated with a field line resonance (FLR). A further consequence of this electric field is the generation of Hall currents which form closed loops around the regions where the field aligned currents enter and exit the ionosphere. In the atmosphere no currents can flow and so the field aligned current, j_z , associated with the incident Alfvén wave is given by [Hughes (1983)],

$$j_z = \frac{1}{\mu_0} (\nabla \times \mathbf{b})_z = \frac{i}{\mu_0} \mathbf{k}_\perp \times \mathbf{b}_{horizontal} = 0. \quad (2.5)$$

Above the ionosphere, the Alfvén mode has $\mathbf{k}_\perp$ perpendicular to the pulsation magnetic field, $\mathbf{b}$, and $\mathbf{b}=(0, b_y, 0)$ is perpendicular to the Earth's magnetic field, $\mathbf{B}$. Thus, in the atmosphere (and at the ground) $\mathbf{b}_{horizontal}$ is either zero or parallel to $\mathbf{k}_\perp$ which is in the x direction. The pulsation magnetic field at the ground is the field associated with the Hall current in the ionosphere. The Pedersen current is shielded from the ground by the current loop associated with a FLR. The magnitude of the ground magnetic signature is the same as that for the wave above the ionosphere, due to the fact that $\Sigma_p \approx \Sigma_h$ (where Σ_h is the height integrated Hall conductivity), but is rotated by 90° relative to it [Hughes and Southwood (1976a,b)]. Hence, the ground magnetic signature of the incident Alfvén ULF wave is a fast mode wave caused entirely by the flow of ionospheric Hall currents and not by the magnetospheric wave directly. The Pedersen current is part of a solenoidal current loop with the field aligned currents and, thus, has no ground signature associated with it [e.g. Hughes (1983)].

In addition, the work of Hughes and Southwood (1976a,b) demonstrated that the ionosphere also attenuates the magnetic signature of a ULF wave with large azimuthal wave number. Below the ionosphere the pulsation magnetic perturbation is evanescent and falls off exponentially as $\exp(-|k_\perp|z)$ [Hughes (1983); Southwood and Hughes (1983)] where z is the vertical height and $k_\perp$ ($\propto m$) is the horizontal component of the wave number of the magnetic field of

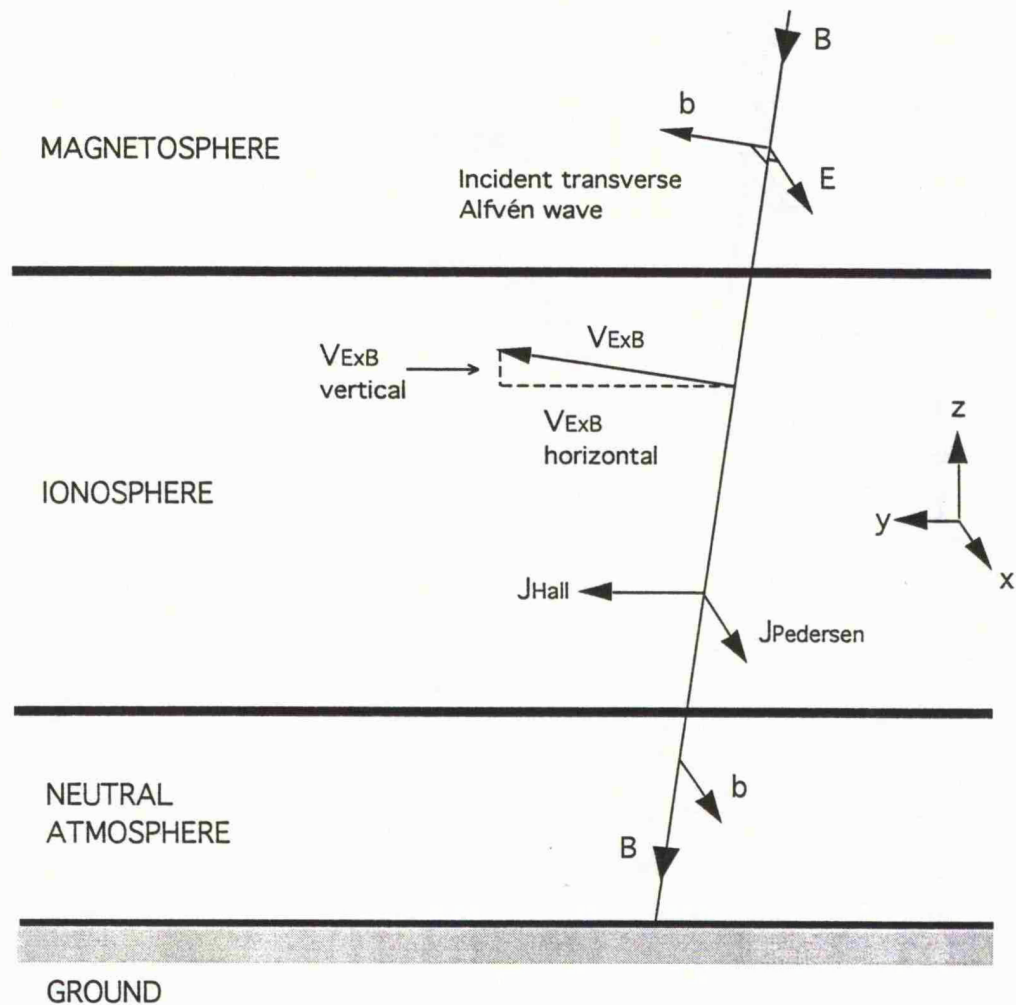


Figure 2.2: A demonstration of how the electric (E) and magnetic (b) perturbations associated with a down going Alfvén wave can, through the 'motor' effect [Rishbeth and Garriot (1964)], cause a vertical motion of the reflection height of a HF radio wave. This is the "advection" mechanism of Poole *et al.* (1988). Note the generation of ionospheric currents and the rotation of the pulsation magnetic field vector between the magnetosphere and the ground.

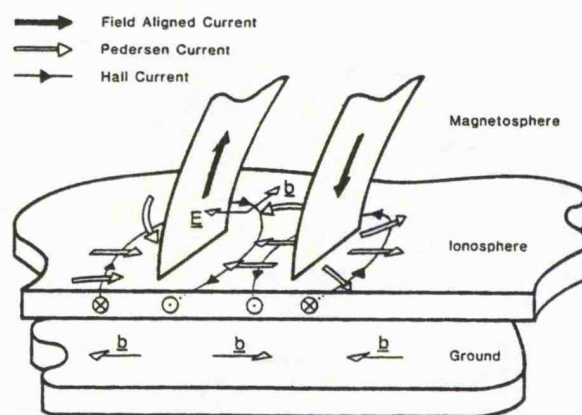


Figure 2.3: The Pedersen and Hall currents generated by the field aligned current system associated with an Alfvén wave. These are necessary in order to maintain current continuity in the magnetosphere-ionosphere system. It follows from this that the pulsation magnetic field, b , is rotated through 90° by the ionosphere. [After Southwood and Hughes (1983)]

the incident wave. Thus, high m waves have far less chance of being detected at the ground. A clear example of this is given in figure 2.4 [Yeoman *et al.* (1992)].

The Spatial Integration of Ground Magnetometers

The attenuation of the ULF wave magnetic field signature below the ionosphere, outlined above, can be understood physically by the simple picture of spatial integration. Magnetometers on the ground are known to integrate ionospheric E-region currents over a large spatial area. The scale size of this area is of the same order as the height of the E-region above the ground (~ 120 km) [Hughes (1983)]. This process will cause phase mixing of all nearby magnetic field sources for a wave with a significant phase variation over this horizontal distance. Thus ULF waves with a high m value (≥ 20) tend to be attenuated in magnetogram records. Only structures with a large spatial scale size are unaffected by the integration effects.

2.2.3 ULF Wave Generation mechanisms

Although the energy source for all ULF waves is ultimately the sun, magnetospheric ULF waves or pulsations may be usefully divided into those driven by sources external and internal to the magnetosphere. External sources are those where the solar wind or IMF interacts with part of the outer magnetosphere exciting a field line resonance or cavity mode oscillation [*e.g.* McDiarmid *et al.* (1994)]. Particle driven pulsations, produced by energetic particles within the magnetosphere, usually from a down tail source, are an example of a wave generation mechanism internal to the magnetosphere. All types can produce global signatures on various ground based and satellite instruments as will be discussed shortly. A useful and detailed review of these mechanisms is provided by Allan and Poulter (1992). This section provides information, relevant to this study, on ULF wave modes and on the mechanisms which generate them.

The Kelvin - Helmholtz Instability and Resonant Field Lines

This instability [*e.g.* Southwood (1974)] is analogous to the surface waves created by a wind blowing over the surface of water. In this case, however, it is the action of magnetosheath plasma, with origins in the solar wind (figure 2.5), on the magnetopause which gives rise to the waves. The solar wind plasma flows from the subsolar point, at the apex of the magnetosphere, around the magnetopause. Surface waves are generated on the dawn and dusk flanks of this boundary which are evanescent inside the cavity. This part of the wave can match the eigenfrequency of a field line well inside the magnetosphere and excite a field line resonance, which is Alfvénic. Because the effect is resonant, energy transfer may

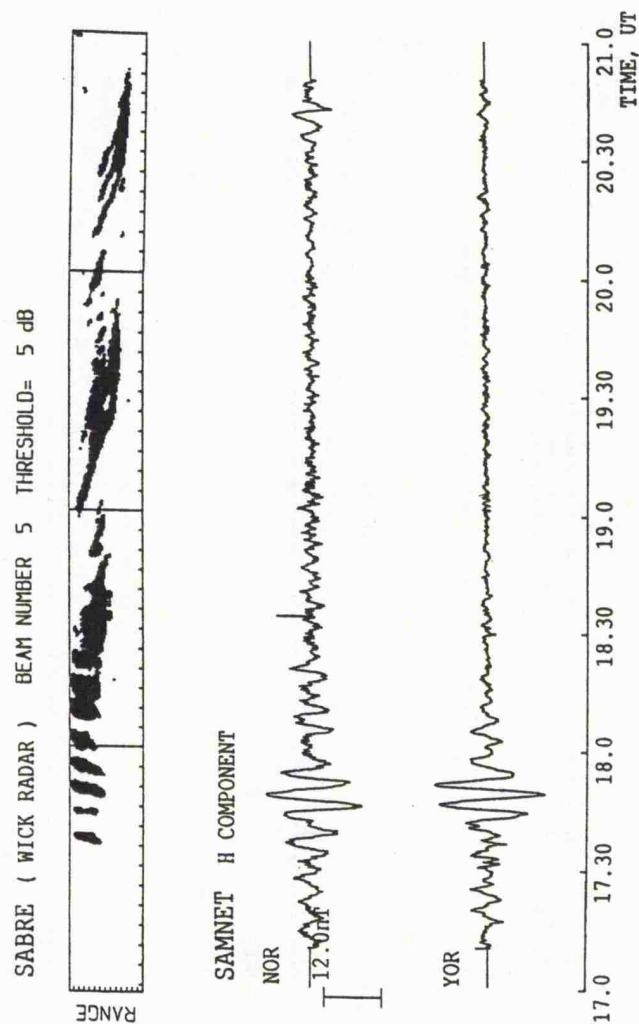


Figure 2.4: An example of how the ground magnetic signature of a ULF wave attenuates with azimuthal wave number, m . The phase variation of the equatorward propagating wave signature between 20 and 21 UT is larger than that of the poleward propagating wave commencing at about 17:30 UT, as seen in SABRE data. The magnetogram signature of the later wave is of much smaller amplitude. [After Yeoman *et al.* (1992)].

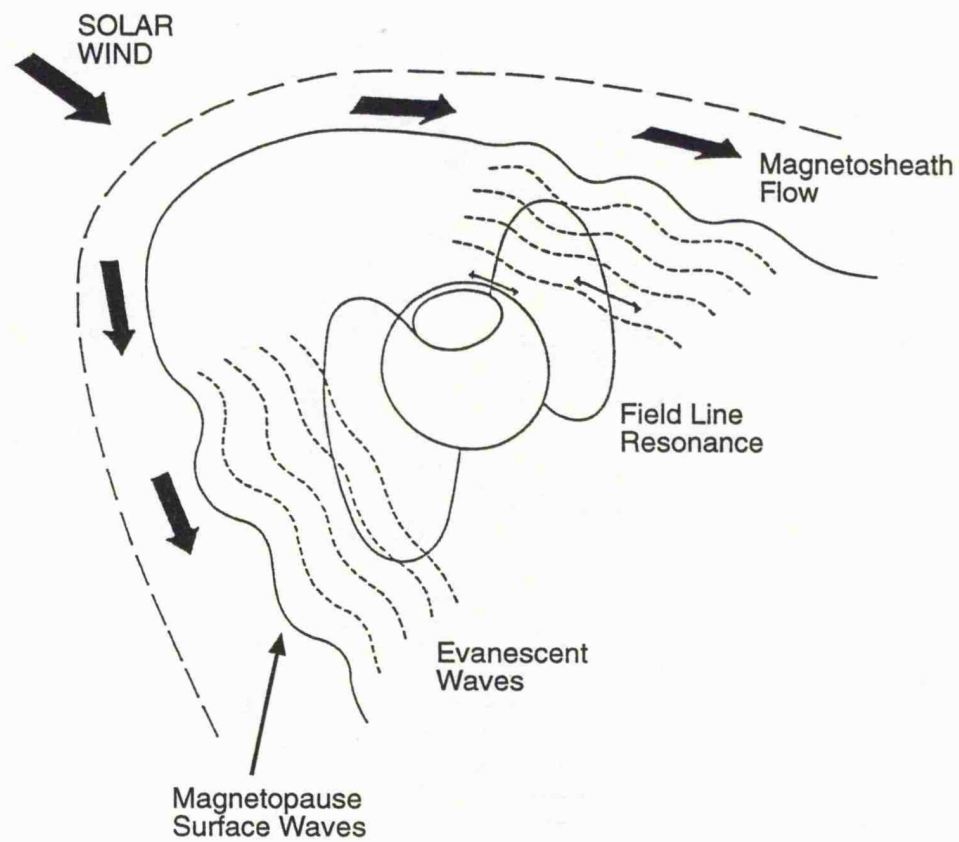


Figure 2.5: A representation of the stimulation of a field line resonance by the Kelvin-Helmholtz instability. The evanescent part of a magnetopause surface wave on the dawn and dusk flanks of the magnetosphere excites a resonance when the wave frequency matches the eigen frequency of the field line. [After Allan and Poulter (1992)]

only take place over a narrow region around the resonance position and, hence, observations of these would be localised. The FLRs generated by this mechanism are toroidal, that is their magnetic perturbations are azimuthally polarised.

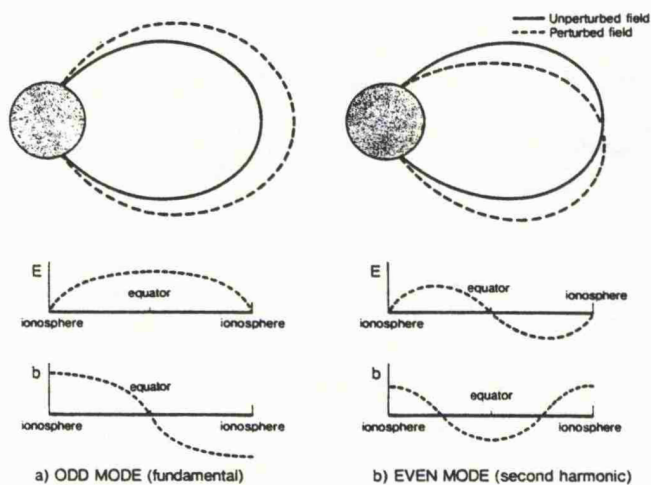
The Alfvénic ULF wave associated with the field line resonance (FLR) travels along the field line and is reflected at the ionospheres of the northern and southern hemispheres. Figure 2.6 illustrates the field configuration of a FLR oscillation in the fundamental (odd) mode and second harmonic (even) mode. Here the ionosphere is assumed to be perfectly conducting and the field lines are fixed. For the fundamental mode, the E-field perturbation maximises at the equator where a node in the magnetic perturbation exists, however, for the second harmonic this situation is reversed. This structure can be observed by satellites at or near the geomagnetic equator. In practice the ionosphere has finite conductivity and the field lines are not fixed which ultimately causes damping of the resonant wave.

An azimuthal or toroidal mode such as that created by the Kelvin-Helmholtz instability will, because of the wave structure excited on the magnetospheric flanks, have an associated wavelength in the azimuthal or y direction. Longitudinally spaced magnetometers can detect and determine this wavelength from the phase difference of the wave observed by the instruments. The value is often expressed as the effective azimuthal wave number, m , which gives the number of degrees of phase change of the wave in the east-west direction per degree of longitude. So, for $m=1$ the wave goes through 360° (2π radians) around the Earth. It is possible to measure m from the ground from the relative phase of a signature on two magnetometers on or near the same geomagnetic latitude but separated in geomagnetic longitude. Assuming that the wave is phase coherent between the two stations, m is the ratio of the phase shift to the longitude difference between the magnetometer locations.

A characteristic feature of a field line resonance is that the phase of the wave changes by 180° at either side of the resonance region, in a magnetic meridian [Southwood (1974)]. Also the phase north of the resonant field line lags that south of it [e.g. Orr (1984)]. An example of an FLR observed on the SABRE radar is reproduced in figure 2.4. The resonance signature is the one occurring earlier on in the data interval and exhibits poleward propagating phase fronts.

External Impulses and Cavity Mode Oscillations

An impulse on the magnetopause will result from a sudden change in the solar wind flow. A change of velocity, plasma density or the associated IMF density may be responsible. Impulsive events incident on the magnetosphere can excite



STANDING OSCILLATIONS IN A DIPOLE FIELD

Figure 2.6: A demonstration of the fundamental and second harmonic modes of oscillation of a field line resonance. It is assumed that the electric field vector of the pulsation has a node at the ionosphere of the two hemispheres. This is equivalent to having a perfectly conducting ionosphere - an ideal situation only. [After Southwood and Hughes (1983)]

the entire cavity into oscillation (figure 2.7). The process, first suggested by Kivelson *et al.* (1984), may set up a fast mode standing wave inside the magnetosphere between the magnetopause and the Earth's neutral atmosphere. The existence of the plasmapause, which has a sharp density gradient, may cause two standing waves to exist: one between the magnetopause and the plasmapause and the second from the plasmapause to the Earth's atmosphere. Kivelson and Southwood (1985) demonstrated that the fast mode wave would occur at the fundamental eigenfrequency of the magnetospheric cavity and at related harmonics. In this situation a coupled cavity mode (CCM) could exist where the fast mode frequency matched the resonant frequency of a field line in the inner magnetosphere. Thus, fast mode energy would be irreversibly converted into an Alfvénic FLR which would, because of ionospheric damping, ultimately dissipate the wave energy in the ionosphere. This is the same as saying that the initial cavity mode which has a poloidal (radial) effect on the field lines is converted to a toroidal (azimuthal) oscillation as time progresses. Allan *et al.* (1986) found that the mode coupling would maximise for $m=3$.

Particle Driven Waves

In section 1.2 the mechanism by which down tail reconnection can lead to the injection of particles energised to tens or even hundreds of keV into the near-Earth magnetosphere on the nightside was discussed. As the plasma encounters the increasing magnetic field strength it is deflected into the ring current which circles the Earth at a few R_E . Charged particles in the magnetosphere experience a force as a result of the electric and magnetic fields in this region. The radial fall in field intensity and the curvature of the field lines cause the particles to follow a path described as gradient-curvature drift. Protons, under the action of this drift, move around the Earth from the nightside through the dusk sector whereas the electrons drift eastwards through the dawn sector around to the dayside (figure 2.8a). Gradient-curvature drift is also responsible for the dispersion of the injected particles, by particle energy, as they move in longitude [Reeves *et al.* (1990)]. Higher energy particles move around the Earth faster than those with lower energy. Figure 2.8b illustrates a good example of this, where a dispersionless injection observed by the Los Alamos National Laboratory (LANL) 1982-019 satellite on the nightside, near local midnight, is later observed by a second LANL satellite (1984-129) situated 7 hours later in local time as being dispersed [Yeoman *et al.* (1994)].

The hot plasma particles have characteristic drift velocities perpendicular to the magnetic field and bounce frequencies parallel to it. Consider a burst or packet of

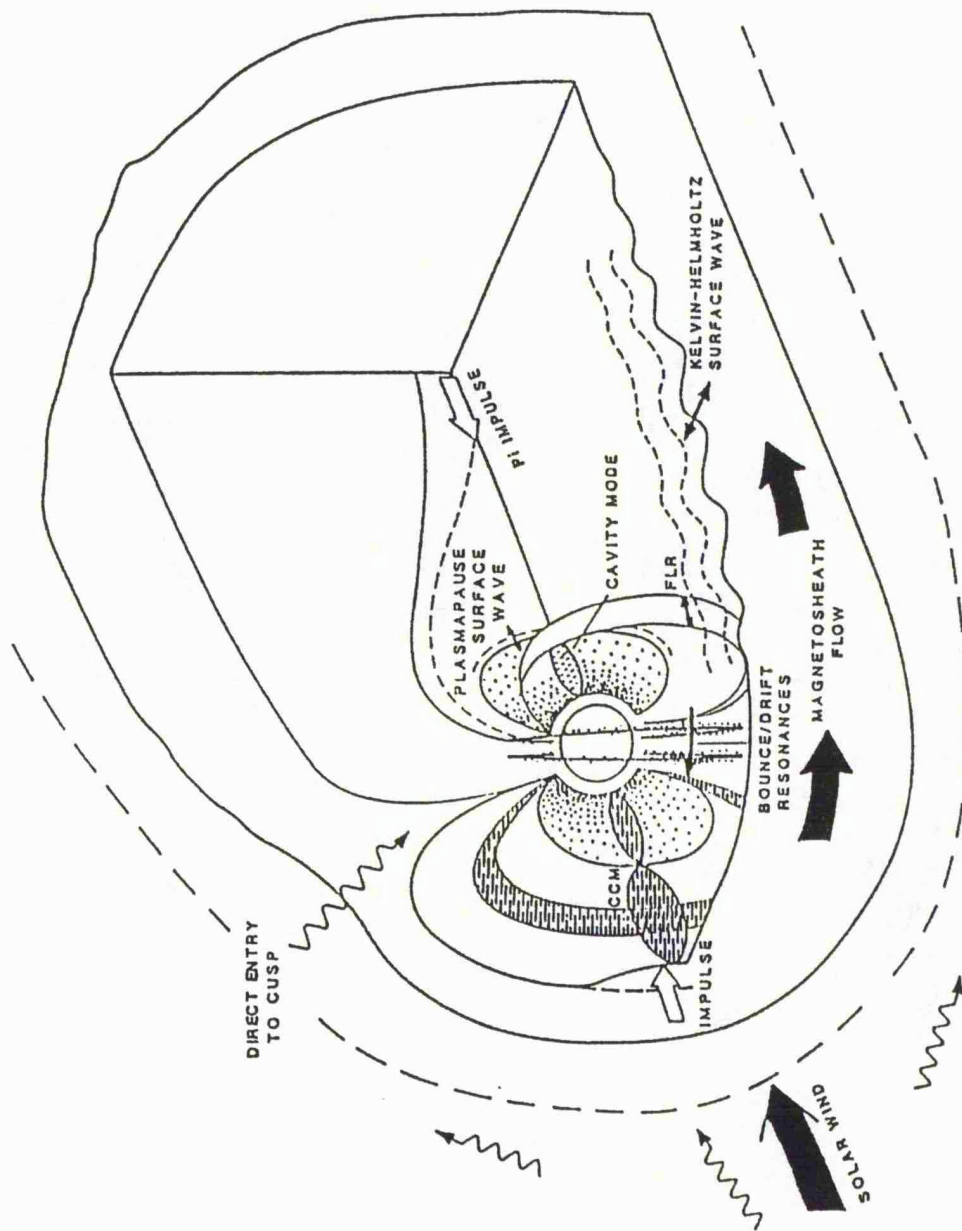


Figure 2.7: A schematic representation of ULF wave generation illustrating all of the mechanisms discussed in section 2.2.3. [After Allan and Poulter (1992)]

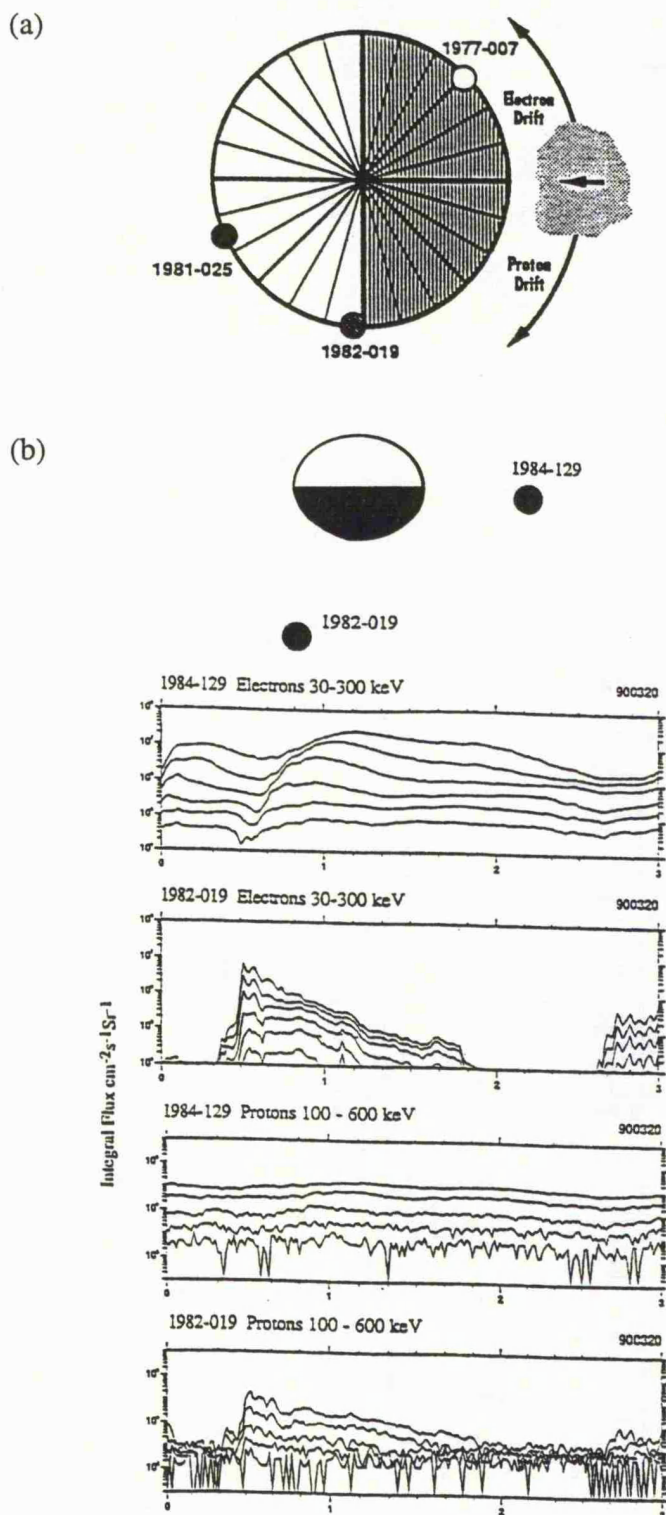


Figure 2.8: (a) A schematic of the nightside injection region and the way in which the particles drift. Particle injection locations may be determined from the delay of observation between separated geosynchronous satellites. [After Reeves *et al.* (1990)] (b) An example of a dispersionless injection of energised plasma as observed by LANL spacecraft. The electrons are observed by both satellites but by the time the particles reach 1984-129 dispersion, caused by energy differences between the particles, has occurred. The protons are not observed by 1984-129 as they drift in the opposite direction around the Earth and are scattered into the atmosphere before reaching the spacecraft. [After Yeoman *et al.* (1994)]

plasma moving around the Earth. Particles from this packet of plasma bounce along the field lines and are reflected by the mirror effect within the ionospheres. Resonance between waves and particles occurs when the particles drift an integral number of wavelengths in the time taken to make one full bounce. This may be expressed in the form [*e.g.* Hughes (1983)],

$$\omega - m\omega_d = N\omega_b \quad (2.6)$$

where ω is the wave frequency, ω_d is the bounce averaged drift frequency, ω_b is the particle bounce frequency and N is an integer. However, as the packet continues to move around the Earth the longitudinal location of the resonating field line will move with it. Figure 2.9 is a schematic illustration of the drift-bounce paths of ions through a fundamental and a second harmonic field line resonance. It is drawn in the reference frame in which the east-west phase velocity is zero. Regions where the wave electric field is eastward and westward are shaded and unshaded respectively. The particles bounce back and forth along field lines whilst, simultaneously, drifting azimuthally. All of the particle orbits have a drift which is an integral number of wavelengths in the time taken to make one complete bounce (equation 2.6).

Drifting particle populations drive poloidal Alfvén waves, slow mode waves or a mode which is a coupling between the other two [*e.g.* Walker (1994) and references therein]. It is accepted that storm time Pc5s and giant pulsations are driven by particles in the ring current but the exact nature of the wave mode is unclear [Allan and Poulter (1992)].

2.3 Statistical Studies of ULF Waves at High Latitudes

Ground based studies of ULF waves have involved high latitude magnetometers [*e.g.* Gupta (1973); Rao and Gupta (1978); Gupta and Niblett (1979); Ziesolleck and McDiarmid (1995)] and coherent VHF auroral radars such as STARE [*e.g.* Greenwald *et al.* (1978); Walker and Greenwald (1981); Allan *et al.* (1982, 1983)] and SABRE [*e.g.* Mao Tian *et al.* (1991); Yeoman *et al.* (1992)]. HF radar observations of these phenomena have recently been presented by Walker *et al.* (1992). In addition, similar studies employing satellite data have been published. For example Arthur and McPherron (1981), Kokubun (1985), Kokubun *et al.* (1989), Anderson *et al.* (1990) and Takahashi and Anderson (1992) all made observations of ULF waves in the magnetosphere with satellite borne magnetometers. Kremser *et al.* (1981) investigated energetic particle flux data provided by instruments on the GOES 2 and GOES 3 satellites and Baker *et al.*

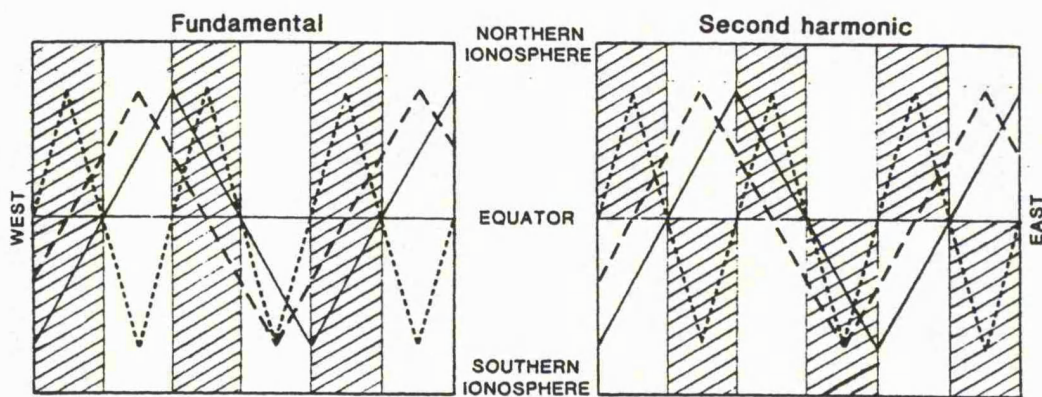


Figure 2.9: Examples of ion drift paths through a fundamental (left) and second harmonic (right). Field lines are represented as vertical lines with ionospheres occurring at the top and bottom of the boxes. The reference frame of the diagram is that in which the east-west phase velocity is zero. Regions where the electric field of the wave is eastward and westward are shaded and unshaded respectively. Net energy exchange occurs between the fundamental and the dashed trajectory and between the second harmonic and the dotted trajectory. [After Hughes (1983)]

(1980) did likewise for the LANL geostationary satellites 1976-059, 1977-077 and 1979-053. In addition, Junginger *et al.* (1984) examined electric field oscillations, in the ULF wave period range, from the electron gun experiment on board GEOS-2.

The high latitude data discussed here were all recorded either on the ground or by orbiting spacecraft on field lines mapping into this region. The VHF radar SABRE is technically sub-auroral but its field of view extends right up to and possibly into the auroral zone, under appropriate magnetospheric conditions. At this stage it is helpful to define some of the nomenclature employed by these authors. The fundamental mode toroidal oscillations described by Anderson *et al.* (1990) and by Takahashi and Anderson (1992) are azimuthally polarised (that is, they have a magnetic field fluctuation in an east-west or longitudinal direction) transverse waves which cause field lines to resonate at their fundamental frequency. These are equivalent to the azimuthal "A-class" waves described by Kokubun (1985). R-class waves have been defined as those which have radial polarisation and which give rise to compressional oscillations. For simplicity, the nomenclature here will follow that of Kokubun (1985) and, generally, refer to waves as A-class or R-class. A summary of the authors, referenced in this study, who have presented work on the diurnal occurrence distributions of observations of ULF waves on various instruments is given in table 2.2.

2.3.1 Diurnal Occurrence Distributions

Both A-class and R-class wave observations in spacecraft magnetometer data have recently been investigated in statistical studies by Anderson *et al.* (1990) and Takahashi and Anderson (1992). Each of the authors has discussed the average diurnal variation of wave occurrence in their data. Anderson *et al.* (1990), when looking at AMPTE-CCE magnetometer data, found that A-class waves for L -shells 6-7 had an occurrence peak around dawn (5-9 MLT) and that they occurred throughout the morning sector and into the afternoon. Takahashi and Anderson (1992) looked at over 4 years of data from the same satellite and showed that at $L=6.5$ and $K_p=2$, azimuthally polarised waves with the period 100 seconds (Pc4) occurred all day and most of the wave energy was observed in the early afternoon. It seems likely that different methods of categorisation of fundamental and harmonic mode events may have lead to the difference between the two studies. Both Anderson *et al.* (1990) and Takahashi and Anderson (1992) were in agreement when they found that R-class waves occurred in the afternoon with a peak at around 15 MLT.

Geomagnetic Conditions	Time Sector		
	Morning	Noon	Afternoon
<i>Quiet</i>	Ground Magnetometers [Pg pulsations]: Green (1979) Chisham and Orr (1991)		
<i>Moderate</i>	Ground magnetometers [peak occurrence]: Gupta (1973) Rao and Gupta (1978) Gupta and Niblett (1979) Ziesolleck and McDiarmid (1995) Satellites [A-class peak occurrence]: Arthur and McPherron (1981) Kokubun (1985) Kokubun <i>et al.</i> (1989) Anderson <i>et al.</i> (1990)[morning peak] Takahashi and Anderson (1992) [all day] VHF radar: Walker and Greenwald (1981) [dawn/dusk, A-class]	Satellites [Noon peak, broad distributions]: Baker <i>et al.</i> (1980) Junginger <i>et al.</i> (1984)	Ground magnetometers: Gupta (1973) Rao and Gupta (1978) Gupta and Niblett (1979) Ziesolleck and McDiarmid (1995) Satellites [R-class peak occurrence]: Arthur and McPherron (1981) Kokubun (1985) Kokubun <i>et al.</i> (1989) Anderson <i>et al.</i> (1990) Takahashi and Anderson (1992) Anderson <i>et al.</i> (1990) [A-class] Takahashi and Anderson (1992) [A-class] VHF radar [peak occurrence, equatorward phase propagation, Mao Tian <i>et al.</i> (1991) Yeoman <i>et al.</i> (1992)]
<i>Disturbed</i>			Satellites: Kremser <i>et al.</i> (1981) [Storm time Pc5s] VHF radar [STARE, Storm time Pc5s]: Allan <i>et al.</i> (1982, 1983)

Table 2.2: A summary of authors referring to the local time occurrence distributions of daytime ULF waves at $L > 5$ observed by various types of instrumentation. All text inside square brackets give additional information. See text (section 2.3) for discussion of this work.

A-class waves are toroidal field line resonances [Southwood (1974); Chen and Hasegawa (1974)] and as a result they are often observed simultaneously in space and at the ground. The magnetic perturbations associated with A-class waves are larger away from the magnetic equator [Kokubun (1985)] and, thus, are believed to be, in general, fundamental mode resonances. The diurnal distribution of occurrence of these waves [Arthur and McPherron (1981); Kokubun (1985); Kokubun *et al.* (1989)] as observed at geostationary orbit, illustrated in figure 2.10a, has been shown to be bimodal with a dawn-dusk asymmetry, where more events occurred at dawn. The distribution presented in this figure, obtained by Kokubun (1985) contains a number of events which had no correlated ground magnetic signature. However, the author suggested that this might be related to a local time effect of satellite position due to deviations of the field from a dipolar configuration. The occurrence rate of the A-class waves is maximum at dawn and has a secondary peak at dusk. It is suggested the Kelvin-Helmholtz instability on the dawn and dusk flanks of the magnetopause is the driving mechanism for this type of wave (see section 2.2.3). This idea is supported by ground based observations because the same bimodal asymmetrical occurrence distribution over local time is observed (figure 2.10b) by high latitude magnetometer stations [Gupta (1973); Rao and Gupta (1978); Gupta and Niblett (1979); Ziesolleck and McDiarmid (1995)], and by the VHF radar STARE [Walker and Greenwald (1981)]. Such A-class waves have coherency over 20° of longitude and a small azimuthal wave number ($m \leq 10$) [Kokubun (1985)]. Rao and Gupta (1978) described the dusk peak in their occurrence distributions as the contribution by small amplitude Pc5s. The observation of waves of this type is consistent with the generation of FLRs by the Kelvin-Helmholtz instability as illustrated in figure 2.5.

Baker *et al.* (1980) conducted a similar statistical study of waves, in the Pc4-5 range, observed in energetic electron flux data from LANL satellites. The work did not distinguish between wave types whether compressional or azimuthal. The observations, made near the magnetic equator, had a broad occurrence maximum around noon but at higher geomagnetic latitudes the distribution became more bimodal with peaks at dawn and dusk. This suggests that A-class waves associated with fundamental mode resonances were observed away from the equator. Junginger *et al.* (1984) however, took electric field oscillation data from the electron gun experiment on board GEOS-2 and stated that Pc5 occurrence was predominantly around local noon. This observation is different from those of other authors from data taken on the ground and in synchronous orbit. The electric field oscillations reported by Junginger *et al.* (1984) occurred without well defined concurrent oscillations in the magnetic field data.

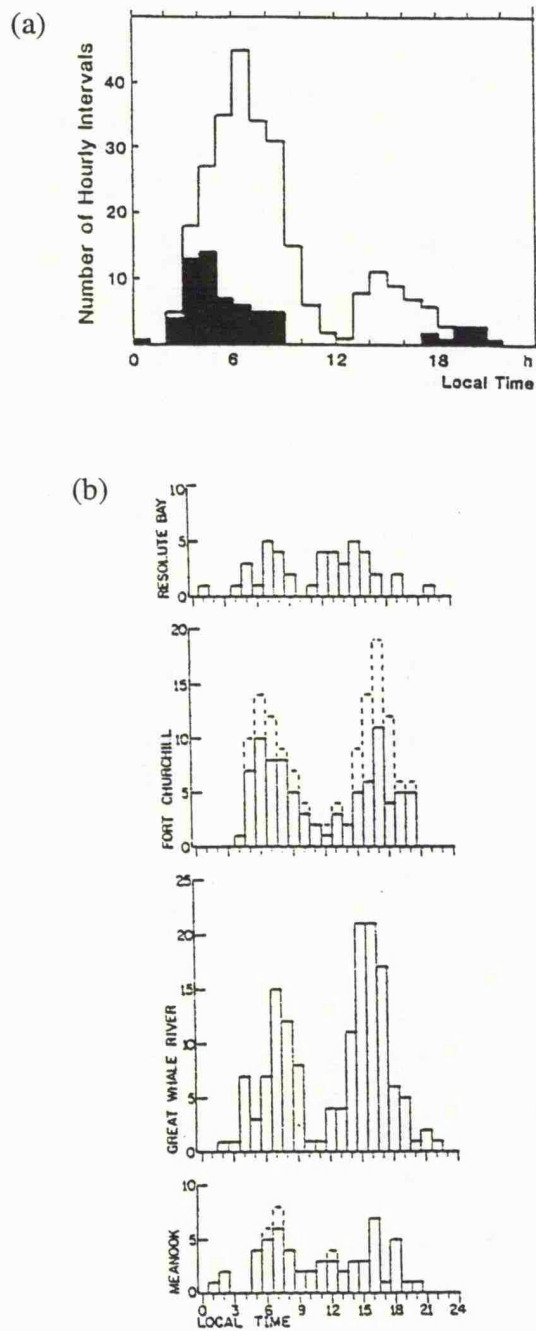


Figure 2.10: (a) Diurnal distribution of A-class Pc5 waves observed at GOES 2. The shaded portion represents events which had no correlated ground magnetic signature [after Kokubun (1985)]. (b) Occurrence of A-class waves at the ground seen on high latitude magnetometers. Solid bars represent data in the interval 1966-75. Measurements prior to this are displayed as dashed bars [after Gupta and Niblett (1979)].

An alternative to the Kelvin - Helmholtz mechanism for generating A-class waves is the impulse driven coupled cavity mode (section 2.2.3). A recent example of this is a multi-instrument study by McDiarmid *et al.* (1994). A short duration compressional event occurred on 14th March 1990 between 14-15 UT which was observed globally on the ground and at geostationary orbit. Subsequently, the driving force appears to have 'switched off' leaving a simple damped field line resonance over Scandinavia and the complex decay of a travelling vortex structure over Canada. The event had a period in the Pc5 range. The study made by McDiarmid *et al.* (1994) is, so far, a reasonably unique one, as it is rare that such a wealth of instrumentation provides simultaneous data for the study of this type of event. Such phenomena may occur at a high enough rate to contribute significantly to statistical studies but it is difficult as yet to specify the LT and magnetic conditions under which they would occur.

R-class waves exhibit several very different characteristics to those of A-class waves. The diurnal occurrence distribution of these waves has previously been determined and indicates that these waves are confined to the postnoon and dusk sectors. Kokubun (1985) and Kokubun *et al.* (1989) both utilised two years worth of GOES 2 and GOES 3 data, GOES 3 being nearer the geomagnetic equator than GOES 2, and demonstrated that the peak in occurrence of Pc5s at geostationary orbit was at around 15 LT. The probability of event occurrence and the wave amplitude at GOES 3 was almost double that at GOES 2 (figure 2.11). These waves are observed under geomagnetically disturbed conditions. Kokubun (1985) subdivided these waves further into two classes; one was R-class waves of long duration (greater than three hours) which generally occurred during the recovery phase of magnetic storms which were observed in the interval 10-14 LT; secondly, there are short duration waves which occur in the interval 13-18 LT and are associated with the expansion phase onset or intensification of a substorm. The ULF wave occurrence was delayed relative to the substorm events.

Results similar to those of Kokubun (1985) have been obtained by other authors. Arthur and McPherron (1981) showed that radially polarised Pc4 waves observed at the geosynchronous satellite ATS-6 had a peak in occurrence at 18 LT but also occurred at all local times. However, their study was based on only 109 events. Anderson *et al.* (1990), as mentioned earlier, observed that R-class Pc4 waves occurred in the afternoon sector. Kremser *et al.* (1981) studied ULF wave signatures in energetic particle flux oscillations associated with "Storm time Pc5s" [e.g. Brown *et al.* (1968)] - a type of R-class wave. They observed that

most events occurred between 14 and 20 LT and had an average duration of about 78 minutes.

Giant (Pg) pulsations, although being compressional in nature, do not follow the trend for R-class waves of a postnoon occurrence peak. An example of this type of pulsation, recorded on two high latitude magnetometers, is given in figure 2.12. All of the 34 events studied by Chisham and Orr (1991) occurred in the dawn/prenoon sector. All were observed on the high latitude EISCAT magnetometer cross chain during quiet geomagnetic intervals.

2.3.2 Comparison of ULF Wave Signatures Observed at the Ground and in Space

Ground magnetometer data from Great Whale River, at the foot point of the GOES 2 satellite, were employed by Kokubun (1985) to establish that R-class waves were rarely ever detected at the ground on magnetometers. ULF waves with a high m number, have been observed in radar auroral backscatter power by SABRE without a concurrent signature on ground magnetometers [Yeoman *et al.* (1992)]. The occurrence distribution for these events, which had equatorward phase propagation, peaked at about 18 UT (about 20 MLT)[Mao Tian *et al.* (1991)]. Similar high m number storm time Pc5s have been detected in STARE data [Allan *et al.* (1982,1983)] with the same lack of event observation in nearby magnetometers. An example of such a wave recorded by STARE is reproduced in figure 2.13 which indicates that the wave is present over the whole latitude range of the radar and persists for several hours. These waves also occur predominantly in the afternoon sector. Yeoman *et al.* (1992) made direct measurements of attenuation for high m and low m Pc5s. They indicated that the difference may be caused by the fact that ground magnetometers are not sensitive, due to the way in which they integrate information over a large spatial scale (see section 2.2.2), to waves which exhibit a large phase change with longitude. Hughes and Southwood (1976a,b) characterised the ionospheric response to ULF waves and were the first to point out that small scale length waves would be attenuated in ground magnetometer observations. The giant pulsations studied by Chisham and Orr (1991) had an average m value of 26. This may explain the rarity of these waves in ground magnetometer data - only 34 in 3 years of data.

2.3.3 Seasonal Variations

Gupta (1973) has studied the seasonal occurrence of Pc5s employing high latitude magnetometer data over an interval of one year. This author reports that more

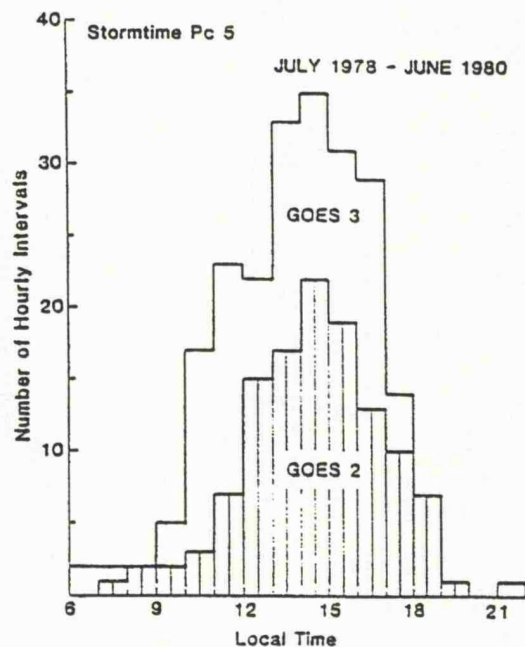


Figure 2.11: The diurnal distribution of R-class waves at geostationary orbit. [After Kokubun (1985)]

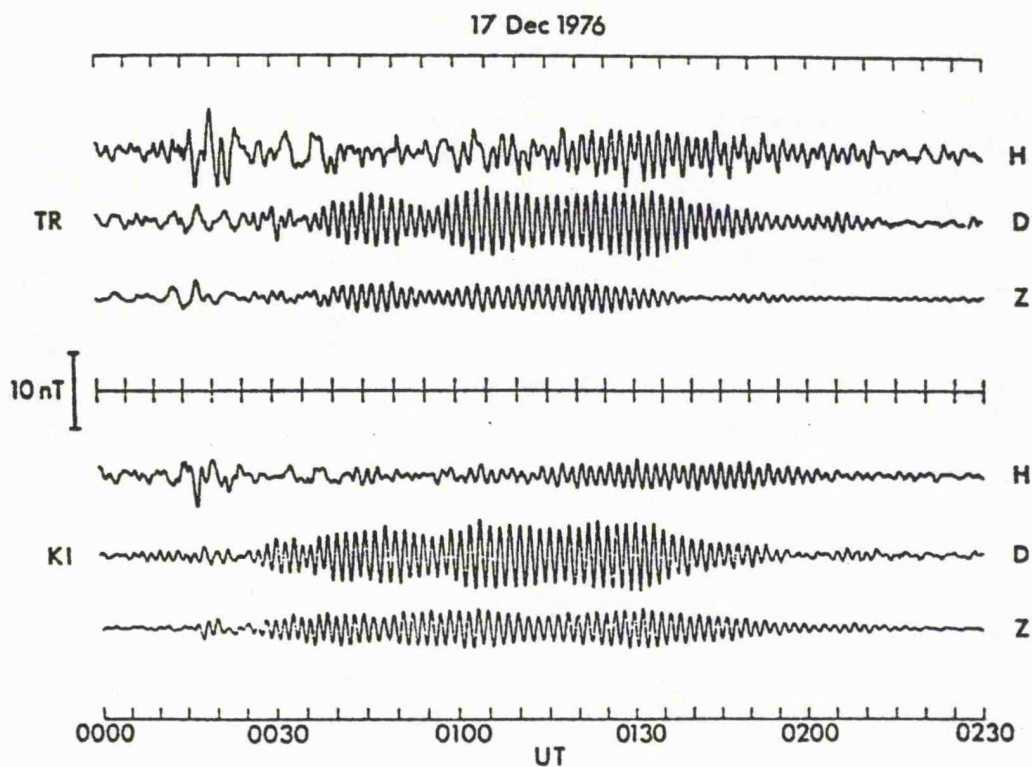


Figure 2.12: An example of a giant (Pg) pulsation observed on high latitude magnetometers at Tromsø, Norway (TR) and Kiruna, Sweden (KR). The event occurred on 17/12/76. The H, D and Z component data have been filtered in the period range 25-250 seconds. The wave had a mean period of 96 seconds. [After Green (1979)]

observations of Pc5s occurred in the Summer months than in the Winter. However, subsequent studies by Gupta and Niblett (1979) report what are described as "quiet time Pc5s" which appear to be A-class waves in character. One event was global and recorded by stations world wide. Using a few high latitude Canadian observatories they determined, from an 11 year data set, that most events occurred between December and March of each year and that a minimum of occurrence generally appeared around May - July. They compared their findings with those of Cummings *et al.* (1972) who selected 222 events from ATS-1 magnetometer records to show a peak in occurrence in the December - February interval. Rao and Gupta (1978) analysed Pc5 characteristics in an 11 year data set from a high latitude magnetometer station. They grouped months together in so-called Lloyds' seasons which comprised May-August, March to April and September to October (data from the equinoxes) and, finally, November to February. Their cumulative occurrence statistics had a maximum at the equinoxes. Baker *et al.* (1980) took data at geostationary orbit and found that near the geomagnetic equator the noon occurrence peak occurred consistently for all seasons. However, at 11.4° N a clear peak in the early afternoon was apparent during late Autumn and Winter and a bimodal distribution with dawn and dusk peaks and fewer absolute events was found to exist in the Spring - Summer interval. More recently, Ziesolleck and McDiarmid (1995) analysed one year of data from four CANOPUS high latitude observatories. They concluded that there was no strong seasonal dependence on Pc5 occurrence rates. However, more events were recorded in the Winter months January - March.

2.3.4 Solar Cycle Related Variations

The variation of pulsation occurrence with the phase of the solar cycle has not, so far, been studied in great detail due to the simple fact that to do so requires a data base which extends over many years. Gupta and Niblett (1979) examined 11 years of available data from high latitude magnetometer stations and concluded that (figure 2.14) that if a relationship exists, then it is a complex one. The number of events did increase with sunspot number but there were large perturbations from this trend. Rao and Gupta (1978) presented a statistical view of solar cycle related effects on Pc5 characteristics from an 11 year data set, spanning 1962 to 1972, obtained at a high latitude magnetometer station. They stated that the diurnal variation of wave occurrence, amplitude and period varied little with sunspot number. However, the measured Pc5 wave periods showed a strong correlation with sunspot number through the solar cycle. A prenoon occurrence peak, centred on 8 LT was consistent throughout the interval.

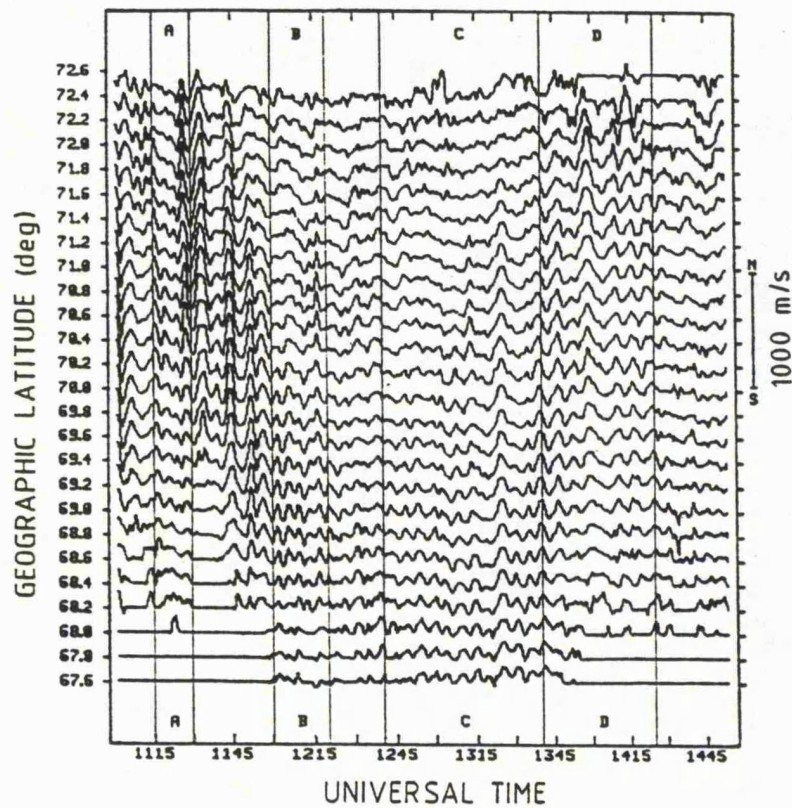


Figure 2.13: An example of a storm time Pc5 event observed by the STARE VHF radar. Illustrated are the geographic N-S components of the $E \times B$ drift velocity as a function of geographic latitude and universal time. [After Allan *et al.* (1982)]

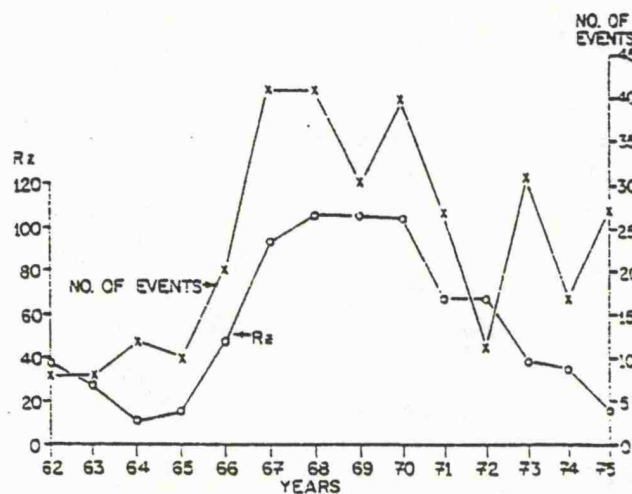


Figure 2.14: Solar cycle variation of Zurich-relative-sunspot numbers (R_z) and of the occurrence of pulsations observed at the ground. [After Gupta and Niblett (1979)]

2.3.5 The Effects of Geomagnetic Activity

Several of the statistical studies previously discussed have attempted to link event occurrence to geomagnetic activity. Gupta and Niblett (1979) established that their quiet time events generally occurred at $K_p \leq 3$ at all stations and for $A_p \leq 15$. Gupta (1973) found that the Pc5 events recorded over one year at high latitude had an occurrence rate which appeared to increase linearly with K_p up to 5 and with the sum of K_p index over the day, ΣK_p , up to around 37. Walker and Greenwald (1981) found that occurrence in STARE data of Pc5s was proportional to K_p up to ~ 4 only and the dependence became complicated at high values of K_p . SABRE observations of such events were discussed by Mao Tian *et al.* (1991) and Yeoman *et al.* (1992). These authors considered different types of event; those with equatorward propagating (E) bands in radar backscatter power and those with poleward propagating (P) bands. E events were associated with the signature of a resonance on the plasmopause and P events with a field line resonance poleward of this position in the plasmatrough (figure 2.4). They estimated the plasmopause position inside the radar's field of view as a function of time and K_p and concluded that E events were more likely to occur at lower values of K_p with a peak at $K_p=3$. P events on the other hand were more likely at higher K_p with a peak at around 4. In addition, Takahashi and Anderson (1992) found that for 10 mHz Pc4 waves at $L=6.5$, observed by the AMPTE-CCE satellite, the energy in the b_z (compressional) component increases on the dayside, distributed around noon and in the evening sector as K_p increased from 0 to 2. At $K_p=4$ a larger increase in early afternoon was observed along with a dramatic increase in compressional energy in the evening sector. By fitting a model plasmopause to their data they were able to conclude that, at $K_p=2$ and MLT=9-12, Pc4 oscillations in the azimuthal (b_y) component generally were confined to regions away from the plasmopause.

The storm time Pc5s observed by Allan *et al.* (1982, 1983) with the STARE radar were seen to occur when $K_p \geq 3$ and all were associated with a significant depression of the D_{st} index which is consistent with an injection of plasma into the ring current from the Earth's geomagnetic tail which, in turn, would lead to the drift waves mentioned in section 2.2.3. Ziesolleck and McDiarmid (1995) illustrated with high latitude magnetometer data that, for events recorded in 1993, most low frequency pulsations (1-2 mHz) occurred when $K_p < 2$ but those at the higher frequency of 3-4 mHz corresponded to a higher K_p (~ 4).

Giant 'Pg' pulsations are a class of ULF wave which have been observed on the ground as well as by orbiting satellites at times of quiet geomagnetic conditions. A paper by Hughes *et al.* (1979) describes multiple satellite observations of a short period (55 seconds) compressional wave at geostationary orbit. These authors deduced that the wave was a second harmonic standing wave which lead to their interpretation of the driving mechanism being a bounce resonance interaction with ring current protons. The wave number, m , calculated was 100. The harmonic mode of this wave is in agreement with the observations made by several other authors [*e.g.* Annexstad and Wilson (1968)]. However, there are others [*e.g.* Green (1979)] who are of the opinion that the waves are odd mode. More recently, Chisham and Orr (1991) presented a statistical study of 34 of these events observed on the EISCAT magnetometer cross in northern Scandinavia. They deduced that Pgs are second harmonic (even mode) standing wave oscillations. The average value of m was ~ 26 for the 34 events.

2.4 Summary

Some of the important types of magnetospheric ULF wave and their respective generation mechanisms have been discussed. In addition, the ionospheric response to two wave modes - specifically the transverse or Alfvén and fast modes - is detailed. This region is important in two ways; (a) it reflects field guided (Alfvén mode) energy back into the magnetosphere and (b) acts to screen the MHD wave mode from the ground.

Statistical studies of observations have enabled a classification of wave types and their characteristics. This provides a useful path to determining the mechanisms involved in generating these waves. In addition, such studies provide a solid basis on which new experiments may be founded. These results will be important in the interpretation of the new data presented in subsequent chapters of this thesis.

Chapter 3

High Frequency Radio Wave Propagation and Doppler Observations of ULF Waves

3.1 Introduction

This thesis is concerned with the experimental investigation of the ionospheric signatures, recorded in a HF Doppler sounder, of ULF waves of magnetospheric origin. Therefore, an understanding of HF radio wave propagation in the ionosphere is important for the application of the Doppler sounding technique and the interpretation of the results obtained. The effects of the high latitude ionosphere on the diagnostic signal are critical to this investigation. The birefractivity of the ionosphere as well as the radio absorption and other variabilities in it will be discussed in this chapter.

Previous Doppler observations of ULF waves have, so far, only been undertaken at low and mid-latitudes. High latitude measurements will provide a means of identifying the types of wave incident on the ionosphere which are not easily seen at other latitudes and will enable the investigation of an important region where energy coupling between the ionosphere and magnetosphere is significant. In addition, measurements may be made in conjunction with the incoherent scatter radar, EISCAT to provide new information on ionospheric conductivity and flows during intervals of ULF wave activity. Previous experimental data are discussed in the context of a new model for describing the mechanisms which couple the magnetospheric wave to its ionospheric signature.

3.2 High Frequency Radio Wave Propagation

In 1901 Marconi transmitted a short wave radio signal from England which was received in Newfoundland, Canada. This was the first time that a long distance communication had been achieved. It proved that radio signals could propagate following the Earth's curvature. Kennelly (1902) and Heaviside (1902) suggested that signals were reflecting from a conducting layer of atmospheric ions at an altitude of approximately 80 km. Appleton and Barnett (1925a,b) and Breit and Tuve (1925, 1926) demonstrated the existence of reflecting layers in the ionosphere and determined their approximate heights. Subsequently, it was shown that the Earth's magnetic field influenced the return of radio waves [Appleton (1925); Nichols and Schelleng (1925)] which led to the development of the magneto-ionic theory by Appleton and Builder (1932).

3.2.1 Reflection of Radio Waves

At heights above 60 km free electrons exist in the atmosphere which influence the propagation of radio waves. The presence of the Earth's magnetic field produces magneto-ionic effects and the medium becomes birefractive. The effects of collisions between the electrons and neutrals give rise to attenuation of the wave and the refractive index thus becomes complex. The refractive index of an electromagnetic wave propagating through an isotropic ionised medium with collisions in the presence of a magnetic field is given by the Appleton-Hartree equation,

$$n^2 = (\mu - i\chi)^2 = 1 - \frac{X}{1 - iZ - \frac{Y_T^2}{2(1 - X - iZ)} \pm \left[\frac{Y_T^4}{4(1 - X - iZ)^2} + Y_L^2 \right]^{1/2}}, \quad (3.1)$$

where n is the complex refractive index, and

$$X = \frac{\omega_p^2}{\omega^2} = \frac{N_e e^2}{\epsilon_0 m_e \omega^2}, \quad Y_{L,T} = \frac{e B_{L,T}}{m_e \omega}, \quad Z = \frac{\nu}{\omega}. \quad (3.2a,b,c)$$

f and ω are the radio wave frequency and angular frequency respectively, related by $\omega = 2\pi f$. Similarly related are f_p and ω_p the plasma frequency and plasma angular frequency respectively (see below), N_e is the electron density, e is the electronic charge, m_e is the electron mass, ϵ_0 is the permittivity of free space, ν is the collision frequency between electrons and neutrals which is dependent on the atmospheric density, and B is the imposed magnetic field of the Earth. The subscripts L and T refer to the longitudinal and transverse components of the magnetic field relative to the direction of phase propagation respectively. The $\pm$ sign in equation 3.1 indicates that two polarisations of the radio wave can exist, termed the ordinary and extraordinary waves for $+$ and $-$ respectively. Thus two independent ray paths will exist in the ionosphere for a transmitted wave of a given frequency.

The plasma frequency, f_p , is the natural frequency of oscillation of electrons in a plasma; from equation 3.2a, electron density (m^{-3}) and plasma frequency (Hz) are related by

$$N_e = \frac{\epsilon_0 m_e}{e^2} \omega_p^2 \approx \frac{f_p^2}{81}, \quad (3.3)$$

which provides a useful way of converting between the two parameters. By means of a radar technique the reflection height of a given frequency and hence the height of the corresponding electron density in the ionosphere can be determined. Sweeping the transmitted frequency performs a type of sounding which is known

as an ionogram where a height profile of frequency and hence electron density is recorded.

Wave Propagation

Two simplifying assumptions can be applied to equation 3.1 to illustrate the basic principles of propagation in the ionosphere. These assume a negligible magnetic field and no collisions.

In the simple case of an isotropic ionosphere with negligible magnetic field ($Y \ll 1$) and no collisions ($Z = 0$), the complex refractive index (equation 3.1) reduces to the real expression

$$\mu^2 = 1 - X = 1 - \frac{f_p^2}{f^2}. \quad (3.4)$$

For vertically propagating waves of frequency f_v , Snells law indicates that reflection occurs when $\mu = 0$, $X = 1$, *i.e.* the plasma frequency and the wave frequency are equal, $f_v = f_p$. For obliquely propagating waves with a flat Earth approximation, reflection occurs when

$$\mu = \sin \varphi, \quad (3.5a)$$

or for a curved earth

$$\mu = \left(\frac{R_e}{h_r + R_e} \right) \sin \varphi, \quad (3.5b)$$

where φ is the angle of incidence of the ray on the ionosphere, h_r is the height of reflection, and R_e is the radius of the earth. Hence, there is a relationship between the frequency of an oblique wave, f_o , and the frequency of a vertical wave, f_v , that reflect at the same plasma frequency, f_p , (from equations 3.4 and 3.5),

$$f_o = f_v \sec \varphi, \quad (3.6)$$

where $\sec \varphi$ is known as the secant factor. A full discussion is provided in Davies (1990).

Maximum Usable Frequency

The maximum electron density in the ionosphere, NmF2 has a corresponding plasma frequency, foF2 (for an ordinary wave), known as the critical frequency of the ionosphere. Consequently, vertically propagating waves with $f > \text{foF2}$, or obliquely propagating waves with $f > \text{foF2} \sec \varphi$ will not be reflected and will penetrate the ionosphere. The maximum frequency that will propagate along a path between two ground positions is known as the maximum usable frequency or MUF.

In the case where collisions are present (and the magnetic field is negligible), $Z > 0$, the refractive index becomes complex and attenuation of the radio wave,

through dissipation of the wave energy by collisions between electrons and neutrals, becomes important. The refractive index can be written, for no magnetic field, as (from equation 3.1):

$$n^2 = (\mu - i\chi)^2 = 1 - \frac{X}{1 - iZ}. \quad (3.7)$$

When $\mu^2 \gg \chi^2$, the absorption coefficient, the attenuation per unit distance, $\kappa = \omega\chi/c$, is

$$\kappa = \frac{\nu}{2\mu c} \frac{\omega_p^2}{\omega^2 + \nu^2}. \quad (3.8)$$

This is discussed more fully in section 3.2.2.

The Ordinary and Extraordinary Modes

The existence of the ordinary and extraordinary HF radio wave modes is a result of the birefractivity of the ionospheric medium under the influence of a magnetic field. Their existence is demonstrated by equation 3.1. The differences in the ordinary and extraordinary ray paths are illustrated in figure 3.1 for three frequencies vertically incident on a mid-latitude ionosphere. When an HF radio signal is transmitted vertically the ordinary wave deviates poleward in the magnetic meridian and the extraordinary wave equatorward. In contrast to the extraordinary mode, the ordinary wave reflects at a higher altitude and most of the wave refraction occurs near to the reflection height. These modes will, henceforth, be referred to as the O-mode (ordinary) wave and X-mode (extraordinary) wave. Figure 3.1 is representative of an HF transmission at mid-latitudes but a similar mode separation occurs at high latitudes. Note that the reflection points for the two modes are separated vertically as well as horizontally. For a wave frequency, f , which is approaching foF2 this separation can be several tens of kilometres in both directions. For more oblique propagation this effect is reduced since the reflection conditions is no longer $\mu \approx 1$.

3.2.2 Attenuation of Radio Waves

Deviative and Non-deviative Absorption

Attenuation or absorption of the propagating signal occurs because of collisions between free electrons and neutral gas molecules which lead to dissipation of the energy of the radio wave. The attenuation of the wave, L , is found by integrating the absorption coefficient, κ , along the ray path

$$L = \int \kappa ds. \quad (3.9)$$

Neglecting the magnetic field, equations 3.3 and 3.8 give

$$\kappa = \frac{e^2}{2\epsilon_0 c m_e} \frac{1}{\mu} \frac{N_e \nu}{\omega^2 + \nu^2}. \quad (3.10)$$

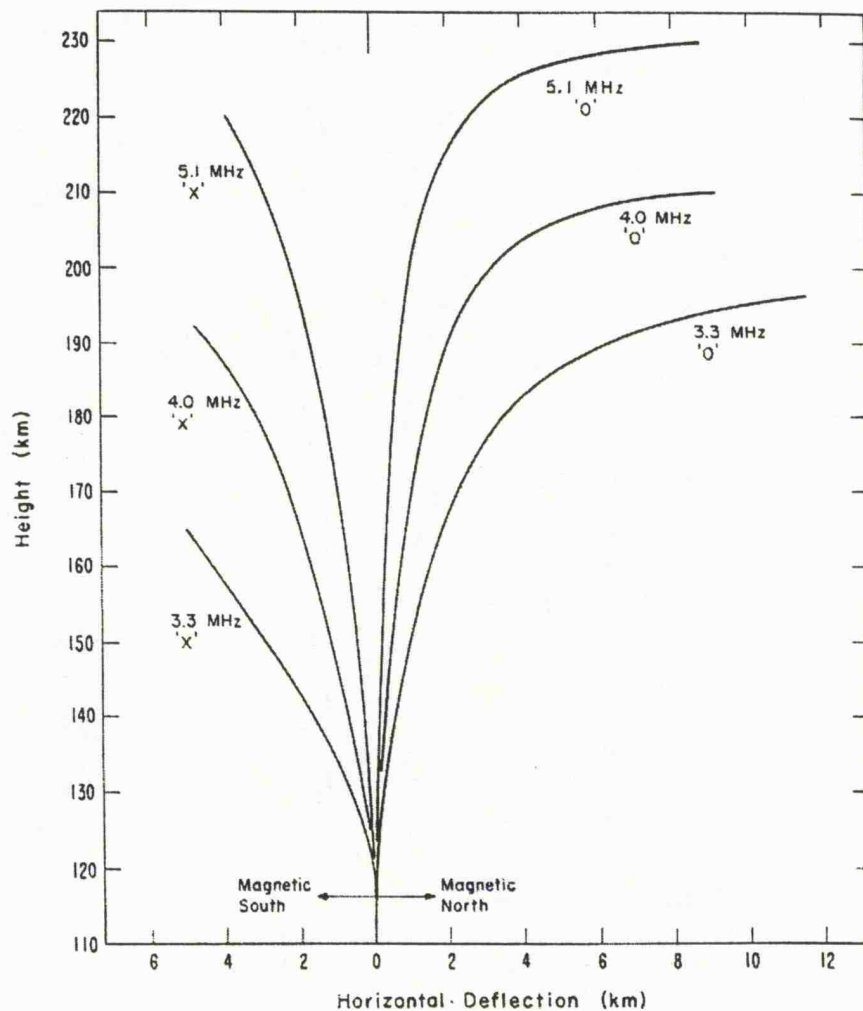


Figure 3.1: An illustration of O- and X-mode ray paths for vertical propagation at a mid latitude site (Boulder, Colorado). Note that deviation occurs only in the magnetic meridian with the O-mode being deflected north and X-mode south. A similar effect happens at high latitude. [After Davies (1990)]

In general, the portions of the ray path in the lower ionosphere and near the reflection height contribute most to L . The processes involved are non-deviative and deviative absorption respectively.

In the D and lower E regions, the value of $N_e \nu$ maximises and consequently κ is large and absorption is high. However, in the lower ionosphere N_e is sufficiently small that the refractive index is close to unity, $\mu \approx 1$, and, hence, attenuation in this region is known as non-deviative absorption. For $\omega^2 \gg \nu^2$ the absorption coefficient for non-deviative absorption (equation 3.10) reduces to

$$\kappa \approx \frac{e^2}{8\pi^2 \epsilon_0 c m} \frac{N_e \nu}{f^2}. \quad (3.11)$$

The absorption is proportional to the electron density in the D region and inversely proportional to the square of the radio wave frequency. As the frequency of transmission is reduced absorption increases and the signal to noise ratio decreases. The limit where signals cannot be detected at the receiver, *i.e.* the limiting frequency, is known as the lowest usable frequency or LUF.

In the limit that $\mu \rightarrow 0$, equation 3.10 indicates that absorption is high. This is known as deviative absorption since it occurs when the radio wave is near reflection and there is marked curvature of the ray path. In the case of oblique propagation, where reflection occurs at $\mu > 0$, the deviative absorption is low, and the major contribution to the attenuation of radio waves is non-deviative absorption.

The non-deviative absorption of an oblique ray can be related to that of a vertically propagating ray passing through the same point in the D region by the factor $\sec \varphi_D$, where φ_D is the angle made by the oblique ray to the vertical in the D region.

$$\tan \varphi_D = \frac{1}{\tan(\Delta + \alpha_D)}, \quad (3.12)$$

where α_D is the angle made at the centre of the earth between the ray at the ground and in the D region (figure 3.2). α_D can be found from the approximate altitude of the D region, h_D (≈ 80 km), and other parameters of the radio wave path, h' , Δ , and α ,

$$\frac{\cos(\Delta + \alpha_D)}{\cos(\Delta + \alpha)} = \frac{R_e + h'}{R_e + h_D}. \quad (3.13)$$

Enhancement of the D region electron density, by factors such as solar illumination or electron precipitation, increases the magnitude of non-deviative absorption. The auroral precipitation of electrons leads to enhanced absorption by

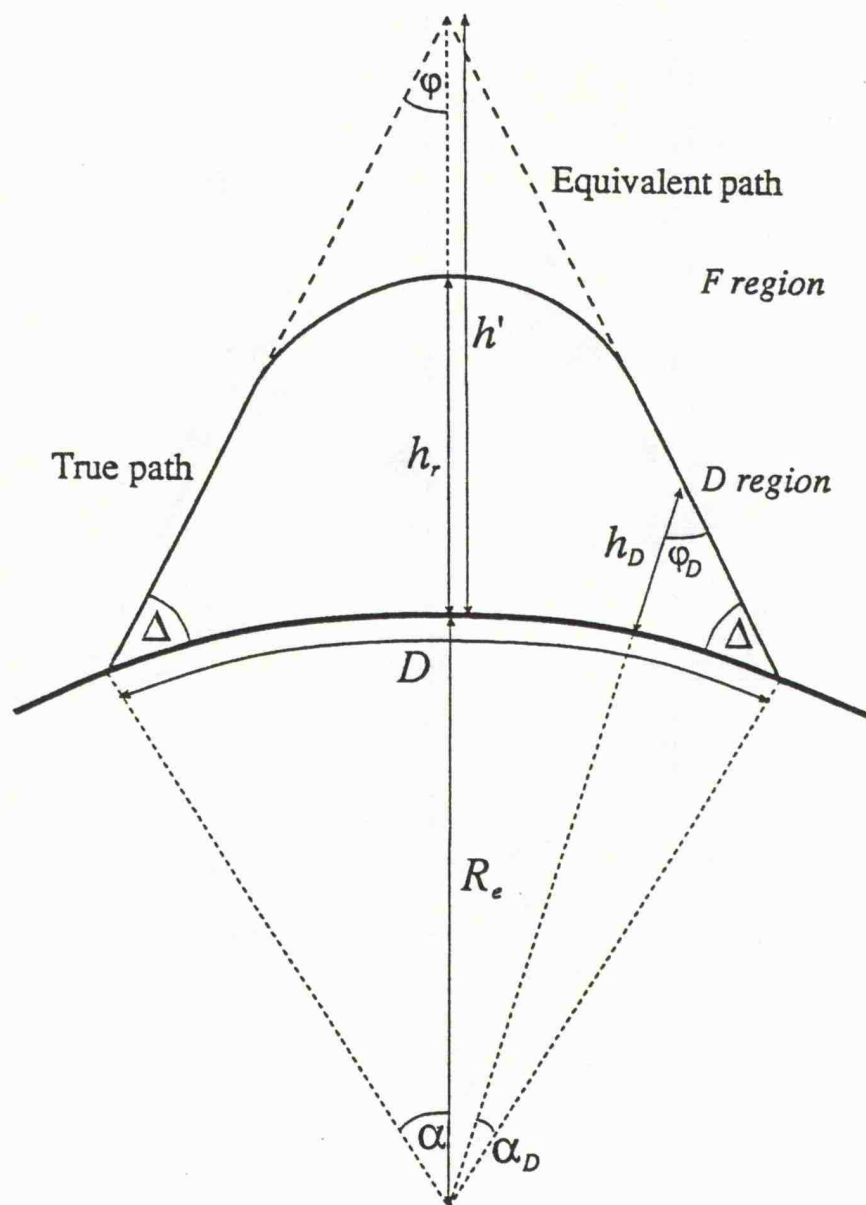


Figure 3.2: The geometry of a radio wave propagating through the ionosphere. The true and equivalent (virtual) paths are illustrated. D is the ground range covered by the one hop path and h_r and h' are the true and virtual heights of reflection respectively. Δ is the elevation angle, φ and φ_D are the angles of incidence at the point of reflection and the D-region. [After Milan (1994)]

the high latitude D-region. The flux of auroral precipitation, and consequently the level of auroral absorption, is dependent on geomagnetic activity, and models require suitable parameterisation of this behaviour. Sunspot number has been employed as a model input [Foppiano and Bradley (1985)], but this does not adequately reflect the much more rapidly varying level of magnetic disturbance at the Earth, and other indices have been employed. These include A_p [Hargreaves *et al.* (1987)] and K_p [Foppiano and Bradley (1983)]. Auroral absorption varies on a time scale of ~10 minutes [Reid (1967)] and consequently the 3-hourly indices A_p and K_p are poor indicators of absorption level.

Differential D-region Absorption of O- and X-mode Radio Waves

When passing through the D-region O- and X-mode HF radio waves are attenuated to a different degree [*e.g.* Robinson (1989)]. In this case the absorption,

$$L_D = \frac{A_D}{(f \pm f_H)^2}, \quad (3.14)$$

where f_H is the electron gyrofrequency and A_D is a frequency independent parameter with a diurnal variation as

$$A_D \propto \cos^n \chi. \quad (3.15)$$

n is a value dependent on latitude and season. The plus in equation 3.14 corresponds to the O-mode and the minus sign to the X-mode. Thus, at a given time of day and position on the Earth The O-mode will always suffer less absorption than the X-mode. In fact, because of the diurnal variation of A_D , the difference maximises at local noon. This enables the identification of the wave modes being received on a pair of crossed dipole antennas once they have been discriminated (see section 4.2.2).

3.2.3 Ionospheric HF Sounding

A great deal of our knowledge about the ionosphere comes from remote sensing by radio waves. HF signals transmitted, reflected in the ionosphere and received back at the ground provide information such as signal amplitude, time of flight, polarisation, phase and, hence, frequency shifts. For example, moving transmitters such as those on board satellites have been employed to study the horizontal structure of the ionosphere. Coherent radars receive signals which have been scattered from field aligned ionospheric irregularities to determine ionospheric current flows. This type of scatter may only occur when the radio wave k vector is orthogonal to the magnetic field. VHF radars employ line of sight propagation to meet this condition whereas HF radars use ionospheric refraction along the wave path. Incoherent radars, on the other hand, receive signals which have scattered

from ion acoustic waves in the ionosphere. Sweep frequency HF sounders, known as ionosondes, can provide detailed information on the local ionosphere. Ground based single frequency sounding, however, is the method employed for the present study. A comprehensive study of radio sounding techniques is given by Hunsucker (1990).

Ionosondes

From equation 3.3 the frequency of a radio wave reflected from the ionosphere can be related to the electron density at the reflection height. An ionosonde is a sweep frequency pulsed radar which takes advantage of this knowledge. There are several types of ionosonde. For example, the oblique chirp sounder [Barry (1971)] utilises a transmitter and receiver which may be separated by thousands of kilometres and whose sweep start time and rate are synchronised. A dynasound [Wright and Pitteway (1982)] is an advanced sounder which permits the full digital processing of the echo signals. By deployment of special arrangements of antennas this instrument allows the echo location (skymaps) of ionospheric structures from direction of arrival measurements. These instruments sample the ionosphere vertically above the ground station. The frequency sweep typically takes a few minutes and thus an ionosonde is not suitable for observing rapid transient changes in the ionosphere.

The ionosonde measures the time of flight of a pulse transmitted from the ground and received again. The virtual or group height h' of the reflecting layer of the ionosphere is then related to the time of flight, t , by

$$h' = \frac{1}{2}ct = \int_0^{h_r} \mu' dh, \quad (3.16)$$

where μ' is the group refractive index, h_r is the real height of reflection. The group (virtual or equivalent) path (figure 3.2) is that which would be taken by the pulse in the same time of flight in free space (*i.e.* $\mu'=\mu=1$) travelling at velocity c . However, due to the retardation - the effective slowing - of the ray near the point of reflection, it follows the so called true path and only achieves a height h_r which is less than equivalent virtual reflection height, h' . At or near the reflection point $\mu \approx \mu'^{-1} \approx 0$, that is, $\mu \rightarrow 0$ and $\mu' \rightarrow \infty$ (see section 3.2.4). Figure 3.3 illustrates a profile, known as an ionogram, of h' versus frequency. It should be noted that such parameters as NmF2 (figure 1.3) have a corresponding plasma frequency called the foF2 for O-mode waves and fxF2 for X-mode waves. The foF2 is the highest frequency at which an O-mode wave can achieve a reflection in the ionosphere along the same path as the signal of the ionosonde which measured the

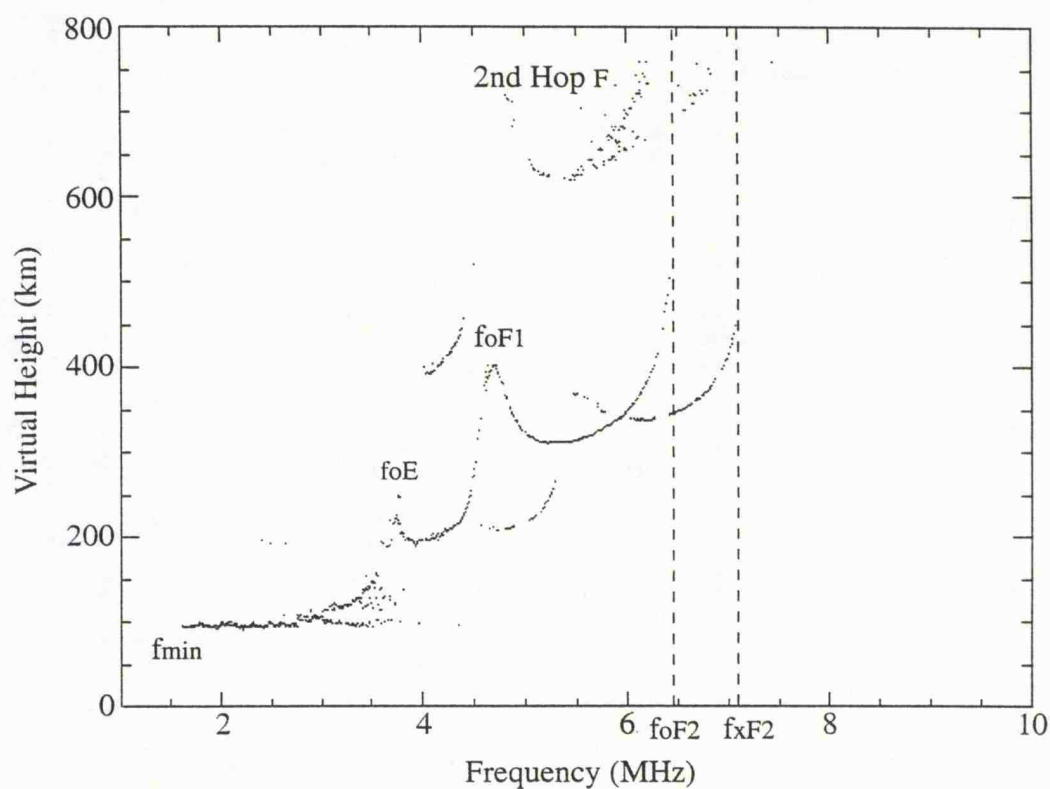


Figure 3.3: An example of an ionogram which clearly illustrates the features associated with the various ionospheric regions. The 2nd hop trace is due to the transmitted signal undergoing reflections at the ionosphere, ground, then ionosphere before being received and thus gaining twice the group delay of a one hop path. The sounding was measured at Bear Lake, Utah, USA on 14/08/93 at 19:00:16-19:01:20 UT. [Image obtained through the Tromsø dynasonde internet site: <http://seldon.eiscat.no/dynasond.html>]

ionogram. f_{min} is determined by the amount of D-region absorption. When absorption is high the LUF increases and so the ionogram trace starts at a higher frequency. The apparent peaks or discontinuities in the ionogram trace occur where the sounding frequency matches the plasma frequency at that layer and the group delay and, hence, h' has become effectively infinite.

At solar minimum and high latitudes the maximum frequency which will reflect from the ionosphere is typically 4-6 MHz and at solar maximum this can increase to about 12 MHz at certain times of the year. The data which will be presented in chapter 6 were recorded around solar minimum.

3.2.4 The Doppler Technique

Doppler sounding of the ionosphere was first reported by Watts and Davies (1960) who developed the technique for monitoring transient changes in the ionosphere such as those produced by nuclear explosions, solar flares and acoustic-gravity waves. In conventional pulse sounding the group path of the signal is determined. If, however, the phase of the signal is measured then small changes in the propagation path of a fraction of a wavelength ($\lambda=30\text{m}$ at 10 MHz) can be detected. Due to the fluctuating motion of the ionosphere, phase recording is impractical since many wavelengths of phase change will occur over time intervals of a few seconds. The strength of the Doppler method is that it depends on the rate of change of phase of the received signal. This makes the technique very sensitive to rapid transient changes (*e.g.* those produced by wave activity) and insensitive to slow changes such as those due to the diurnal solar control of the ionosphere. It is therefore an ideal tool for investigating ionospheric changes induced by ULF waves.

In a Doppler sounder a phase stable continuous wave (CW) signal is usually employed. Both the receiver and transmitter units require a reference oscillator which is frequency stable to at least one part in 10^8 so that the frequency drift over long periods is very much less than 0.1 Hz. This stability is necessary because the effects produced in the ionosphere lead to frequency changes which are typically around ± 0.5 Hz. The ionospherically reflected signal is received and mixed with the reference frequency in order to determine the frequency shift, Δf , which was incurred along the ray path, given by

$$\Delta f = -\frac{1}{\lambda} \frac{dP}{dt} \quad (3.17)$$

where P is the phase path of the signal and λ is the free space signal wavelength.

Two effects can cause changes in phase path and hence frequency. One occurs where there is a change in the height of reflection due to a vertical motion of the ionosphere. In this case

$$\Delta f \propto f \quad (3.18)$$

Secondly, a change in the refractive index such as that due to enhanced ionisation in the lower ionosphere through which the wave passes, leads to a frequency shift which is inversely proportional to the wave frequency, *i.e.*

$$\Delta f \propto f^{-1} \quad (3.19)$$

These two types of effect cannot unfortunately be distinguished by a single frequency diagnostic.

For a Doppler sounder on a near vertical path, such as those utilised in this work, any vertical motion of the reflection point of the radio wave will cause an associated Doppler shift on the wave frequency. The frequency shift is related to the vertical velocity of the ionospheric layer by

$$\Delta f = -2f \frac{v}{c} \cos \phi, \quad (3.20)$$

where v is the velocity of the layer (positive upwards), ϕ is the angle of incidence of the ray on the ionosphere and c is the velocity of light in free space.

The production of a Doppler signature by a travelling ionospheric disturbance (TID) [*e.g.* Hines (1960)], which is a type of transient ionospheric disturbance, is illustrated schematically in figure 3.4 [Georges (1967)]. As the disturbance passes over the sounder the reflection height begins to increase producing a negative Doppler shift in the frequency of the received signal. The rate of change in height increases as the feature propagates, giving the maximum in measured Doppler shift. As the peak of the displacement is approached the rate of change of phase path decreases until it becomes zero. Then, as the reflection height decreases again during the second half of the disturbance a similar Doppler trace is observed but with a positive frequency change.

Sensitivity as a Function of Sounder Frequency

In addition to the linear variation of measured Doppler shift with sounder frequency (equation 3.20), the sensitivity increases as the sounder frequency approaches the ionospheric critical frequency and $\mu \rightarrow 0$. The Doppler shift observed, as mentioned earlier, is a measure of the change in phase path along which the ray travels and, hence, is also a measure of the phase velocity of the wave. It is well known that for an electromagnetic wave

$$\sqrt{v_g v_p} = c \quad (3.21)$$

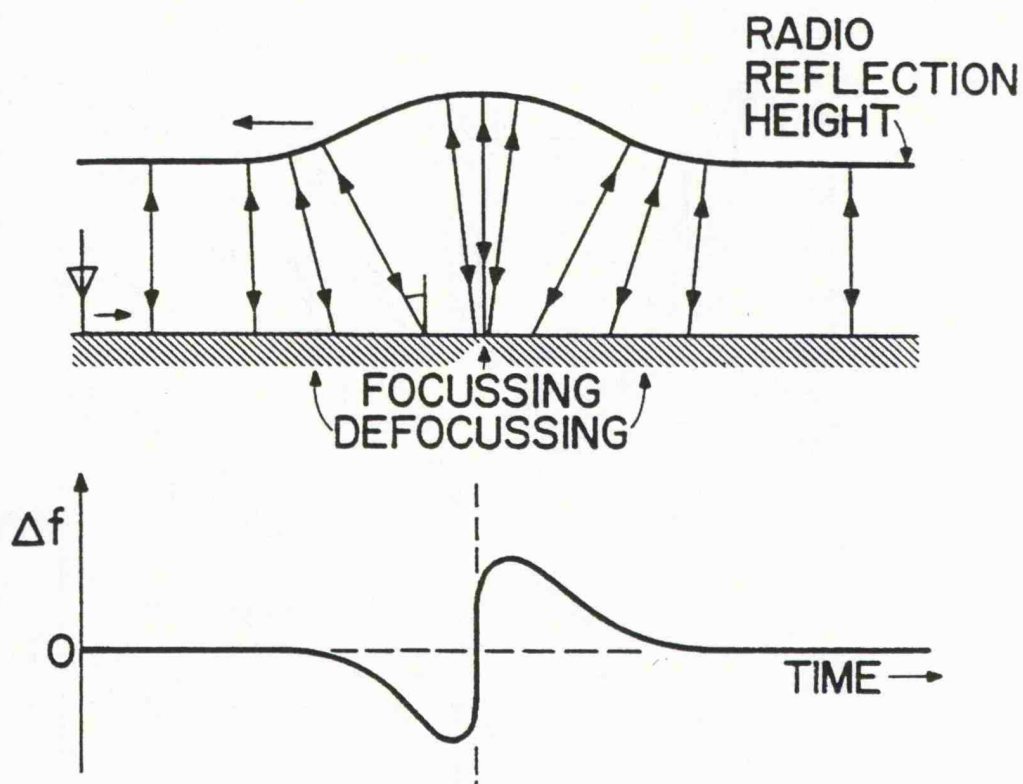


Figure 3.4: A schematic to illustrate how a travelling ionospheric disturbance (TID) affects the frequency of a probing HF radio wave. For simplicity the vertical sounder (top, far left) is assumed to move under the stationary TID. The disturbance acts to cause an effective vertical movement of the reflection height of the diagnostic. It should be noted that as the reflection level increases a negative frequency shift is measured and vice versa. [After Georges (1967)]

where v_p is the phase velocity of the wave and v_g the group velocity (the velocity at which energy propagates along the ray path).

For a sounding frequency which is very close to the critical frequency of the ionosphere (foF2) the group delay on the ray as it passes through the medium becomes large and can be seen as the discontinuity on the ionogram in figure 3.3 at foF2. Similar discontinuities occur at the peaks of the E and F1 layers at frequencies foE and foF1 respectively. In other words $v_g \rightarrow 0$ and therefore $v_p \rightarrow \infty$. So, small changes in phase path lead to a very enhanced effect on the Doppler phase path and frequency shift when the signal frequency approaches the critical frequency. This effect essentially acts as a magnifying mechanism for observations of ionospheric wave signatures. As the sounding frequency increases and approaches foF2 the same wave signature would appear to increase in magnitude.

Spatial Resolution in a HF Doppler Sounder

It is of relevance to this work to determine the spatial resolution of a Doppler sounder and to compare this to that of a typical ground magnetometer. The area over which a sounder integrates data is determined by the region of specular reflection which, to a first approximation, is given by the area of the first Fresnel zone of the reflecting plane of the ionosphere. A simplified relation for the radius of the first Fresnel zone, assuming an idealised mirror like reflection, is given by [Georges (1967)]

$$R = \sqrt{r_0 \lambda} \quad (3.22)$$

where r_0 is, for a vertical incidence sounder, the height of reflection and λ is the wavelength of the diagnostic signal. For an F-region reflection at $r_0 \approx 250$ km and a sounder frequency of 4 MHz ($\lambda = 75$ m) then $R \approx 4$ km. These values are typical for the near vertical sounders employed for this study. Comparing this value of R with the typical horizontal scale size of the integration area for a ground magnetometer (about 120 km) or a VHF coherent ionospheric radar (15-45 km) it is evident that a Doppler sounder has a spatial resolution far higher than that of a ground magnetometer, and is in excess of the best available with a coherent radar. The incoherent radar EISCAT, in contrast, has a beam width in the order of 2 km at F-region heights.

Doppler Data Analysis

The base band signal from the Doppler system receiver, is at a frequency of a few Hz which corresponds to Δf plus some arbitrary offset. This was, in the past, recorded directly onto slow moving audio tape which was later played back at

high speed and fed into a spectrum analyser which plotted data as an analogue trace (*e.g.* figure 5.1). However, for this study a more modern method was employed - the signal was digitally sampled and the bytes stored, through PC control, on digital audio tape (DAT). This improved data handling and analysis as will be detailed in chapter 4.

The complex data (real and imaginary parts of the receiver output) are analysed by passing N time-consecutive samples through a Fast Fourier Transform (FFT) employing a cosine bell window. This produces an N point frequency spectrum which is taken to be representative of the sampled signal at a time half way through the data interval. The total bandwidth of the spectrum is the same as the sample rate (in Hz) of the data and the frequency resolution of the spectrum is simply the bandwidth divided by N . For the data sampled by the DOPE system (chapters 4 and 6) the sample rate was 40 Hz and the 512 points (equivalent to 12.8 seconds) of data, typically used, gave a frequency resolution of 0.078 Hz, which is consistent with Nyquist theorem. It is clear that the Fourier theorem dictates that this limit can only be improved at the expense of temporal resolution.

The spectral component with the highest amplitude, assuming the received signal amplitude was high enough, represents the specularly reflected component of the diagnostic wave. A threshold is applied to the spectral data so that this peak and the points closest in amplitude to it are selected. These are plotted at their respective frequencies for the time of each interval. What builds up then is a plot of Doppler shift, Δf , versus time known as a Doppler trace. Any changes or oscillations in the frequency of the signal represent the time evolution of an ionospheric signature measured at the diagnostic reflection point.

In contrast to the method described here, some experimental setups employ analogue data recording techniques, involving a frequency to voltage converter, to improve the temporal resolution [*e.g.* Menk (1992)] beyond that available via Fourier analysis techniques. However, under these conditions information is lost in the recorded frequency bandwidth which can be useful for identifying local interferers and noisy signals.

3.3 HF Doppler Observations of ULF Wave Signatures

3.3.1 Experimental Observations

Fenwick and Villard (1960) were the first to suggest that rapid fluctuations in the frequency of a HF CW transmission might be correlated with magnetic field

changes. A correlation between impulsive “magnetic sudden commencements” and frequency variations of the standard frequency broadcasts of WWV and PR (Puerto Rico) on 20 and 18 MHz, at mid-latitudes, were later reported by Chan *et al.* (1962). Since then there have been various studies into these effects at low and mid-latitudes. Jacobs and Watanabe (1966) and, later, Klostermeyer and Röttger (1976) both investigated HF Doppler oscillations in the mHz range which were associated with geomagnetic pulsations. Jacobs and Watanabe (1966) examined the relationship between the magnitude of the ionospheric electric field variation of a pulsation, derived from magnetometer data and the corresponding Doppler shift observed. They found a linear relationship for sudden commencements of geomagnetic storms but not for ULF waves under geomagnetically disturbed conditions. Klostermeyer and Röttger (1976) employed a near vertical HF sounder at mid-latitudes to explore the mechanisms which generate the ionospheric signature. Their events were mostly Pi2s which occur on the nightside. Figure 3.5 illustrates three of the events they reported. These authors noted that all events start simultaneously in the Doppler and magnetic records. However, the three panels illustrate examples of three different types of observation; (a) those where the Doppler correlated with the magnetic oscillation for several cycles (figure 3.5a), (b) those where, more rarely, there was only one cycle associated with the event (figure 3.5b) and (c) those which showed little correlation at all (figure 3.5c).

More recently, Watermann (1987) and Yumoto *et al.* (1989) related the effects on HF sounder signals of magnetic storm phenomena. Watermann (1987) performed an analysis of mid-latitude data related to storm sudden commencements (SSC), sudden impulses and Pi2s. He found that not all of the geomagnetic phenomena had associated radio frequency shifts but that those which did correlate could be interpreted as being due to a vertical motion of the ionospheric F-layer. A statistically significant annual variation was demonstrated which had largest occurrence at the equinoxes and rare occurrences at the solstices. Yumoto *et al.* (1989) presented a case study of low latitude observations made by a HF Doppler sounder during the magnetic storm of February 1986. Their 5 MHz HF sounder data were correlated with an SSC in one interval and with a sudden impulse followed by a pulsation signature. They associated the former event with the dynamo-motor effect but the latter with a compressional wave through the mechanism suggested by Poole *et al.* (1988) (see section 3.3.2). Both of these effects will be discussed in section 3.3.2. Other low latitude observations have been presented by Menk *et al.* (1983) and Menk (1992). These papers examined the same data set which was taken in Australia between 1979-80. Multiple

frequency HF Doppler soundings were recorded in the F-region simultaneously with ground magnetometer measurements. An example of one of their events is given in figure 3.6. They associated the event with a vertical bulk motion of the ionosphere. Menk (1992) studied the effects of Pc3-4 events on the dayside and Pi2 events at night and attempted to fit these observations to the model of Poole *et al.* (1988), Sutcliffe and Poole (1989, 1990) and Sutcliffe (1994). The data fitted predictions for dayside events but was less successful for the nighttime Pi2s.

3.3.2 Modelling Work

The simplified model by Jacobs and Watanabe (1966) only accounted for changes in phase path due to changes in refractive index below the reflection level. It did not account for movements of the reflection level itself nor for changes in electron density due to compression of the magnetic field. It is not surprising, therefore, that their work matched storm sudden commencements which would tend to increase, for example, the D-region electron density (and hence the refractive index) but did not follow for a short period ULF wave in which the field compression and reflection height variation is important, as will be discussed shortly. In contrast to Jacobs and Watanabe (1966), Klostermeyer and Röttger (1976) attempted to explain their Doppler observations with the dynamo-motor effect as laid down by Rishbeth and Garriot (1964). The “dynamo” part of this mechanism relates to E-region electric fields, generated by the motion of the ionospheric plasma caused by neutral winds, which map up field lines into the F-region. This then drives the “motor” part of this mechanism which induces an $\mathbf{E} \times \mathbf{B}$ motion of the plasma in the F-region ionosphere if an oscillating electric field is present. The vertical component of the resulting bulk motion may be detected by a HF Doppler sounder. Klostermeyer and Röttger (1976) demonstrated that their results could not be explained by an E-region dynamo effect but were consistent with a hydromagnetic wave approach, where the motor effect was caused by the oscillating electric field associated with the pulsation instead. This method of generating ionospheric signatures of hydrodynamic waves has recently been labelled the “advection” mechanism by Sutcliffe and Poole (1989) in their modelling work. This will be discussed shortly. A conclusion drawn by Klostermeyer and Röttger (1976) was that their observations were broadly consistent with a MHD mode driving an F-region $\mathbf{E} \times \mathbf{B}$ motion but that important discrepancies existed. They stated that more work needed to be done in accounting for the reflection and attenuation of hydromagnetic waves in the ionosphere and this will be addressed in this investigation.

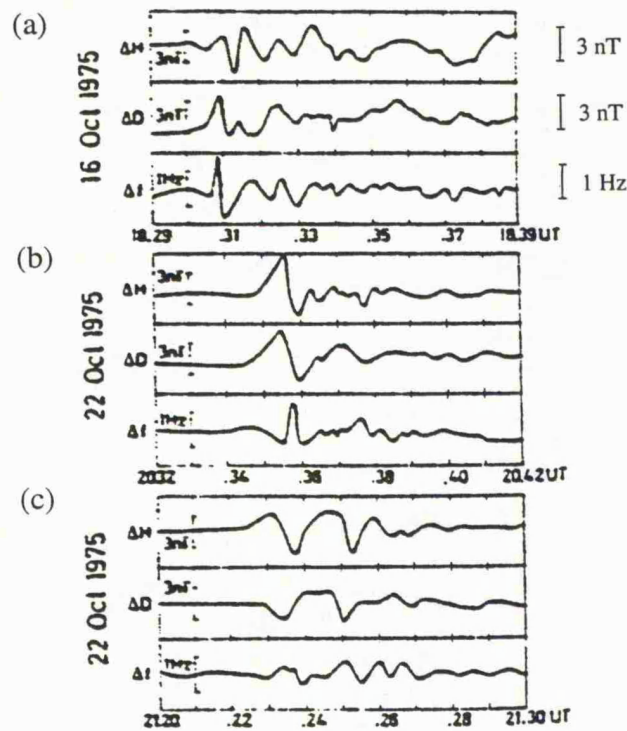


Figure 3.5: Three mid latitude events taken from Klostermeyer and Röttger (1976). One event (a) has a correlation between Doppler shift (lower panel) and the ground magnetometer H and D component signatures (upper and middle panels respectively) over several cycles of the oscillation, another (c) barely correlates at all other than for a simultaneous start and the middle panels (b) consists of an event which causes a disturbance for a single cycle only. In each case the scale sizes of 3 nT (top two panels) and 1 Hz (lower panel) applies.

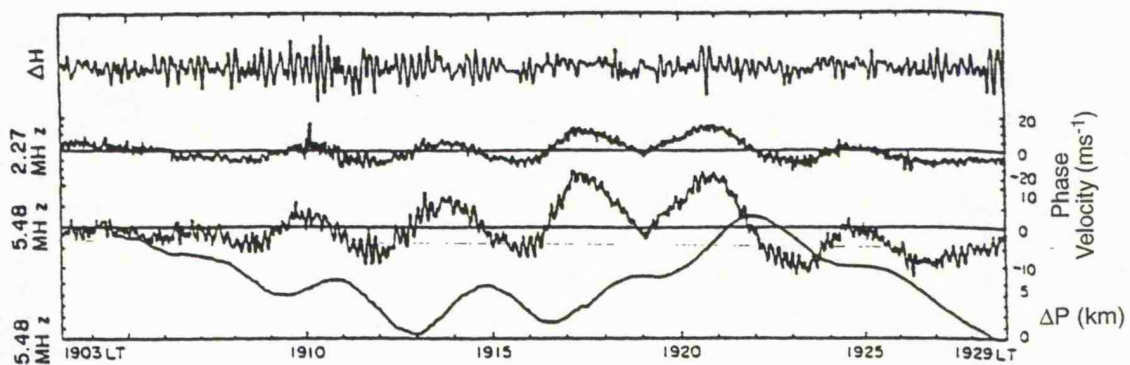


Figure 3.6: An example, from Menk *et al.* (1983), of a ULF wave signature on multiple frequency HF radio paths at low latitude. The author attributes the long period oscillation to the action of an acoustic gravity wave and the short period oscillation to the ULF wave. All of the sounder signals were reflected in the F-region. ΔP is the change in phase path length in km.

It was not until some years later that Poole *et al.* (1988), Sutcliffe and Poole (1989, 1990) and Sutcliffe (1994) presented work on a model defining the mechanisms which relate an incident ULF wave to its associated ionospheric Doppler signature. They modified previous models which employed only the motor effect [Rishbeth and Garriot (1964); Klostermeyer and Röttger (1976)], where the electric field associated with a geomagnetic pulsation drives an $\mathbf{E} \times \mathbf{B}$ bulk drift of plasma which, due to the inclination of the field, has a vertical component as illustrated in figure 2.2. This is applicable to Alfvén mode waves with associated magnetic field perturbation, b , and electric field amplitude, E . Poole *et al.* (1988) accounted for changes in refractive index along the radio wave path and also included terms to compensate for magnetic field compression in the ionosphere. The possibility of source and loss mechanisms for the plasma were also discussed but this has so far been neglected.

The development of the model of Poole *et al.* (1988) was necessitated by the fact that so many HF Doppler signatures of ULF waves could not be explained by the motor effect alone. By neglecting source and loss processes for the ionospheric plasma, their model was separated into three main mechanisms. The “magnetic” mechanism accounts for changes in the refractive index due to changes in the magnetic field intensity, requiring no bodily movement of electrons. The “advection” mechanism, as discussed earlier, describes the motor effect on the ionospheric plasma caused by the electric and magnetic perturbations associated with an incident ULF wave. The conversion of the Alfvén wave to an evanescent fast mode wave in the ionospheric E-region, which is detected at the ground (section 2.2.2), results in compression of the magnetic field, leading to changes in the local plasma density and, hence, the refractive index. The “compression” term, in the nomenclature of Poole *et al.* (1988) and Sutcliffe and Poole (1989, 1990), deals with this mechanism. Initially [Poole *et al.* (1988)], field aligned currents associated with the Alfvén wave were assumed to be small but later Sutcliffe and Poole (1989, 1990) and Sutcliffe (1994) modified the model to include these currents and to take account of the effects of collisions.

Each mechanism included in the model described above contributes a component to the Doppler velocity measured by a sounder (equation 3.20). The velocity components are added vectorially so that relative phase of the mechanisms is accounted for. Figure 3.7 illustrates the results of their model for an ionospherically reflected Alfvén wave. Height profiles for pulsation electric field and Pedersen and Hall conductivities were calculated and input into the model. A mid-latitude ionospheric profile for midday in midsummer and at solar maximum

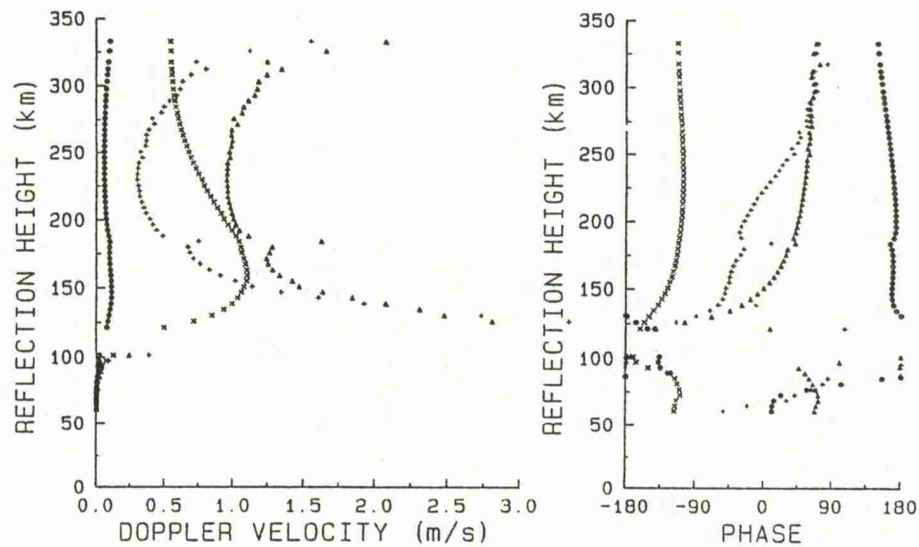


Figure 3.7: Results of the model by Sutcliffe and Poole (1990) for an incident Alfvén mode wave and for an O-mode Doppler diagnostic signal. Left: the height profiles of the velocity contributions from the various mechanisms. Right: the relative phases of each component. Symbols: Total Doppler velocity (+); contributing mechanisms: "magnetic" (o); "advection" (x) and "compressional" (Δ). All are measured relative to a north south wave magnetic perturbation, b_x , at the ground with an amplitude of 1 nT and phase of 0° .

was taken from the International Reference Ionosphere (IRI) 1979. The HF radio wave frequency modelled was 7.3 MHz which was very close to the ionospheric critical frequency. The total Doppler velocity along with the individual component from each mechanism is plotted along with their respective phases. It can be seen from this that the total Doppler velocity which affects the HF radio wave is not simply the vertical velocity associated with the advection or $\mathbf{E} \times \mathbf{B}$ mechanism. Note that, particularly in the upper F-region, the advection and compression effects are 180° out of phase. Also, in the upper F-region the phase profiles of the various mechanisms as well as that of the total velocity are constant with height.

This model has only been applied to an Alfvén mode but may also apply to a purely compressional wave incident on the ionosphere. In this case terms due to the advection mechanism and field aligned currents would be negligible because fast mode waves do not tend to cause currents to flow and they are not field guided. It is important to note that this model has been developed for low and mid-latitude conditions because, in contrast to the high latitude ionosphere, these are regions of low precipitation. However, a source/loss mechanism, which was included in the model but has not previously been implemented, should enable high latitude observations also to be successfully modelled. A thorough test of this model requires spatially separated simultaneous soundings of the ionosphere in order to determine phase-height profiles of the wave signatures. This may be achieved by application of a multi-station multiple frequency system which could make measurements at reflection points separated in three dimensions. The work by Al'perovich *et al.* (1991) and Menk (1992) attempted this at mid- and low latitudes respectively but Al'perovich *et al.* (1991) considered only Pi2 signatures. They concluded that their observations gave Doppler velocities which were an order of magnitude different to those predicted by the model. No discussion on the relative phase of contributing components was given. The Pi2 observations made by Menk (1992) similarly did not follow the theory. However, Pc3-4 events recorded by the same author exhibited some degree of agreement with the prediction. The relative phase between the observed Doppler and ground magnetometer signatures was reported to be often in-phase but often there was a phase drift, making a general inference difficult. Spatial integration effects (see section 2.2.2) of the ground magnetometers were proposed as causing the lack of consistent phase comparisons with the Doppler records. Contamination from surrounding source regions may have affected the data and as the author only had single station multiple frequency measurements then horizontal variations in the wave field could not be determined. It is appropriate to mention at this time that a

single frequency transmission with O- and X-mode resolution may, for a sounding close to the critical frequency, offer two reflection points separated by up to 50 km vertically and somewhat less in the north - south meridian (section 3.2.1). The Doppler velocities measured by Menk (1992) were about 20 times larger than expected by the model of Sutcliffe and Poole (1990). It was, however, pointed out that the horizontal scale length employed by the model previously had been fixed at 500 km. Menk (1992) argued that a smaller scale size (~80 km) would be appropriate for some of the observed waves and that this would correspondingly increase the expected Doppler velocities.

3.4 Summary

The HF sounding is a technique of major importance for investigating the ionosphere. The applications and limitations of it have been examined through a description of HF radio wave propagation theory. In particular, the role of HF Doppler sounders, as ionospheric diagnostics is discussed. Their high spatial resolution makes them an ideal tool for studying the effects of ULF waves in this region.

There is a wealth of ground magnetometer data covering all latitude ranges on the Earth from which geomagnetic pulsation features have been studied. However, to date Doppler observations of ionospheric ULF wave signatures have been restricted to low and mid-latitudes. In addition, recent models of the processes which couple magnetospheric waves to ionospheric effects remain largely untested even at low and mid-latitudes. Multi-point measurements which are spatially separated, horizontally as well as vertically, are necessary to validate them.

Chapter 4

The Development of a New HF Doppler Sounder

4.1 Introduction

This chapter describes the construction and operation of a Doppler sounder, built by the Radio and Space Plasma Physics group at Leicester University, for ULF wave studies. A low power, frequency stable transmitter and a computer controlled receiver have been designed and built. Computer software was written to control the receiver and store and display the data collected in real time. It is a compact system which is easily relocatable and which can run unattended at remote sites for extended periods.

The Doppler sounder was tested in the UK and then deployed near Tromsø, Norway (69.6°N 19.2°E) in order to obtain measurements in conjunction with EISCAT (see section 4.4). Section 4.2 of this chapter gives details of the system hardware which, for the most part, was designed and constructed by the technical staff of the Leicester group. Details of the system are included since the available hardware is an important constraint on the system. Subsequent to this, work which forms part of this thesis submission is presented. Section 4.3 describes, in detail, the software designed and developed for real time control and data logging for the sounder. A number of software and hardware innovations were developed. These include: (a) an automatic gain controller (AGC) which employs the parallel printer port (LPT) of the PC for communication with the receiver; (b) timing software designed to detect signals, external to the PC, which are derived from the receiver's stable reference oscillator and to maintain the correct time when power failures at remote sites occur; (c) a graphical user interface (GUI) and a real time data display for easy operation in the field and during experimental campaigns; (d) software dedicated to sensing the status of the external main power supply and to executing specific instructions when power failure occurs. Finally, the deployment of the sounder in Norway and the experimental arrangement is described.

4.2 The System Hardware

For this project a HF transmitter and receiver were designed to meet the requirements of the Doppler technique [Watts and Davies (1960)]. That is, the transmitted continuous wave (CW) signal had to be very stable in frequency - of the order of 1 part in 10^8 (see section 3.2.4) or better in order that Doppler shifts

of 0.1 Hz or less could be accurately resolved. Technical details of the transmitter and receiver employed are given by Chapman (1996).

4.2.1 The Transmitter

The HF transmitter was built to satisfy several design criteria. Firstly, it needed to be of robust construction since it was to be deployed at a remote field site inside the Arctic circle. Secondly, the transmitted frequency had to be extremely stable requiring the use of a double oven crystal oscillator which achieved a stability of a few parts in 10^9 . From switch on, the transmitter and receiver references take around 20 minutes to warm up and stabilise. For this experiment an unmodulated HF CW signal at a frequency of 4.45 MHz was transmitted at a power of about 20 W.

Figure 4.1 is a photograph of the transmitter site. The transmitter is housed in a caravan located on the shore of a fjord at Seljelnes, Norway, which is about 50 km south of the receiver location at the EISCAT site in Ramfjordmoen. The caravan is unheated and so the temperature may fall to as low as $-20\text{ }^{\circ}\text{C}$ in the winter and the transmitter has been designed to cope with this as indicated above. The HF transmit antenna is erected just outside. The site is at the edge of a main road and is, therefore, easily accessible during experimental campaigns.

The Transmit Antenna

The HF CW signal is transmitted through a loaded folded dipole. This type of antenna is broad band which allows the transmitter frequency to be changed without retuning the antenna. It is about 30 m in length and adds considerably to the time necessary to set up the transmitter site. The antenna is raised in the centre on a 10 m mast into an “inverted-V” configuration with the ends raised about 2 m off the ground. Thus the major lobe of the antenna radiation pattern is in the vertical direction.

4.2.2 The Receiver

A twin channel receiver was also constructed for the project in order to receive both O- and X-mode signal components simultaneously. The high frequency stability required was provided in the same way as for the transmitter *i.e.* by employing the same type of reference oscillator. The receiver has narrow and wide band mode capability allowing versatility for future experiments. Since an unmodulated HF CW signal was employed for the experiment described in this thesis, only the narrow band ($\sim 15\text{ Hz}$) mode has been employed thus providing



Figure 4.1: The transmitter site at Seljelnes, Norway. The transmitter unit is housed in an unheated caravan. The centre of the HF antenna is raised into an inverted-V configuration by the mast at the right hand side of the caravan. The mountains behind the site prevent a ground wave from reaching the receiver which is situated 50 km north. A main road (just off the right side of the photograph) allows easy access to the site.

good noise and co-channel interference rejection. O-X mode signal discrimination is achieved by employing crossed dipole antennas (see later) and a 180° phase shifter. This gives the flexibility to receive O-, X- or linear mode signals on the two channels. Each receiver channel operates independently and so each may receive a different frequency or wave mode. A schematic of the main components of the receiver is given in figure 4.2. Note that the RF input in this figure represents the output from one channel of the O-X mode discriminator.

The radio frequency (RF) input signal is mixed with a local oscillator (LO) signal, which is derived from the reference oscillator, to produce one at the intermediate frequency (IF) of the receiver, i.e.

$$F_{LO} - F_{RF} = F_{IF}. \quad (4.1)$$

F_{LO} is selected by means of a thumbwheel on the front of the receiver unit and is greater than F_{IF} . The method of setting F_{LO} is described, in detail, by Wright (1996a). However, because the mixer can produce sum and difference frequencies then it is possible that an RF input signal frequency, F_{RF} , could be received such that

$$F_{RF} = F_{LO} + F_{IF}. \quad (4.2)$$

This is known as the “image” frequency and is unwanted as it would contaminate the intermediate frequency. Thus, at the RF stage (figure 4.2) the input is filtered to remove the image frequency. In this receiver the filter range is 2.5 - 5.75 MHz which is adequate for the present experiment.

The received signal amplitude is very variable due to ionospheric fading and absorption. The dynamic range of the 12 bit analogue to digital converter (ADC) is about 40 dB and is smaller than that of the receiver. Therefore, to enable adequate ‘tracking’ of the signal amplitude the design of a suitable Automatic Gain Controller (AGC) was necessary. Each receiver channel has a programmable attenuator which is controlled by the PC. The AGC takes the form of a dedicated software routine (see section 4.3.2). The parallel printer port was utilised to link the AGC to the receiver instead of buying a digital I/O card, resulting in a considerable financial saving. A series of TTL (Transistor-Transistor Logic) lines from this port connect the PC to the receiver attenuators. The sampled signal amplitude is monitored by the control computer and if the signal level increases outside the range of the ADC, an attenuator is switched in by setting one of the parallel lines high. The opposite occurs where the signal level falls.

In the IF stage (see figure 4.2) the output of the mixer is filtered to remove interfering signals at frequencies near to the IF. The receiver was designed with an

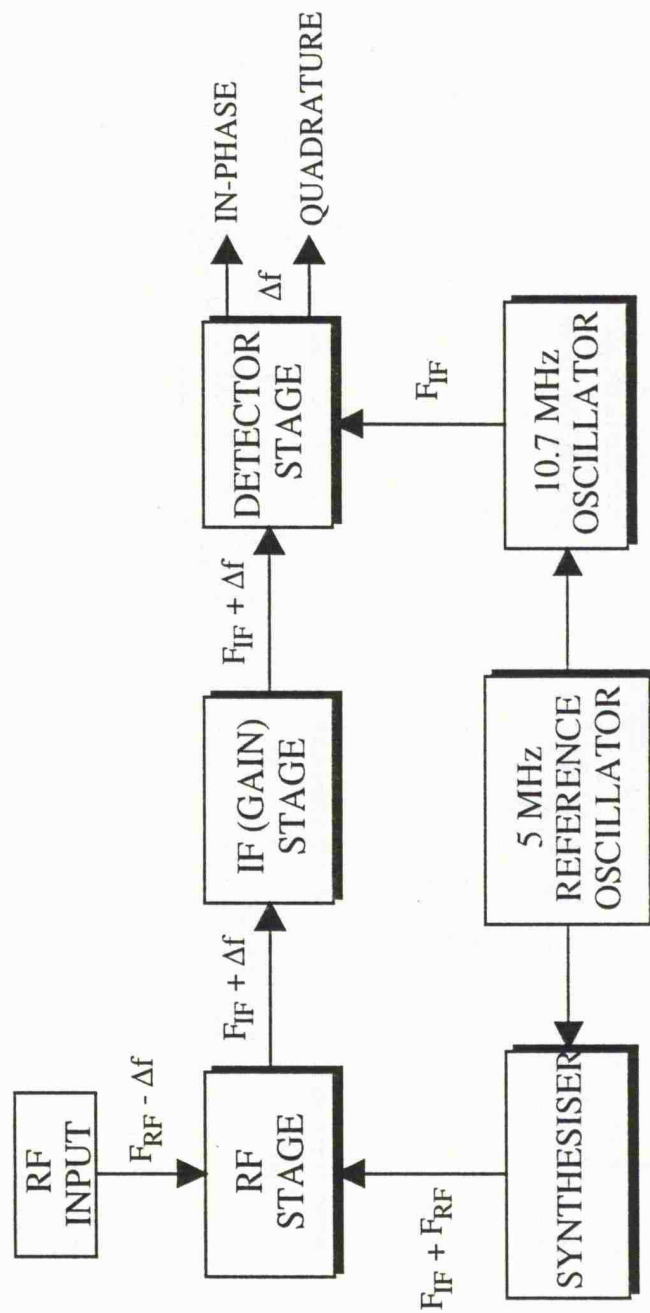


Figure 4.2: The various stages of one channel of the Doppler receiver. The radio frequency input is provided by the output of the O-X mode discriminator unit.

IF of 10.7 MHz and the attenuators are incorporated at this stage. The filtered signal is amplified and then attenuated, as appropriate, by the AGC.

Finally, the signal is passed into the detector stage where it is mixed with a 10.7 MHz reference which is phase locked to the 5 MHz reference in the receiver. This results in a signal oscillating at a few Hz which represents the Doppler shift plus an arbitrary offset (which may be introduced at the transmitter or receiver as a means of identifying the ionospherically reflected wave). The receiver output takes the form of the in-phase (real) and quadrature (imaginary) parts of the signal which allow the direction of the Doppler shift to be determined. Filters on the receiver output prevent signal aliasing outside the 0-15 Hz range. The output in-phase (I) and quadrature (Q) signals have a frequency Δf *i.e.* the shift frequency of the input RF wave, which is digitally sampled by the ADC and the samples stored by the PC. Subsequent data analysis determines Δf .

The Receiver Antennas

The ionospherically reflected HF signal is received on a pair of crossed (*i.e.* perpendicular) active dipole antennas. They are “active” as they require power in order to operate. This is provided by a 12 volt supply unit in the receiver rack. The two signals from these dipoles, when fed into the discriminator, permit the O- and X-mode components (section 3.2.1) of the wave to be resolved. As this type of antenna is reactive they utilise an impedance matching unit so that the output has a 50 Ω impedance suitable for input to the receiver. Consequently the active antennas act like standard dipoles with a very similar signal to noise ratio. They are raised about 3 m off the ground and the received power comes mainly from vertically above. The impedance matching unit contains an amplifier so the signal strength increases by a few decibels. However, the effective aperture of an active antenna, which are only about 2 m in length, is smaller than that of a long dipole. So this is compensated, in part, by the signal gain produced by the matching units.

As a result, active dipoles are also broad band HF antennas. They offer the considerable advantage that they are small in size and fast to construct and erect. This is in contrast to standard dipoles which would have to be tens of metres long in order to do an equivalent task. In order to discriminate between the two wave modes, however, proper phase matching must exist between the two signals. Hence, the coaxial feeder cables, from each active dipole and the RF input, must be identical in length.

4.2.3 The Data Logging Hardware

A 486-DX PC was utilised to control the receiver attenuation and data sampling during this experiment. A PC has the advantage that it is commercially available, relatively cheap and allows the flexibility for easy hardware and software modification. It operates under the QNX operating system which will be discussed in section 4.3.1. All control software is written in the 'C' programming language or shell-script. Figure 4.3 is a photograph of the Doppler receiver set up. It consists of the twin channel HF receiver with power unit, the control PC and an Uninterruptible Power Supply (UPS).

A 16-channel, 12 bit ADC card is installed in the PC. Four of these ADC channels sample the I (real) and Q (imaginary) outputs from the two receiver channels. The parallel printer port, LPT, was physically modified and is configured to send and accept signals from the receiver (see section 4.3.2). A DDS1/2 Digital Audio Tape (DAT) drive unit acts as a data storage device. The benefits of this are that, firstly, a software driver was supplied with the operating system, thereby simplifying software design and that, secondly, at the sampling rate employed a single DAT can store at least one month of data. These tapes are mailed to Leicester, monthly, by technical staff working in the Heating building at the EISCAT site. The receiver part of DOPE is illustrated schematically in figure 4.4, where sampling, attenuation control and data handling are all centralised to the PC.

The file structure of the QNX operating system is sensitive to power failures (section 4.3.2). If a file is open when power loss occurs then the file structure will be corrupted when the power returns. Therefore, should this happen whilst the system is running unattended then operation would be lost from that point on. To overcome this problem an Uninterruptible Power Supply (UPS) was connected to the PC. A special electronic circuit was designed so that the PC can detect when a mains failure has occurred. The UPS maintains power to the PC for a few minutes more which is adequate time for a safe software shutdown.

Whereas the transmitter and receiver could operate over large extremes of temperature [Chapman (1996)], such as those in the Arctic winter, the PC system is not as versatile. This part of the hardware has to be run in an environment at room temperature in order that the PC and DAT drive operate reliably and to prevent the damaging effects of condensation build up on the PC hard disk and DAT drive heads. The PC has an ethernet board installed and the computer is connected to the network of the Heating building at the EISCAT site in

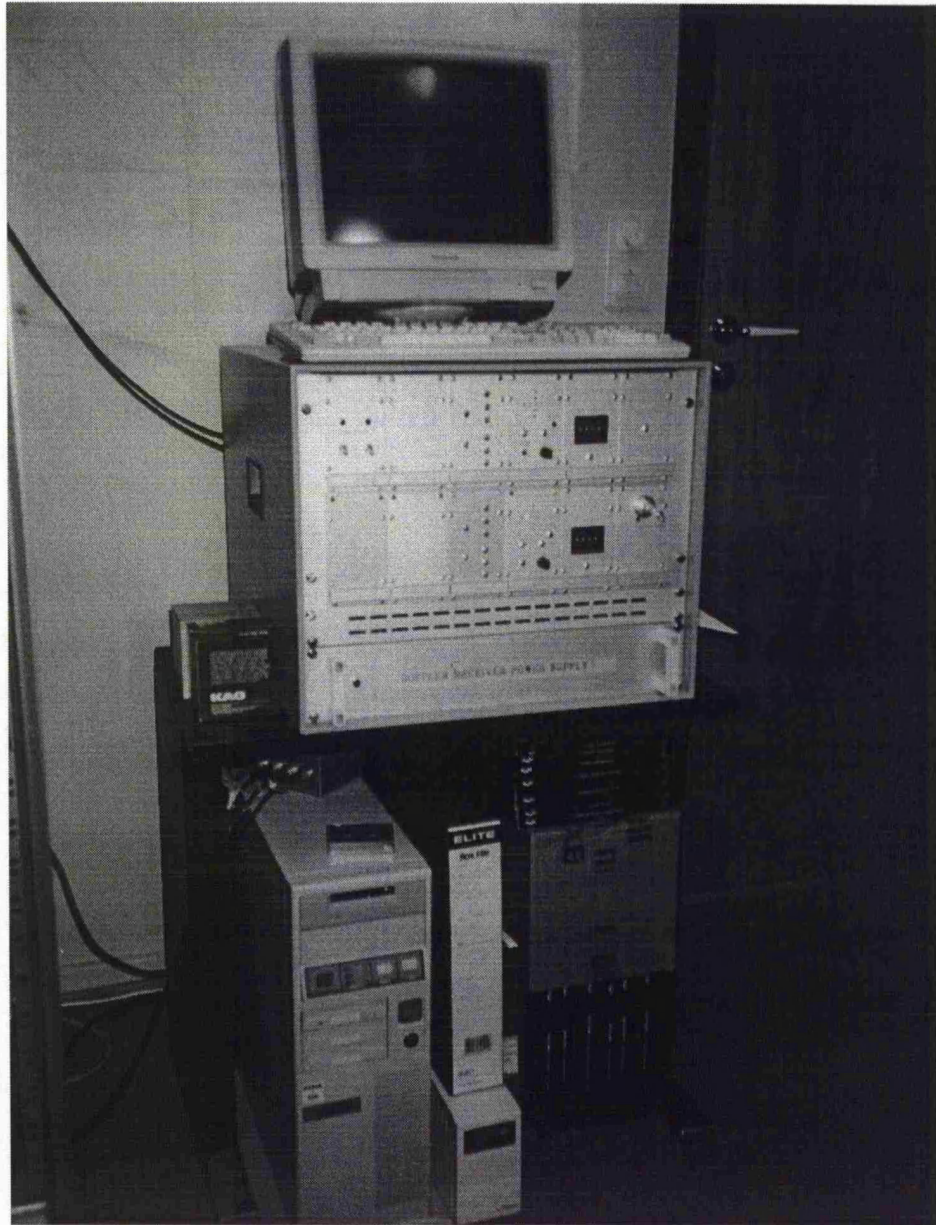


Figure 4.3: The Doppler sounder receiver system located in the Heating building at the EISCAT site in Ramfjordmoen, Norway. Pictured are the twin channel receiver and power unit (centre), the tower of the control PC (bottom) and the UPS supply (bottom, right). The PC monitor (top) provides, on request, the real time data display.

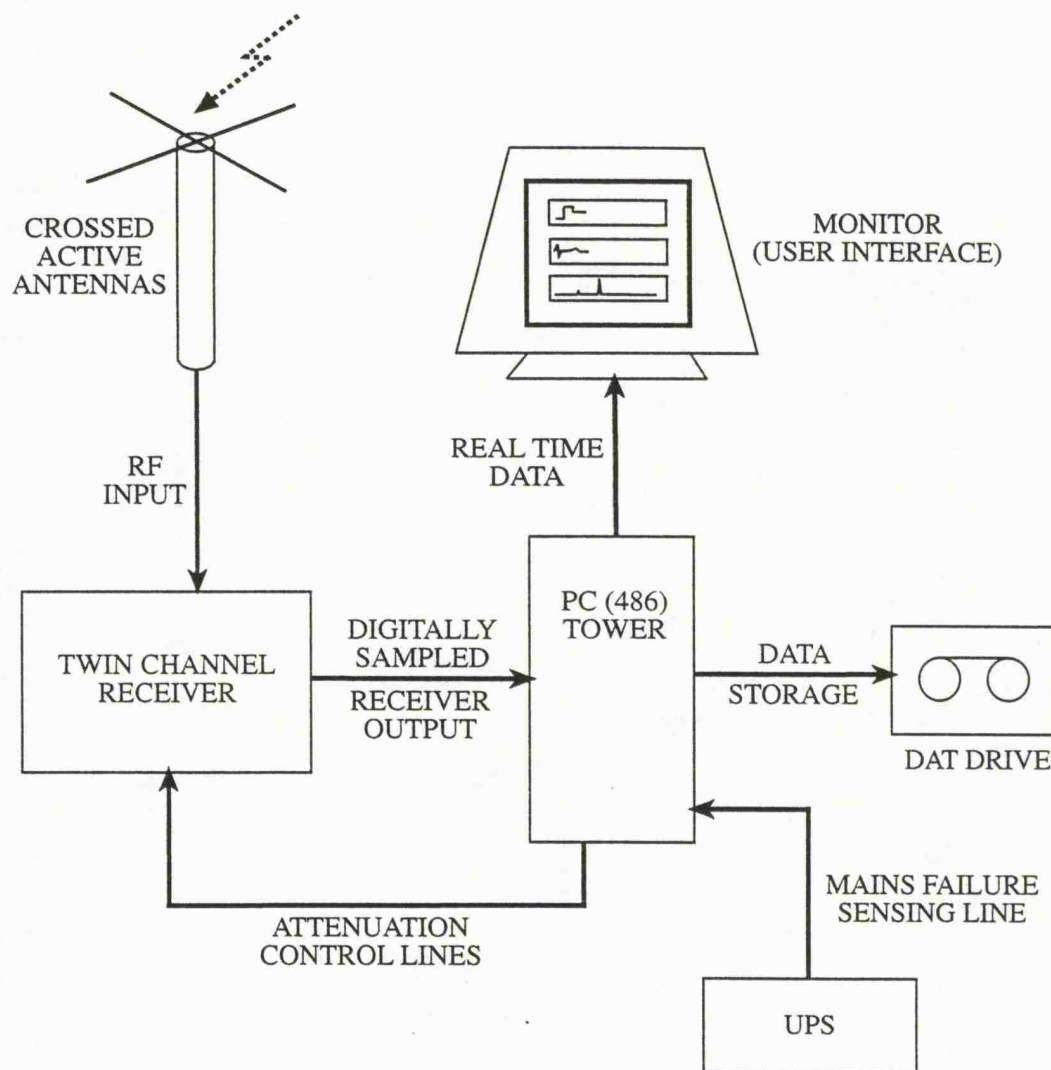


Figure 4.4: A schematic illustration of the Doppler receiver system including control PC, twin channel receiver, uninterruptible power supply and crossed active dipole antennas.

Ramfjordmoen. This makes it possible for software upgrades and minor system changes to be performed remotely when necessary.

4.3 The Control Software

Considerable effort was devoted to developing the software required to control the experiment, log the data and store it for further analysis. Programs were written in 'C' and QNX shell script to control the following aspects of the receiver system:-

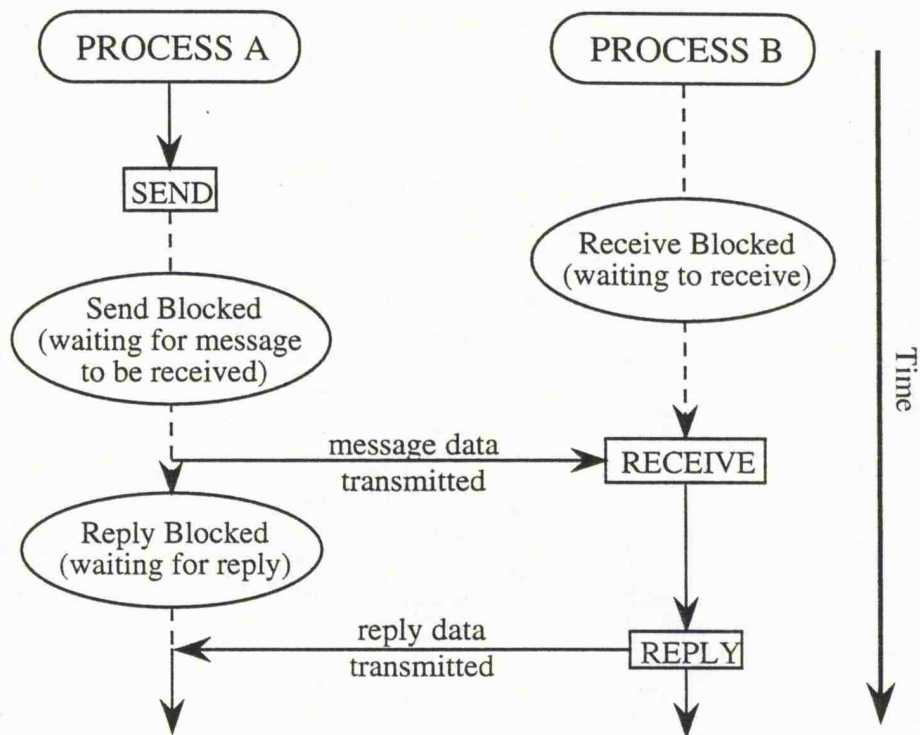
- data sampling
- receiver attenuation
- data storage
- a graphical user interface
- real time data display
- timing
- shutdown during power failures

As expected with a system of moderate complexity, there is a great deal of computer code so the details are not given here. However, relevant parts of it are now discussed. A modular approach has been adopted to maximise the expandability and versatility of the control software. A programmers guide to the system [Wright (1996b)] and a users guide [Wright (1996a)] contain detailed discussions of this software and are designed to facilitate the process of continuous system upgrade and development.

4.3.1 QNX and the 'C' Language

The QNX operating system has a number of features for real time operations which are exploited by the custom software and these are briefly reviewed here. It is a UNIX-like proprietary operating system for IBM compatible PC hardware [QNX Software Systems Ltd. (1995)], which provides a multi-tasking programming environment designed for use with real time control systems. A specialist feature of QNX is that it provides a simple and well structured way for independent processes to communicate with each other. This is known as interprocess communication (IPC). The two forms of IPC which were used at the programmers level are known as 'proxies' and 'messages' [QNX Software Systems Ltd. (1995)]. A 'proxy' is a simple signal triggered by one process and received by another one waiting for it. 'Messages' are however, more complex in that a process must reply to a message which it receives. Figure 4.5 illustrates this. Messages can also send information, such as an array variable, as part of the

(a) IPC via messages



(b) IPC via proxies. Process does not become blocked.

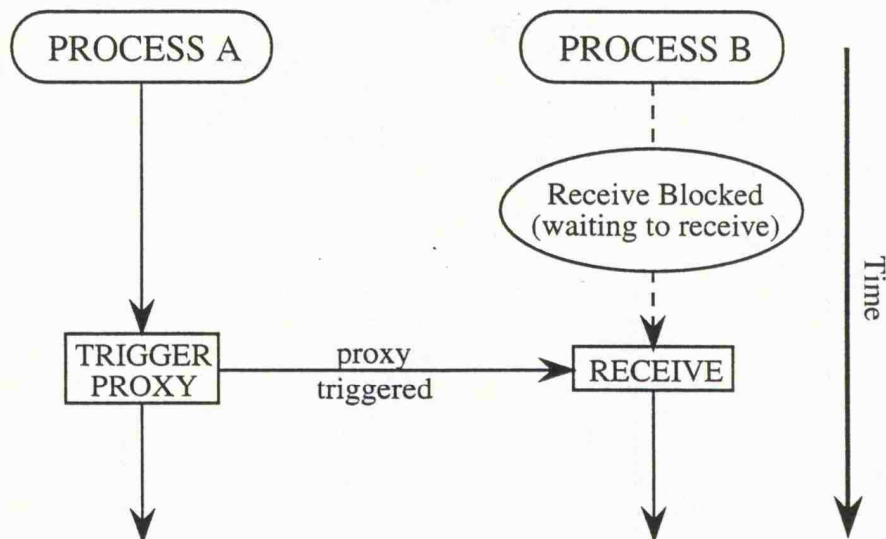


Figure 4.5: Methods of interprocess communication under the QNX operating system. (a) messages and (b) proxies are illustrated.

transfer. Passing proxies does not leave the triggering process blocked, unlike IPC messages where the sending process has to wait for a reply, and hence proxies are useful for sampling processes where it would be undesirable for a reply-blocked delay to occur.

The 'C' language is powerful in that it can link high level processes such as file structure maintenance and fast data manipulation with low level commands such as communicating with hardware via I/O ports in the PC. It, can be used to execute commands in the shell - the QNX work area - or to run these commands in a shell script file. This is a language which is interpreted by the shell itself. Finally, programs written in 'C' have the potential to be well structured and easily documented. They are also portable and may be installed with little difficulty onto other PCs.

4.3.2 The Software

Because the PC is required to control an external electrical device (the receiver) much of the software required low level programming. That is, it has to communicate with the internal hardware of the PC. This is achieved through the use of signal lines known as "interrupts" which are employed by PCs for basic interchange between electronic components. They operate, in keeping with digital electronics at TTL levels. Externally driven pulses can be detected by system software if they are fed into the PC through an interrupt. However, because PC hardware is very sensitive to interrupt signals, they must be properly managed and consequently interrupt handlers must be employed to control the signals which are sent from the receiver into the PC. The data sampling and timing routines both employ interrupts. In addition, a further low level task which the software is required to perform is the programming of the analogue to digital converter (ADC). The ADC card installed into the PC is the PC-26AT model manufactured by Amplicon which has a programmable sample rate. The square wave output of a TTL clock chip on this board drives an interrupt line which triggers the sampling by the PC of the receiver output levels. Table 4.1 lists the major 'C' source files, and some of the functions, specifically written for this system which will now be discussed.

In total, when the system is fully operational, there are four independent processes running on the control PC (figure 4.6). These are the Graphical User Interface (GUI), the sampling process and processes which take care of the bulk data handling and archiving of data files to DAT storage. IPCs are sent between processes and a section of the PC's memory is allocated as shareable. It is this

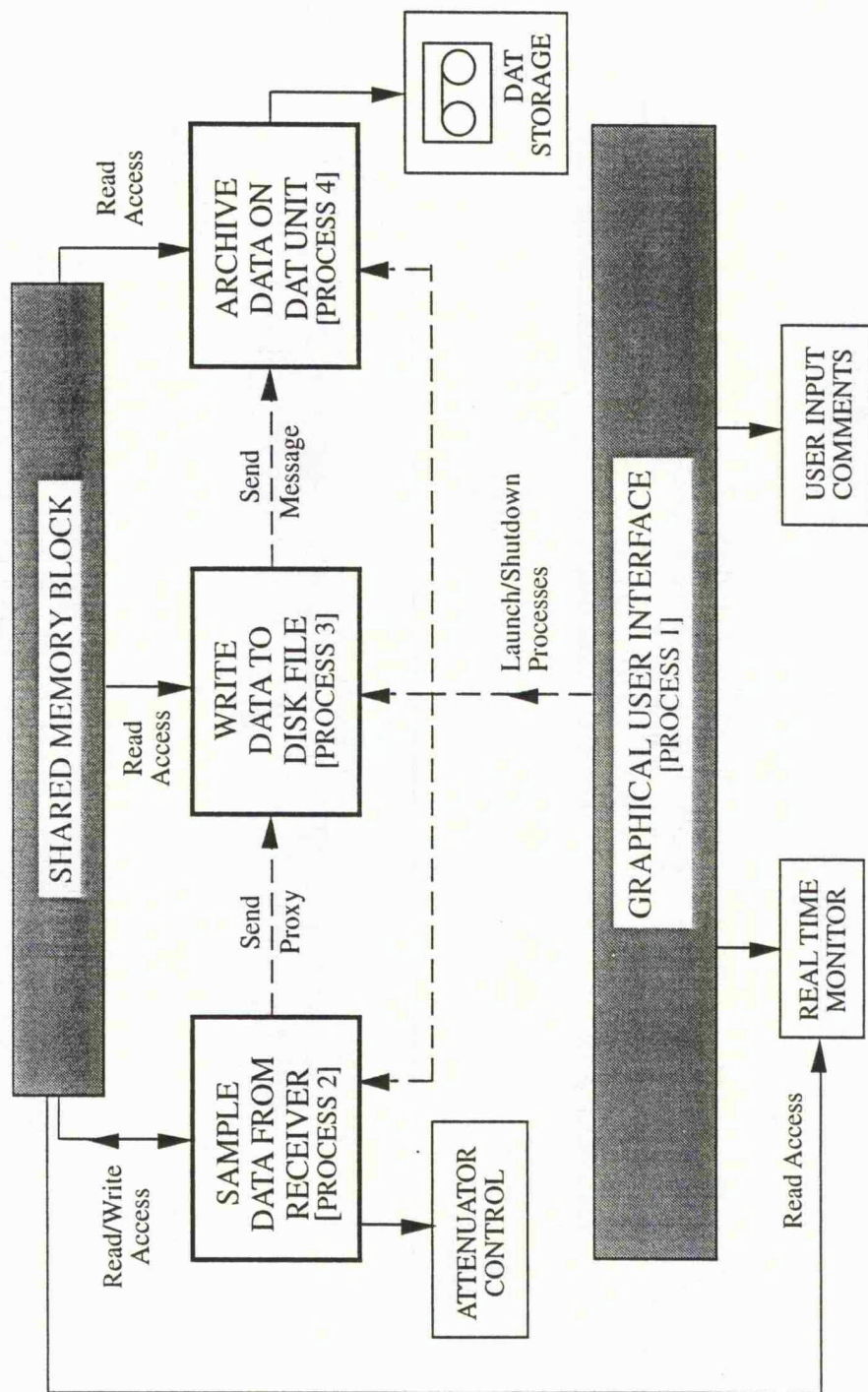


Figure 4.6: The software process interactions and intercommunications which occur on the Doppler receiver control PC.

aspect which most clearly illustrates the advantages of employing multi-tasking operating systems for control purposes.

SOFTWARE TOPIC	SOURCE CODE NAME	MAIN FUNCTION NAME
Data Sampling	digi_samp1.c digi_samp2.c	main()* intscanad()
Signal Attenuation Control	rx_atten.c	gain_test()
Data Handling	digi_dhand.c	data2file()
Data Archiving	digi_dat.c	main()*
Graphical User Interface	front.c commnt.c	main()* comm_scrn()
Real Time Display	fftcall.c fft.c cosbel.c mplot.c mplot1.c	rtm_mon()
Timing	dmw_dopp_clock.c	main()*

* several main() routines due to multiple independent processes.

Table 4.1: An overview of the 'C' software code

Data Sampling

The chips on the ADC card, installed inside the PC, have to be preprogrammed before conversions and sampling may commence. The ADC board provides an 82C55 Programmable Peripheral Interface (PPI) and an 82C53 Programmable Interval Timer (PIT). The PPI is simply a data bus from which the sampled data are read, once a conversion is complete. The ADC board can be programmed via the PPI. A control word sent to the PPI configures it so that two ports on it are used to supply the data to the PC and a third port is used to change the channel which is read by the ADC. There are 16 of these channels onto which an analogue signal may be passed so that it can be digitised. They may only be read one at a time and so a multiplexer is used to switch between them. However, it should be noted that the multiplexer has a finite settling time before that channel may be accessed. A software delay of the order of 60-70 microseconds is created to allow for this. There are four channels of the ADC in use. These are for the in-phase and quadrature outputs of the two receiver channels. They are sampled at a rate determined by the PIT.

The PIT consists of a 1 MHz square wave oscillator which is divided down by three counters. These counters are set by the software when the ADC board is initialised. The present system is set to sample at 40 Hz and this fact is hard wired into the software. This is adequate to sample the receiver output, which is filtered to give a 10 Hz (at the 3 dB point) baseband, without aliasing of the data. The ADC card itself was physically modified such that the output of the PIT was connected directly to the interrupt line in the PC. In this way, an interrupt is sent into the system whenever a rising edge of the 40 Hz square wave occurs. The sampling process senses the interrupt and subsequently takes data from the ADC which was also triggered by the PIT.

An interrupt handler is essentially a piece of code which is linked to a given interrupt line. When an interrupt signal is received on that line then the handler instructions are executed. These cannot, however, be complex high level functions. The handler controlling data sampling simply “kicks” an IPC proxy. The proxy is received by Process Two and the important code (`intscanad()`) is then executed. A series of digitised samples are taken from the four channels and stored in shared memory along with receiver gain information. Once complete, the cycle resets itself and waits for the next proxy to be triggered.

The shared memory allocation created by this process means that the other processes, such as the data handler and the real time display routine, can access the data without disturbing the sampling process itself. The memory is in the form of two buffers. Whilst one buffer is filled with data by the sampling process the other one is accessed by Process Three (when called upon to do so) which writes this buffer to disk file. Again, this is an attempt to allow the sampling process to run undisturbed.

The received signal strength is tested in this process by calling the `gain_test()` function after the samples are taken. Receiver attenuation may then change as described in the next section.

Receiver Attenuation Control

The variability of the HF signal amplitude necessitated the design of an AGC to avoid overloading the receiver. A 12 bit ADC such as the one utilised in this system has a dynamic range of about 40 dB. So in order to make use of the full effective dynamic range of the receiver controlled attenuators which track the signal amplitude are employed.

Each time data are sampled the signal amplitudes are tested in the `gain_test()` function. The receiver attenuation is decreased or increased if, respectively, the signal level has fallen towards the noise level of the ADC or is in danger of saturating the ADC. The attenuators are switched by sending signals down ten parallel lines from the PC's parallel printer port (LPT1). In the source file `rx_atten.c` a series of hexadecimal codes are listed. Sending these codes will cause switching and latching of appropriate attenuators. The switching sequence has been designed in order to optimise the signal to noise ratio (SNR) as attenuation increases. The initial motivation for reconfiguring the printer port was to avoid the expense of purchasing a digital input output (DIO) board. Although this type of board is designed for such a task, the present method is adequate. It has the disadvantage that a printer cannot be connected to the PC whilst the system is logging.

Data Storage

For rapid access by the sampling process, data are initially stored in the PC memory. This, as described earlier, is a twin buffer shareable memory block. The size of this block is limited only by the amount of available RAM (Random Access Memory) in the PC and may be adjusted in the software prior to compilation. Presently, each buffer holds an amount of data equivalent to half an hour of continuous sampling. Time information and a mains power supply indicator flag are also stored in RAM.

A large memory block has been chosen for two reasons. Firstly, handling and archiving large amounts of data is much more efficient, in terms of processor power, than moving each byte set as it is sampled. Secondly, it means that the real time monitor (see below) has access to and can display up to one hour of previously recorded data during the course of the experiments.

The sampling process keeps track of how full the memory buffers are and when one is filled it sends an IPC proxy signal to Process Three, the data handling process (see figure 4.6), which is simply waiting for this signal. As the buffers switch and newly sampled data are placed in the other buffer, the old one is accessed by the data handling process and the data are copied to a disk file. When this file contains two buffers of data (a one hour equivalent) it is then closed and a new one is opened, ready for the next transfer.

When a disk file is complete, Process Three sends an IPC message to Process Four indicating that data are ready to be transferred to a DAT unit. The message sent includes time information of the data in the file and a software status flag,

indicating whether this is a system shutdown or a standard file transfer. The disk file is renamed with time information and then archived to the DAT using the POSIX standard “tar” tape archive function. Two possible occurrences can modify these actions, firstly, system shutdown which will initiate procedures to write system log files to the DAT archive and secondly, a power cut which causes an additional warning message to be written. This method of data storage has the additional advantage that data files are portable and easily extracted by other machines.

The Graphical User Interface

The first process to be run before any data logging commences is a specially written ‘front end’ graphical user interface (GUI) designed to make the system simple to operate, relatively secure and to make all complex processes invisible to the user. The GUI incorporates a screen saver which displays the current date, time and system status. A more detailed description of the GUI and the operation of the system can be found in the user manual [Wright (1996a)].

The GUI makes the whole Doppler system relatively easy to operate via an on-screen menu system and warning messages. Once it is running, an operator can stop data logging and restart it by only a few key presses. This is necessary whenever the DAT tape is changed. The shutdown and start up procedures are simple and the operator does not necessarily need to have any detailed knowledge of the system. Thus, an inexperienced operator can retrieve the data tapes and mail them to Leicester for analysis - at present, this is a member of EISCAT staff at Ramfjordmoen.

The main source file for the GUI is `front.c` (see Table 4.1). This code, when compiled and running, launches all the other application including shutdown and restart of data logging and the real time monitor (RTM). As will be discussed later, the GUI can detect when a power cut has occurred to the system. When this happens the GUI shuts down processes and maintains the system in a dormant state. This is a safety measure designed to protect the file structure of the PC in case the UPS fails (after a long power cut) and power is totally lost to the system.

When the GUI starts or stops the system logging, it does so by executing QNX shell scripts which are initiated by the standard ‘C’ function called “system”. This method means the processes launched are then kept independent of the GUI process. However, the RTM is part of the GUI itself and called using the `rtm_mon()` routine.

A menu is included in the GUI which allows the user to input various typed comments whilst the system is running. A simple but straightforward graphical text editor was written for this purpose. Any comments input are stored in a file and written to the DAT after the last data file before midnight of that day or at shutdown. This is a useful feature when the system is being operated on a campaign basis.

Lastly, the GUI modifies the QNX shell in which it runs so that it cannot be turned off without a specific password. This prevents an user from accidentally 'killing' the process or from modifying the source code. In addition, this front end is run as part of the PC's boot up profile. Hence, the software automatically runs when the machine is activated, a feature which is useful if a power cut occurs at a remote site. In case something should go wrong a menu option offers a forced, but safe, PC reboot.

Real Time Data Display

The real time monitor (RTM) is a feature of the system specifically designed to display the data as they are being logged. It runs when a user selects it from the main menu. When invoked, the user is prompted for input parameters such as the scales to place on axes. Three plots are then generated on the screen for either, but not both of the receiver channels (see figure 4.7).

The first two plots present the signal amplitude and frequency (Doppler) shift as a function of time (figure 4.7, upper and middle panels respectively). If it exists the previous half an hour of data will be displayed along with the up to date data which are continually added to the shared memory buffer presently in use. The third panel (figure 4.7, lower) contains the most recently recorded frequency spectrum of the sampled signal over a range of $\pm S/2$, where S is the data sampling rate, in Hz. The time resolution of these plots are, presently, one second for amplitude and 25.6 seconds (corresponding to a fast Fourier transform with 1024 data points) for the others. However, these can be changed by a simple modification of the source files and recompilation [Wright (1996b)].

The displayed information enables the user to monitor the progress of the experiment, in real time, through parameters such as the received signal strength, the amplitude fading rate, ionospheric activity such as wave signatures, and the external interference or noise environment. The frequency (Doppler) shift panel only works effectively when there is an acceptable signal to noise ratio. Only the peak amplitude of the spectrum is plotted in order to provide an uncluttered Doppler record (section 3.2.4; section 6.2.1; figure 6.2). If the signal appears as a

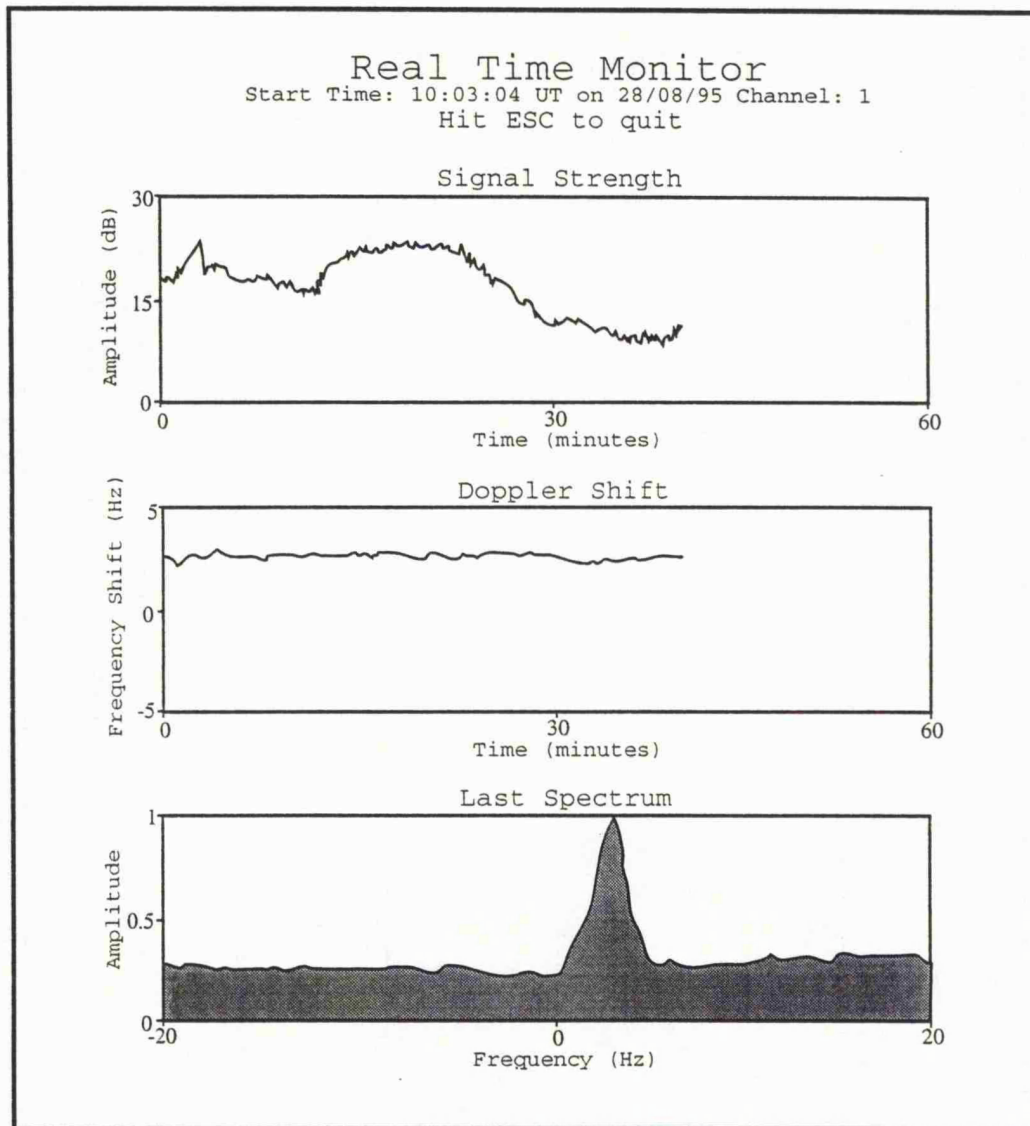


Figure 4.7: An example of the real time monitor display screen which is available to a user during an experiment. The panels illustrate the time evolution of the signal amplitude (dB) at 1 second resolution (upper panel), the frequency shift (Hz) of the peak spectral component updated every 25.6 seconds (middle) and the frequency spectrum of the last 25.6 seconds of data (lower).

sharp peak well above the noise floor then an accurate representation of the frequency shift with time will be displayed. However, the received signals are often noisy or have a broad spectral peak and must be interpreted with care.

Maintaining the Correct Time

Since the system is to be left unattended for long periods at remote sites it is important that an accurate time is kept by the system. This is not easy to achieve as many oscillators from which clock signals are derived tend to drift in frequency and hence the time will be inaccurate. If a system such as this is to make simultaneous measurements in conjunction with other instruments then they must be temporally synchronised. The periods of the wave signatures relevant to this study are typically of the order of 200 seconds. Thus, phase comparisons between signatures in Doppler data and in magnetometer data will only be reliable if the two data sets are accurate in time to within about one second of each other. The internal clocks of PCs drift in time to an extent of the order of a minute per month so the time may become very inaccurate over a long period.

A clock for the Doppler system has been designed which is accurate and reliable based on a signal which is derived from the stable frequency reference inside the receiver and which is managed by a software procedure. This method was relatively simple and cost considerably less than other available alternatives such as the Global Positioning Satellite (GPS) system.

The receiver has a stable 5 MHz reference accurate to one part in 10^9 which is available since the PC is always collocated with the receiver. An 8 Hz TTL square wave signal is derived from the 5 MHz reference signal and fed, via a coaxial cable, directly to a pin on the ADC card which is connected to another of the PC's interrupt lines. Specially written software (`dmw_dopp_clock.c`) links a proxy to this interrupt which it kicks when a rising edge of the square wave is detected. On start up of the software it reads the time stored on the PC. A counter then keeps score of the number of proxies which it receives. Essentially, this is an accurate 8 Hz counter which works in the same manner as the way in which a proxy triggers the sampling process to collect data.

In this way the PC can accurately maintain relative time. However, the absolute time of the clock relies on an accurate input Universal Time (UT) when the system is first started. A major advantage of this method is that it can compensate for a power failure. The software clock updates the time on the PC clock every few minutes. Should a power failure occur, then the PC clock which is battery powered will not lead to significant drift in time provided that the power cut is not

more than a few hours. When power returns to the system the software clock remains dormant long enough for the receiver reference to warm up (20 minutes at most) and stabilise before reading the PC clock and starting to count again. The Doppler system time is found to drift by a negligible amount per month.

Coping With Power Failures

The system has been designed to run unattended and has the capability to cope with and recover from power cuts. During data logging there are several files open at any one time and a sudden loss of power to the PC would deprive it of the ability to close these files properly and in the case of the QNX operating system a corruption of the file structure would occur. Hence, when the PC rebooted after a power cut it would no longer operate reliably.

With this consideration in mind, an Uninterruptible Power Supply (UPS) was added to the system. When a mains failure occurs the UPS provides the PC with enough power so that it has time to close all necessary files. Following this the Doppler system, by means of the GUI, remains in a dormant “waiting” state. The PC itself can sense when the mains are present. So, if the power should return quickly, then the GUI simply restarts the logging process.

However, should the power cut be long enough then the UPS energy will completely drain at which point the PC will turn off. When mains are restored the UPS begins to recharge. When a sufficient amount of energy has been accumulated by the UPS then the PC will reactivate. The GUI and the logging software automatically restart (following a delay intended to allow the reference oscillator to warm up) and read a log file written at the previous shutdown. If the file indicates that the last shutdown was due to a power failure then the DAT is repositioned to the end of data, so that data are not overwritten, and a comment is written to the log file stating when the system restarted.

The UPS was modified to allow the software to sense whether the nominal mains are present. A switch in the UPS is activated at the loss of the mains power. It is linked, through an opto-isolator (transistor), to one of the parallel lines into the PC port, LPT1. This line is monitored by the software and when the TTL level changes, as happens during a power cut, then the system responds appropriately. An opto-isolator was necessary as there was a relative potential between the ground plates of the PC and UPS. Initial attempts to link the two directly, without an isolator, lead to a leakage current flowing into the PC which lead to contamination of the recorded data.

4.4 The Doppler Pulsation Experiment (DOPE)

4.4.1 Deployment of the Leicester Doppler Sounder

In the Doppler sounder part of DOPE, the transmitter and receiver are separated by about 50 km in order to receive only the signal which has been reflected by the ionosphere and to minimise the ground wave amplitude. The receiver is located in the Heating building on the EISCAT site at Ramfjordmoen, Norway, which is surrounded by high ground thus ensuring that the ground wave does not reach the receiver. The transmitter is located 50 km to the south in a town called Seljelnes and is kept in a caravan which is owned and maintained by the Leicester group. The system was deployed at this high latitude location (69.6° N) in order to sound the auroral ionosphere where the magnetic pulsations commonly have amplitudes greater than those detected at lower latitudes. Ionospheric models were employed to determine that a sounder operating frequency in the range 3.5-4.5 MHz would be optimum for conditions around sunspot minimum at Tromsø. Initially, a frequency of 4.45 MHz has been selected in order to maximise the sensitivity (see chapter 3) with which the sounder can detect small amplitude waves. This frequency can be changed as appropriate to the ambient conditions.

4.4.2 The European Incoherent Scatter Radar (EISCAT)

The EISCAT UHF (ultra high frequency) radar operates at around 933 MHz. It is an incoherent scatter radar, which means that it detects signals which are transmitted and returned to the ground after being scattered by ion acoustic waves in the ionosphere. The facility consists of three 32 m UHF dishes: one transmit-receive site at Tromsø and one each at Sodankylä, Finland and Kiruna, Sweden which are receive only. Thus tristatic measurements of ion flow velocity enables the $\mathbf{ExB}$ velocity vector in the F-region to be determined. The program written to run on EISCAT for this experiment is SP-UK-DOPE, a special program which is similar to the CP-1 common program. Both utilise an alternating code pulse scheme at low altitude (below 150 km) and a long pulse scheme at higher altitudes. A constant pointing direction allows measurements to be made with a high time resolution. SP-UK-DOPE has the flexibility to allow the experimenter to quickly change the interaction altitude of the radar, *i.e.* the height at which the tristatic flow velocity is measured. The interaction height can therefore be set to a position where the signal to noise ratio of the returned signals is high thus minimising the amount of post-integration necessary on the data. It is desirable to match the reflection height of the HF sounder wave with the interaction height of EISCAT (figure 4.8) so that any ULF wave effects are monitored at the same part

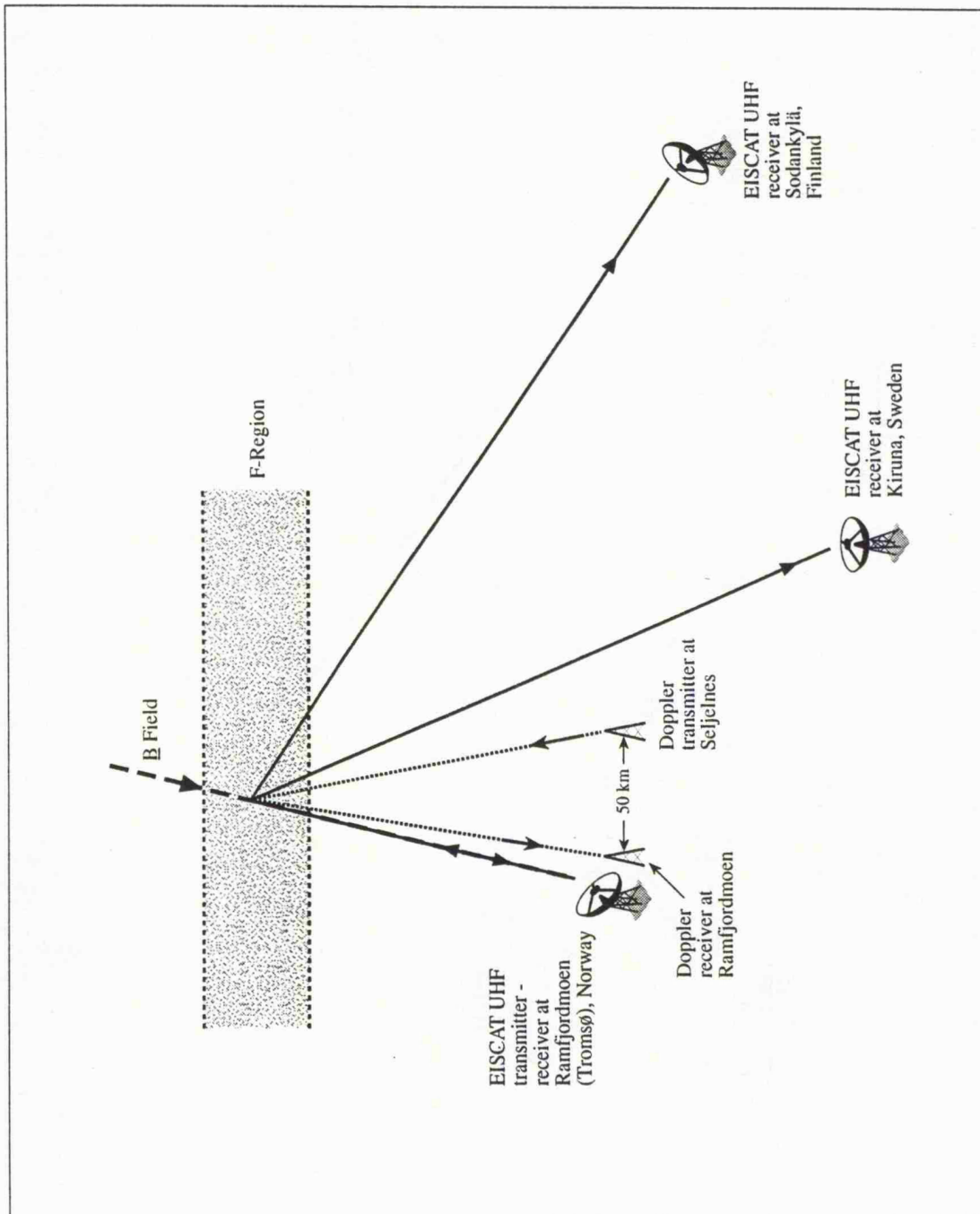


Figure 4.8: Schematic illustrating the layout of the DOPE experiment. The European Incoherent Scatter radar (EISCAT) is a tristatic radar and the Doppler system situated at Ramfjordmoen, Norway is a single frequency diagnostic. Magnetometers at Tromsø, in the vicinity of Ramfjordmoen, and Sodankylä, Finland, have provided data for this study.

of their vertical profile with both instruments. The height of the HF Doppler wave reflection point can be determined, in near real time, by either inverting a recent ionogram measured by the Dynasonde - a digital ionosonde - at Tromsø or by examining the electron density information of the local ionosphere provided by EISCAT power profile measurements. This latter method is now available via a limited access on-line real time World Wide Web page running on the EISCAT home page.

4.4.3 Ground Magnetometer Measurements

The ionospheric conductivity measurements made by EISCAT enable a detailed interpretation of the Doppler data to be undertaken in terms of the magnetic field and plasma variations of the ULF wave field (see chapter 2). The deduced ionospheric field variations can then be compared with ground-based magnetic field measurements from Tromsø (part of IMAGE as of January 1996), and from the IMAGE and SAMNET magnetometer arrays. Figure 4.9 illustrates the geographical locations of these instruments. Throughout this thesis two coordinate systems will be employed for magnetometer data. Recent data such as that from Tromsø (TRO), Norway and Sodankylä (SOD), Finland will be given in XYZ coordinates which represent, respectively, the north-south, east-west and vertical components in a right handed set. Some older data may occur with a HDZ coordinate system. These represent the magnitude of the horizontal field component (H), the angle between H and geomagnetic north *i.e.* declination (D) and the magnitude in the vertical direction (Z).

4.5 Summary

A complete and in depth description of the Doppler sounder system has been presented. This includes the hardware, software and the operation of the system. Its ability to run completely unattended in a remote environment is a major feature of this equipment. In addition to this the overall compactness and relative cheapness of the sounder means that it is a valuable diagnostic which can be reproduced and deployed at many sites. Modern advances in digital electronics and digital data storage along with the RF electronics expertise in the group have made this possible. The use of commercially available equipment, such as the PC and its peripherals, also affords the possibility of easy upgrade and repair to the system, even in relatively remote locations.

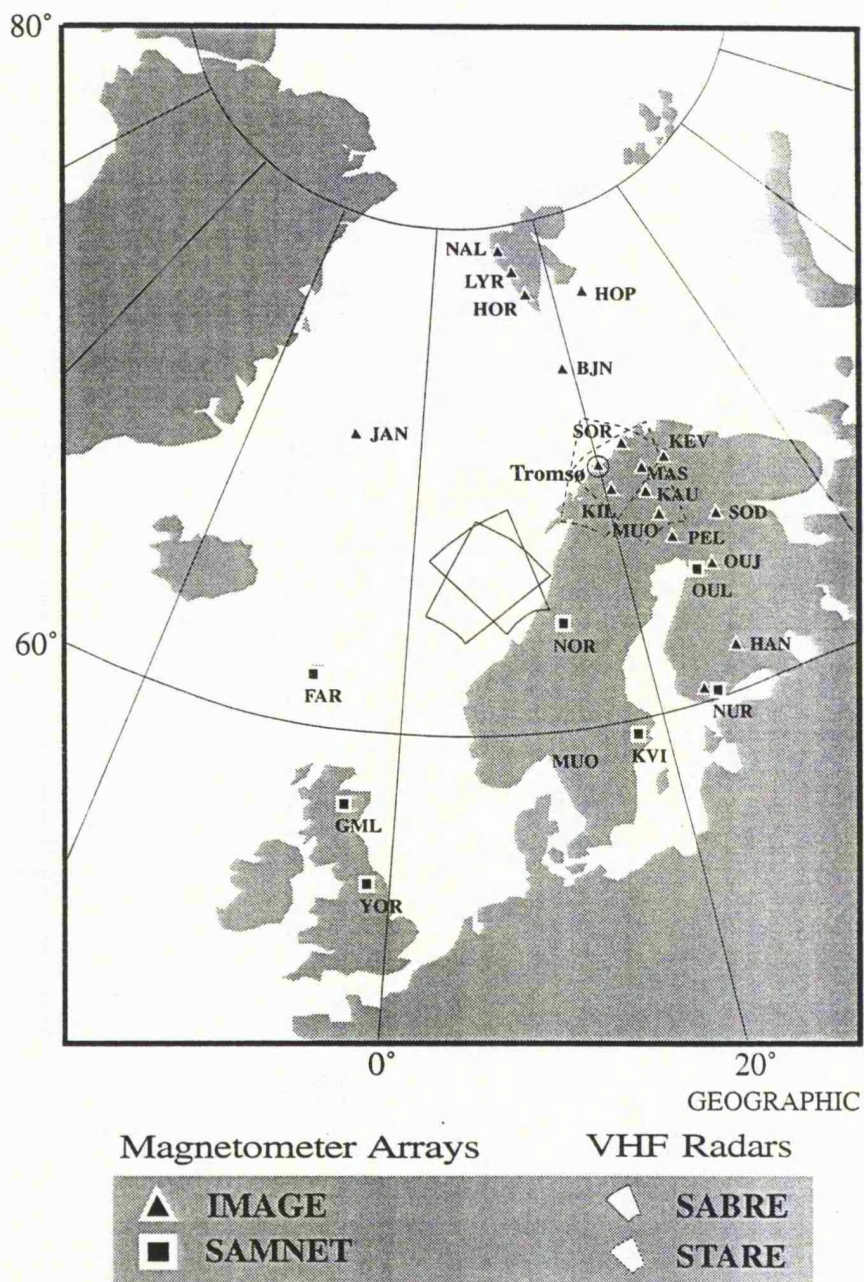


Figure 4.9: The geographic locations of the Sub-Auroral Magnetometer Network (SAMNET), the IMAGE magnetometer chain (formerly known as the EISCAT cross). Also, the Sweden and Britain Radar-auroral Experiment (SABRE) and the Scandinavian Twin Auroral Radar Experiment (STARE) VHF radar fields of view are included.

Chapter 4: The Development of a New HF Doppler Sounder

A series of innovative hardware and software measures have lead to a cost effective approach in the development of this system. In particular, the timing and receiver attenuation control were possible by means of small modifications to already existing hardware and the design of dedicated software.

Chapter 5

Statistics of ULF Wave Occurrence in a Doppler Sounder

5.1 Introduction

Between 1979 and 1984 a data set was obtained from a fixed frequency, continuous wave (CW) sounder situated in the vicinity of Tromsø, Norway (69.7°N, 19.2°E). The experimental arrangement was essentially an analogue version of the digitally controlled Doppler sounder described in chapter 4. However, it was deployed for studies of acoustic gravity wave propagation. The data from this experiment have been re-examined in order to identify ULF wave signatures and a statistical study of the local time occurrence of these waves undertaken. The results of this study are discussed in relation to other statistical studies of ULF wave occurrence obtained with a variety of space and ground based instrumentation.

The main motivation for this study was to establish the optimum configuration for the new high latitude experiment (DOPE) described in chapters 4 and 6. The results provided information on the likelihood that the experiment would observe pulsation effects at a given time of year for a given sounding frequency. The data also enabled the effects of sunspot number, geomagnetic activity and season on the efficiency of the Doppler system and on the intrinsic rate of pulsation occurrence to be examined. This information was important in the planning of the new experimental campaigns at Tromsø. The data set also allowed the investigation of ULF wave modes and sources provided by information derived from the data and a comparison was made with data from other experimental techniques.

5.2. Instrumentation and Data Acquisition and Selection

5.2.1 The Early Sounder in Tromsø, Norway

The data utilised in the study were recorded on a sounder transmitting a low power (20 Watts) HF continuous wave signal over a near vertical path. The signal frequency was fixed at 4.4 MHz prior to September 1979 and at 3.5 MHz after this time which provided a ray reflection point in the F-region ionosphere in both cases. A ground distance of about 50 km separated the transmitter and receiver. No discrimination of O- and X-mode waves was undertaken although it was

sometimes possible to distinguish the O-mode during times of high absorption when the X-mode signal was completely attenuated (see section 3.2.2).

In this instrument the received signal was mixed with a secondary signal at an intermediate frequency (IF) in the receiver (see chapter 3) until an audio tone (at less than 12 Hz), which represented the Doppler shift plus some arbitrary frequency offset, was obtained. This tone was recorded on a very slow moving analogue magnetic tape. When the tapes were returned to Leicester, UK, analogue records were reproduced on a paper roll by utilising a 'Rayspan' analogue frequency analyser [Robinson (1983)]. The output displayed the shift in frequency of the ionospherically reflected signal as a function of time. Time marks provided by a time code generator were also recorded on the tape. These appeared as marks every 10 minutes on the 'Rayspan' traces.

5.2.2 Event Selection

In total, 42 whole or partial months of data were available for study. This comprised all data in the interval 1979-84 which was available on paper records. Events were selected visually following the criteria laid out in table 5.1. The smallest waves which could be visually discerned on the paper records defined the lower wavelength limit. The upper limit for the wave period covers the longest periods of Pc5 waves (see section 2.2.1) which is smaller than the Brunt-Vaisala period which governs the low period cut off of about 20 minutes for the acoustic gravity waves [Georges (1967); Hines (1960)]. Thus atmospheric acoustic-gravity waves are excluded from this study. A good example of the type of event selected for the study is shown in figure 5.1. Note that on this figure time runs from right to left. This is due the way in which the frequency analyser printed the output. The figure illustrates the temporal variation of received signal frequency. An acoustic-gravity wave (AGW) [Hines (1960)] with period around 30 minutes is modulated with a shorter period ULF oscillation (about 2 minutes) commencing some time soon after 03:00 UT. This pulsation lies in the Pc4 period range.

5.2.3 Compiling the Statistical Data Set

Analogue records such as that in figure 5.1 were examined visually in 3 hour Universal Time (UT) sections. The intervals were categorised in one of three ways. Firstly they were either periods when a good signal was being received or periods when a poor signal was being received. A 'poor' signal is, here, defined as one where the signal had either penetrated the ionosphere, which would lead to a very low received signal amplitude, or was spread in frequency, most probably

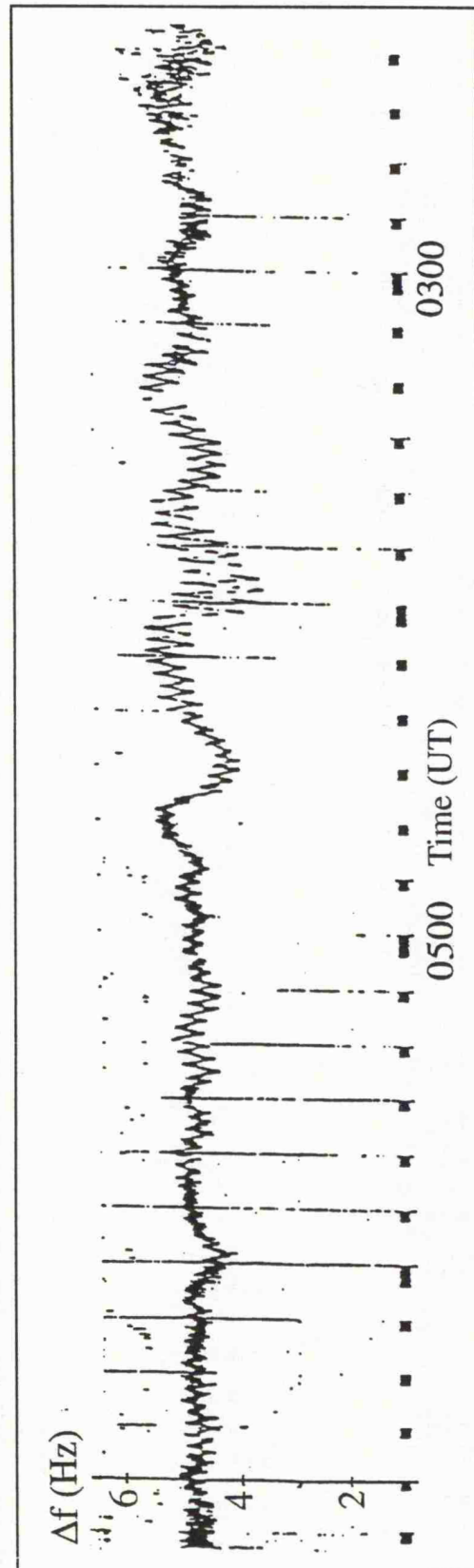


Figure 5.1: Typical example of a ULF wave signature in the analogue Doppler records from Tromsø between 1979 and 1984 [after Robinson and Jones (1980)].

Chapter 5: Statistics of ULF Wave Occurrence in a Doppler sounder

due to geomagnetic disturbance. A ‘good’ signal was one where a reasonably clear trace, resulting from a ray path with an ionospheric reflection, is apparent. It is necessary to make such a definition as no amplitude information was included on the original analogue paper records. The intervals with good signals have been further subdivided into two additional categories, depending on whether waves matching the criteria in table 5.1 were observed during each 3 hour interval. This method was applied only to times when the system was operating normally and not, say, when the transmitter had failed.

Parameter	Constraints
Wave Period	> 60 sec and < 1000 sec
Wave Amplitude (as frequency shift)	≥ 0.2 Hz (peak to peak)

Table 5.1: Event Selection Criteria.

A typical occurrence plot for the three categories of observation obtained from this data set is given in figure 5.2. This figure represents the total data set for this study and illustrates the relative occurrence of each of the three categories for each of the three hour UT bins. Each bin is scaled to 100% which refers to the total number of observations made for that bin value. The total number of days of observation for each UT bin is represented by the overlaid line.

5.3 Results of the Occurrence Statistics

The analysis has produced some interesting results regarding the diurnal, seasonal and solar cycle variations of ULF wave activity. In addition, the dependence of ULF wave occurrence on geomagnetic activity has also been investigated.

5.3.1 Diurnal Variation in ULF Wave Occurrence

Figure 5.3a is a typical monthly plot in the same format as that used for the total data set in figure 5.2. It presents data for October 1979 and is chosen due to its relatively high observation count - at least 20 days per bin out of a possible 31. Furthermore, it displays a very similar overall structure to the total data set (figure 5.2). This is, in general, representative of the whole data interval.

As expected there is a marked diurnal variation in the occurrence of useful observations, which cannot be obtained at night when the signals have penetrated the ionosphere. Figure 5.3b illustrates the relative occurrences of ‘good’ observations to all observations, henceforth to be known as ratio A, and is a

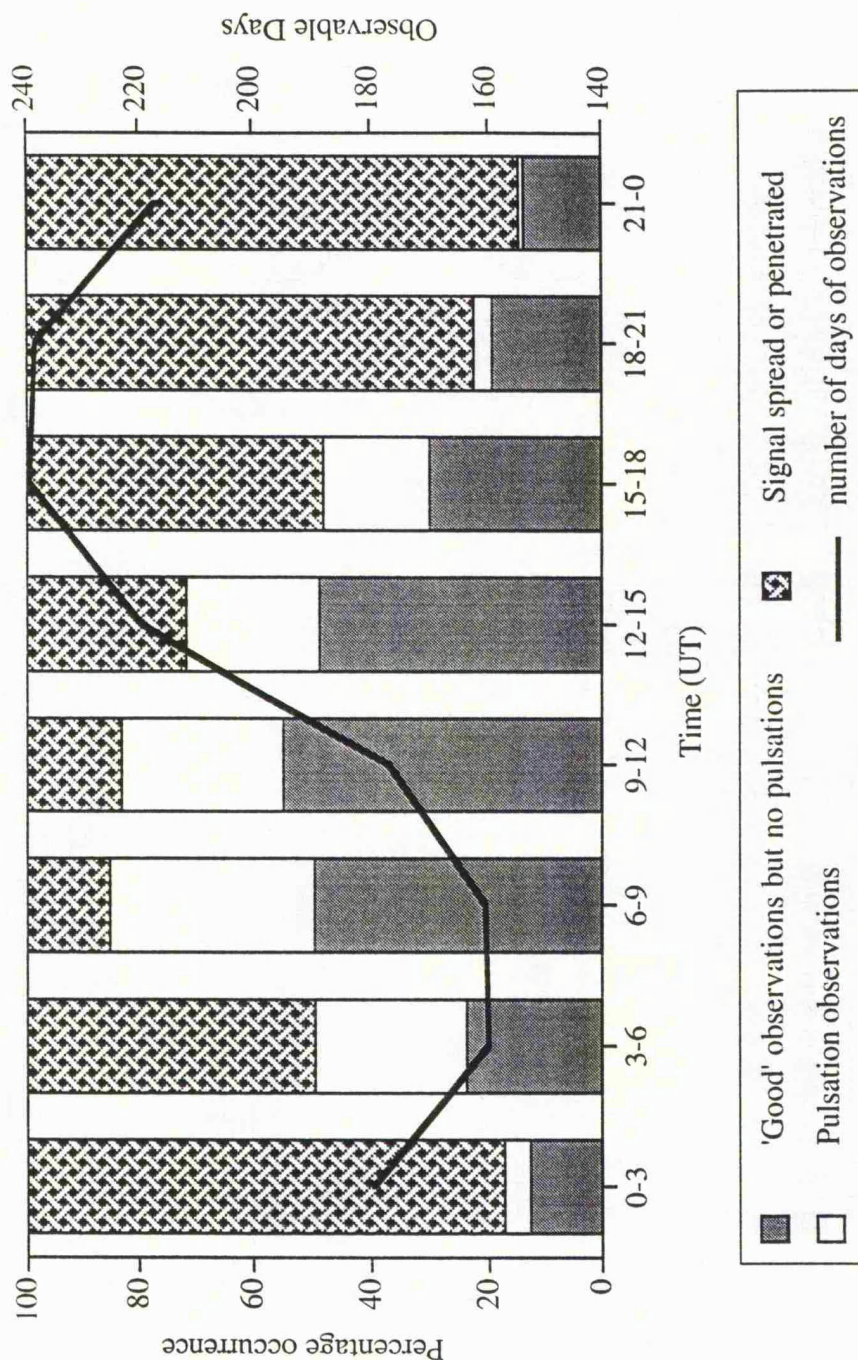


Figure 5.2: Occurrence distribution for the whole data set. Data include all available observations between January and December 1979-84.

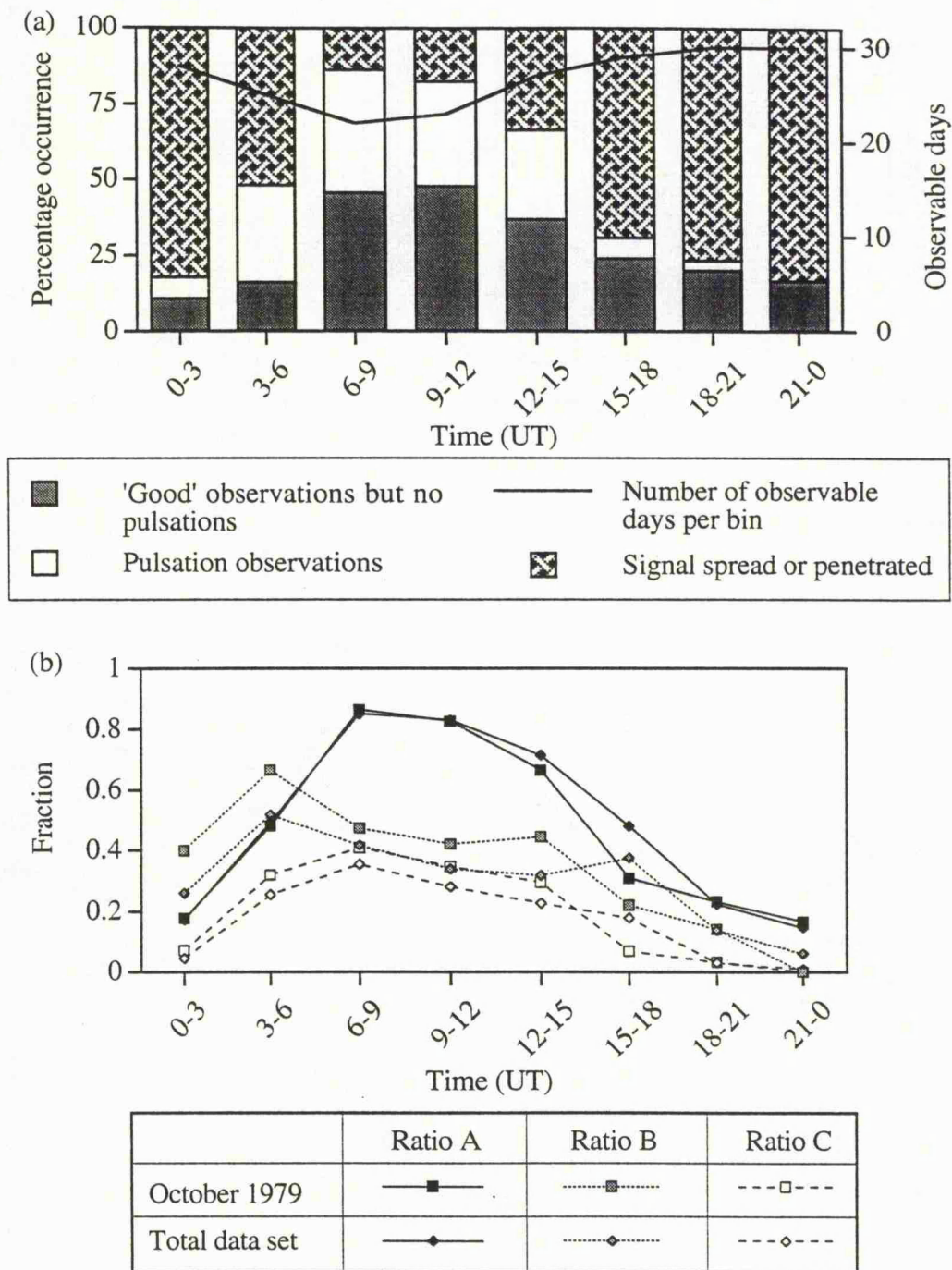


Figure 5.3: (a) Occurrence statistics for waves in the ULF band in October 1979 at Tromsø, Norway (upper panel). (b) The relative occurrence of 'good' to all signal observations (Ratio A), of pulsation to 'good' observations (Ratio B) and of pulsation to all observations (Ratio C) for October 1979 and for the total data set. Values are obtained from Figure 5.2 and Figure 5.3a.

Chapter 5: Statistics of ULF Wave Occurrence in a Doppler sounder

measure of the suitability of the ionosphere for Doppler studies at this frequency. The number of pulsations recorded out of all the ‘good’ observations is to be termed here ratio B, a measure of the intrinsic pulsation occurrence. Ratio C is that of the number of pulsations to all observations. This is a measure of the ‘effectiveness’ of the Doppler system for pulsation observation. These ratios are summarised in table 5.2 and displayed for the total data set and for the chosen example of October 1979. When examining the data in this form it must be remembered that the total data set represents the average picture over all months.

Ratio	Definition	Interpretation
A	The relative occurrence of ‘good’ observations to all the observations made (including intervals when the signal had penetrated)	The suitability of the ionosphere for Doppler studies.
B	The fraction of ‘good’ observations which were pulsations	The intrinsic occurrence of ULF waves
C	The ratio of pulsation occurrence to all observations made	The ‘effectiveness’ of the sounder for observing ULF waves.

Table 5.2: Definitions of the three ratios utilised in the statistical study and their interpretation in the context of the Doppler sounder.

Ratios A and B exhibit very different behaviour and are consistent for both the intervals under study. The form of ratio A is similar to that of the diurnal variation of foF2, the maximum frequency at which an O-mode signal can propagate, as illustrated in figure 5.4. Here, median foF2 values for October 1979 at Kiruna, Sweden (a high latitude Scandinavian station) are reproduced. However, Ratio B does not follow this pattern. In both cases, the ratio of the number of observed pulsation type events to the number of useful observations peaks in the 03-06 UT bin and tails off throughout the day with a secondary peak in the afternoon-dusk sector approaching zero in the 21-00 UT bin. The sensitivity of the Doppler diagnostic might be expected to modulate, to some extent, the form of ratio B because it may be insensitive to wave signatures at certain times of day (see section 3.2.4). The sensitivity of the diagnostic signal tends to maximise when the radio frequency approaches the critical frequency of the ionosphere. This is particularly the case for ULF wave signatures which tend to have smaller effects on the ionosphere than AGWs [Hines (1960)]. The value of ratio C in figure 5.3b represents the relative number of pulsation events in all observations per UT bin. It follows the same form, with lower amplitude, as that of ratio A.

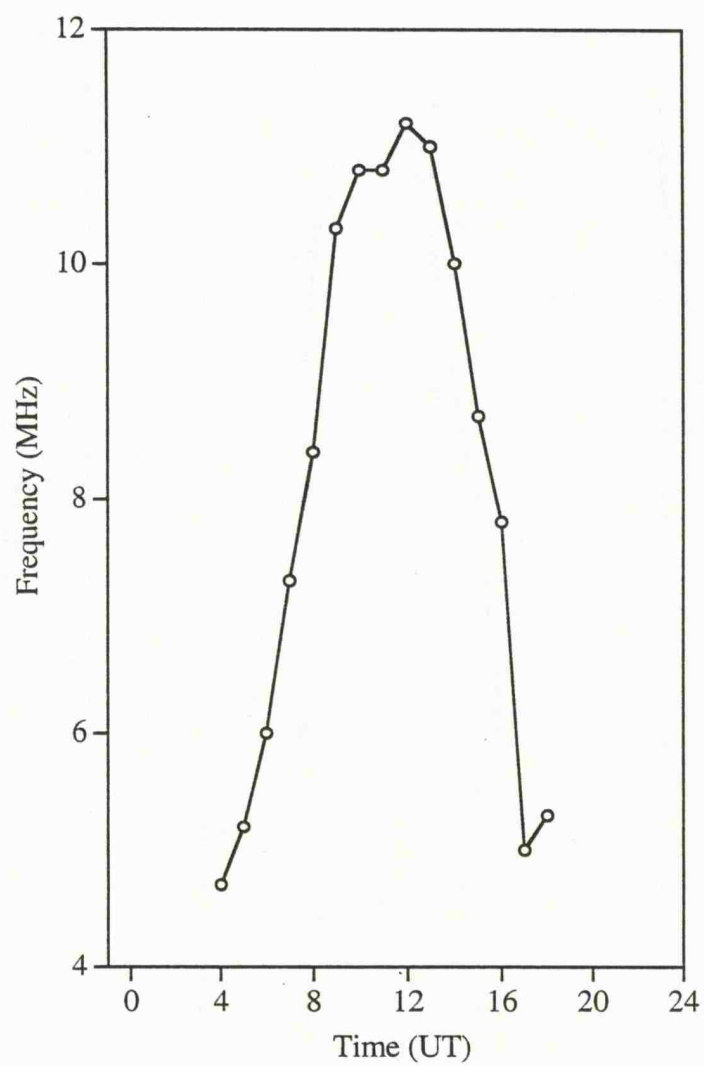


Figure 5.4: Median foF2 values from Kiruna, Sweden for October 1979. Data supplied by the World Data Centre, WDC-C1.

5.3.2 Seasonal Effects

In this section attention will be focused on the difference in results obtained during the solar equinoxes and the solstices. Figure 5.5 illustrates the occurrence of the selected wave events in the usual form. Table 5.3 indicates the months included in the four panels of figure 5.5. In each case data from the two months around the equinox or solstice for each year were selected if available.

The form of ratio A (figure 5.6) is similar for the equinoxes and winter, with a UT distribution for each which resembles that in figure 5.2. However, the form of ratio A around the summer solstice is broader. Figure 5.7 illustrates median foF2 values around the equinoxes and solstices at Sodankylä, Finland, which is at a similar latitude to Tromsø and were the only data available. Data for the summer solstice are considerably different to those in the other seasons, a fact which supports the suggestion in the previous section that ratio A is dependent on foF2.

Ratio B (figure 5.6) demonstrates that although the number of useful observations made in the summer (ratio A) is, averaged over all UT, the highest, pulsation occurrence is optimised at the equinoxes and ratio B peaks there. Ratio C is also displayed in figure 5.6. It gives an indication of the best season for the DOPE experiment operating at a similar frequency and suggests that the worst time for making useful measurements is in the summer.

Panel	Data Utilised to Compile Panel
Spring Equinox	7 months of March/April data
Summer Solstice	7 months of June/July data
Autumn Equinox	7 months of September/October data
Winter Solstice	8 months of December/January data

Table 5.3: Data from 1979-84 taken to compile the four panels of figure 5.5.

5.3.3 Variations Associated With Solar Cycle Effects

The occurrence plots also display features which can be linked to the Solar cycle. Figure 5.8 illustrates averaged distributions for two separate intervals in the 11 year cycle. For each panel four months of data from January to April are included. One panel is for 1980 and the other is for 1984. Figure 5.9 is a plot of the mean monthly sunspot number for the entire interval of 1979 - 84. This figure shows average values of sunspot number of around 160 for the 1980 interval and about 60 for the 1984 average.

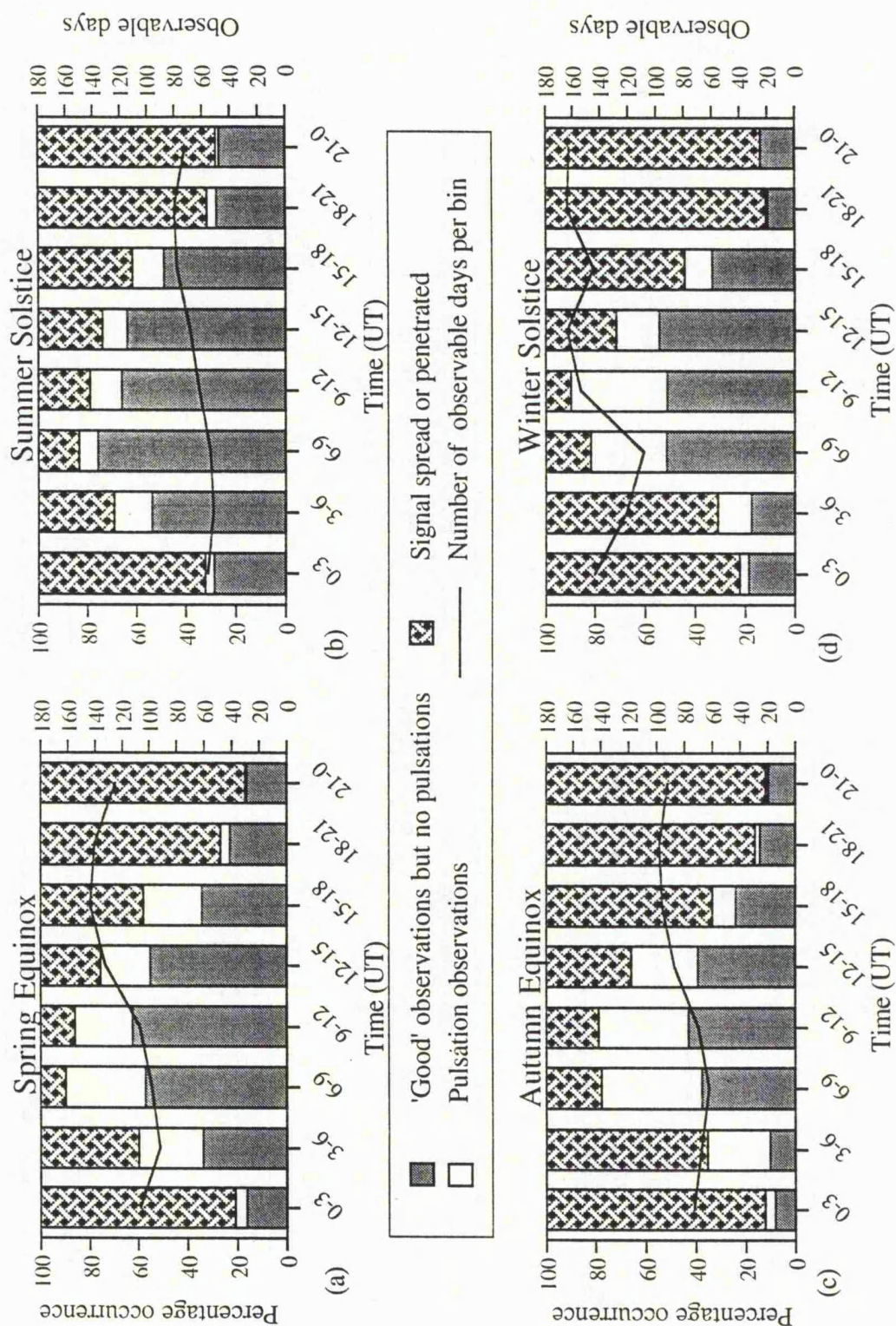


Figure 5.5: Pulsation occurrence plots illustrating the differences in distribution between the (a) Spring equinox, (b) Summer solstice, (c) Autumn equinox and (d) Winter solstice.

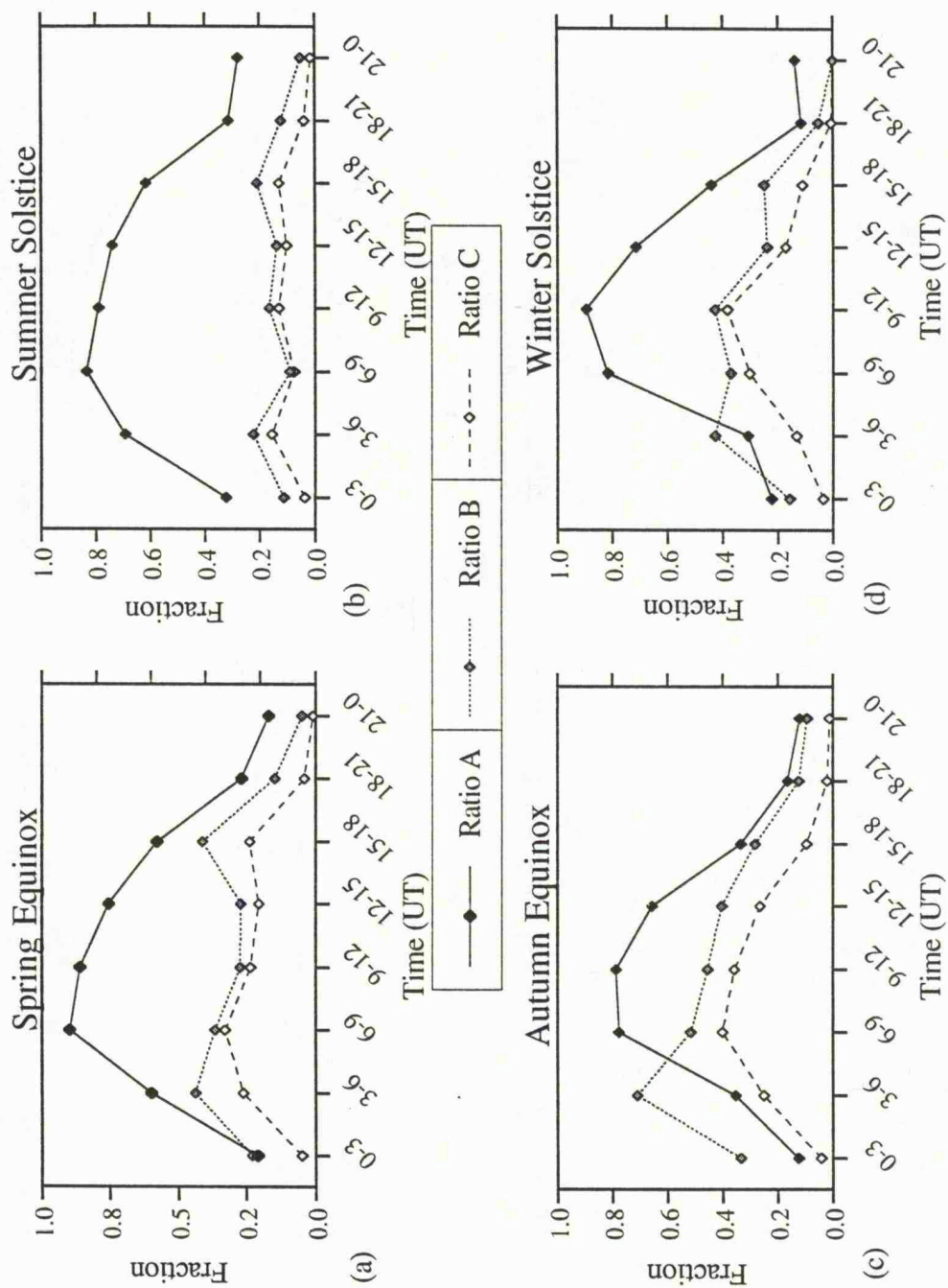


Figure 5.6: Diurnal relative occurrence of events observed at Tromsø around (a) Spring equinox, (b) Summer solstice, (c) Autumn equinox and (d) Winter solstice. Data were taken from Figure 5.5. The plot format is the same as that for figure 5.3b.

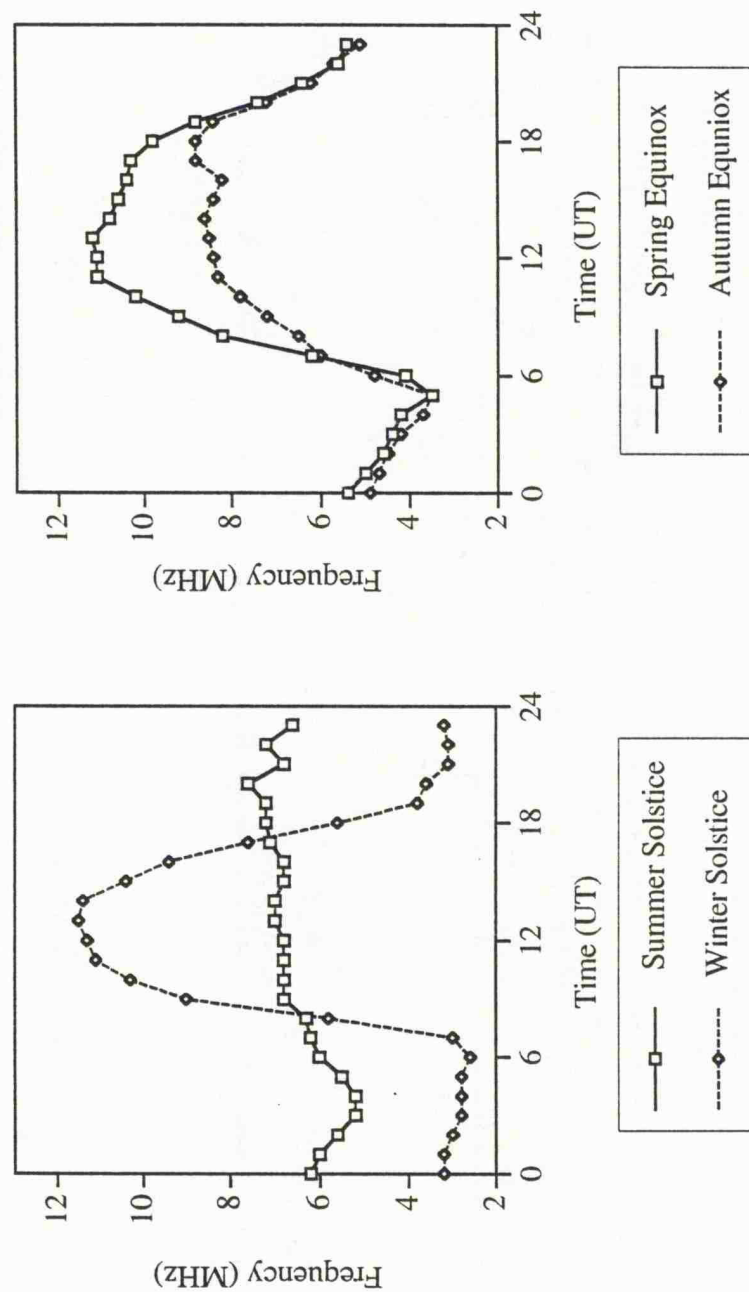


Figure 5.7: The diurnal variation of the ionospheric critical frequency (f_oF_2) typical of the data interval given in figure 5.5. The data are those recorded in 1982 at Sodankylä, Finland (67.4°N , 26.6°E) and were provided by the World Data Centre, WDC-C1.

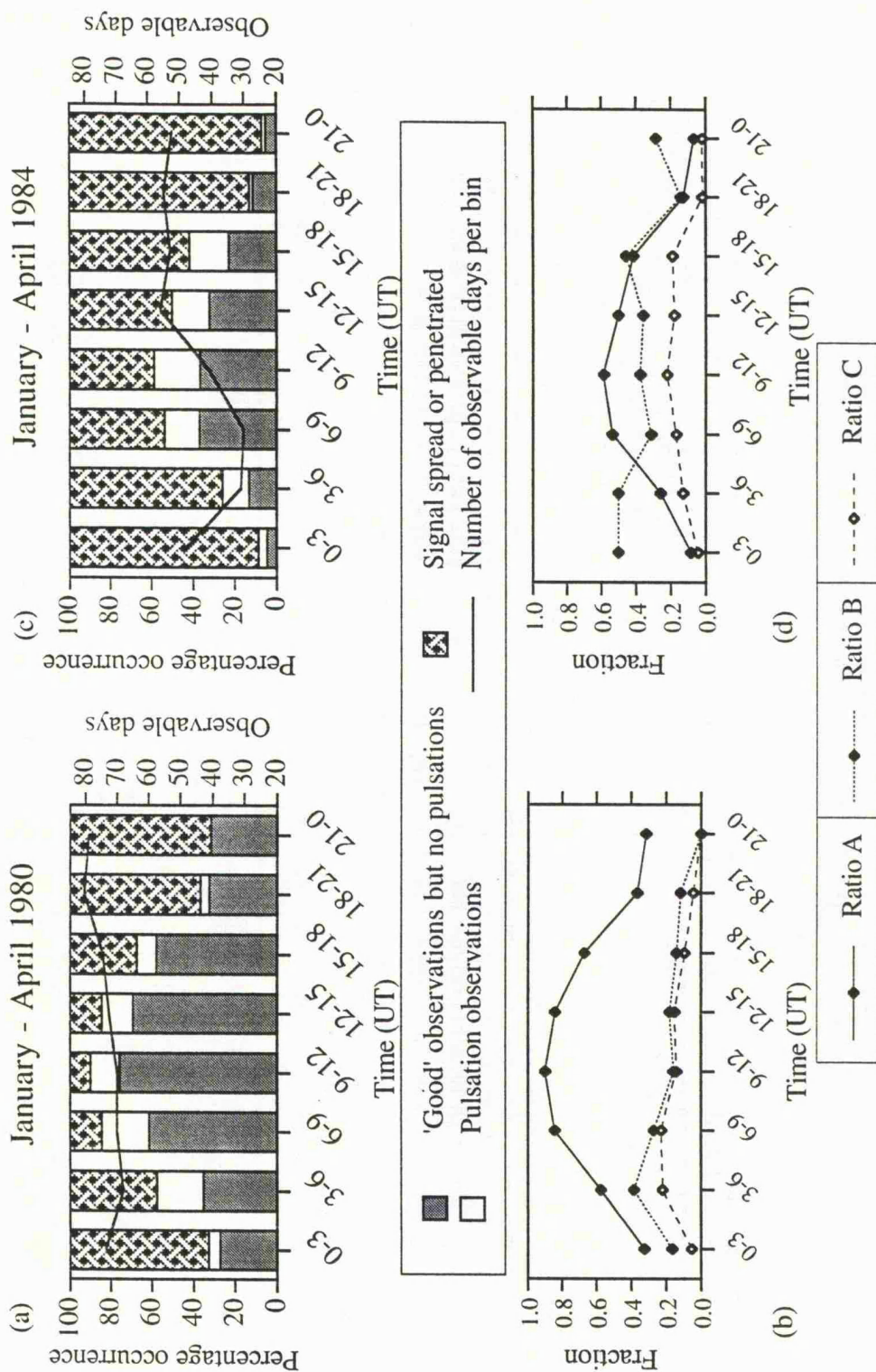


Figure 5.8: Pulsation occurrence plots for the intervals January-April 1980 (a,b) and January-April 1984 (c,d) where the sunspot numbers were 60 and 160 respectively. The format is the same as that for figures 5.5 and 5.6.

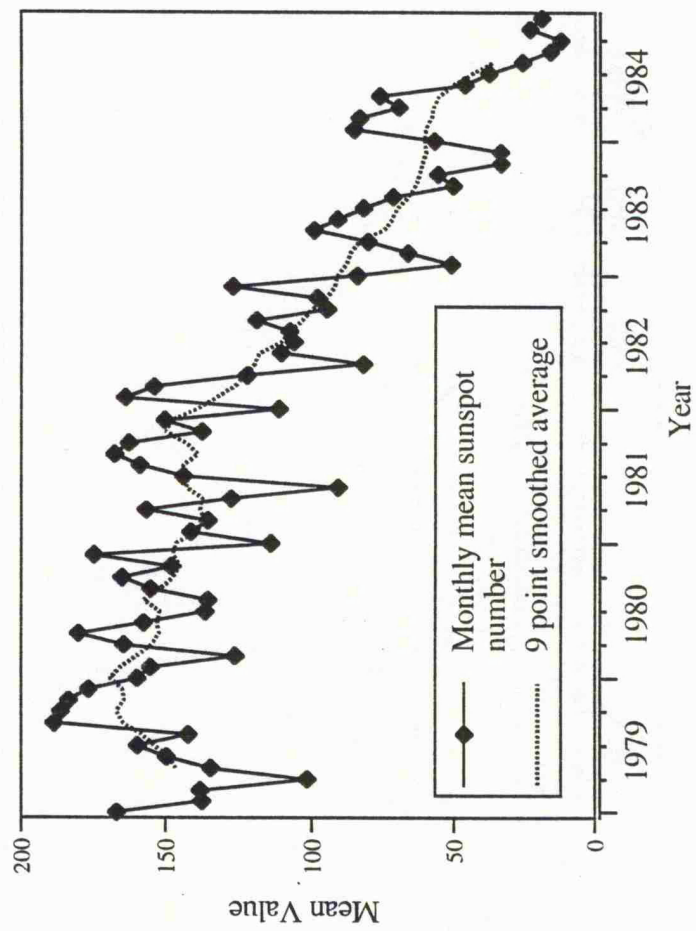


Figure 5.9: Monthly mean sunspot numbers for 1979-84.

The most apparent feature of figure 5.8 is that the ratio of useful observations to total observations (ratio A) is much larger in 1980 than in 1984. Consideration of the typical foF2 values during these intervals helps to explain this observation. Figure 5.10 gives median foF2 values for March 1980 and for March 1984 and can be considered as typical profiles for these sunspot numbers. The values are again for Sodankylä, Finland as data from Tromsø are not available. However, the station at Sodankylä is near enough to Tromsø to make the data useful for this study. The foF2 profile for the 1980 data, which is close to sunspot maximum, is consistently higher throughout the day and the maximum overall change in foF2 is considerably greater than that for March 1984. This would suggest that the fixed frequency diagnostic in the 1984 interval would have a tendency to penetrate the F-layer more often and this would explain the reduction in useful observations. However, the fraction of 'good' observations which are pulsations (ratio B) is much higher for the 1984 interval.

5.3.4 Comparison with Levels of Geomagnetic Activity

The dependence of the occurrence of events on geomagnetic activity (indicated by the index A_p) is now examined. Two monthly intervals, March 1980 and March 1984, have been chosen because there were a large number of observations per bin and which are also good representations of the general case. Selecting the same month for the two different years should suppress any seasonal variations. A_p has been summed over all three hour bins each day for each of these months and is illustrated in figure 5.11. This method allows the general activity level over the month to be plotted.

Figure 5.12 presents the monthly occurrence statistics for March 1980 and March 1984. The mean level of A_p for March 1984 was considerably higher than for March 1980 indicating that the former was geomagnetically more active. The number of observed pulsation events relative to the number of useful observations (ratio B) is clearly larger for the 1984 interval than for that of March 1980. However, the level of ratio A is considerably greater for the March 1980 interval. From the above data, it seems reasonable to suggest that the value of ratio A is mainly controlled by the value of foF2 which is dependent on, and slowly varies with, sunspot number. Geomagnetic activity, on the other hand, controls ratio B and is also related to solar cycle, but varies on a much shorter time scale. Although figure 5.12 displays data for intervals where there is a high sunspot number and low A_p and vice versa, the opposite situation has also been tested employing data from months at and away from sunspot maximum where A_p was, respectively, high and low. The amount of data available for this task was limited

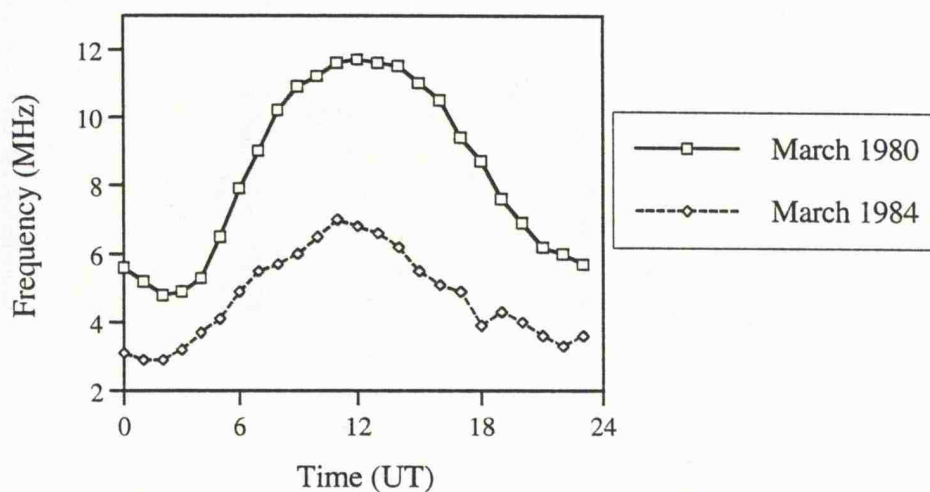


Figure 5.10: Averaged hourly median foF2 values at Sodankylä, Finland (67.4°N 26.6°E) for March 1980 and March 1984. Data were provided by the World Data Centre, WDC-C1.

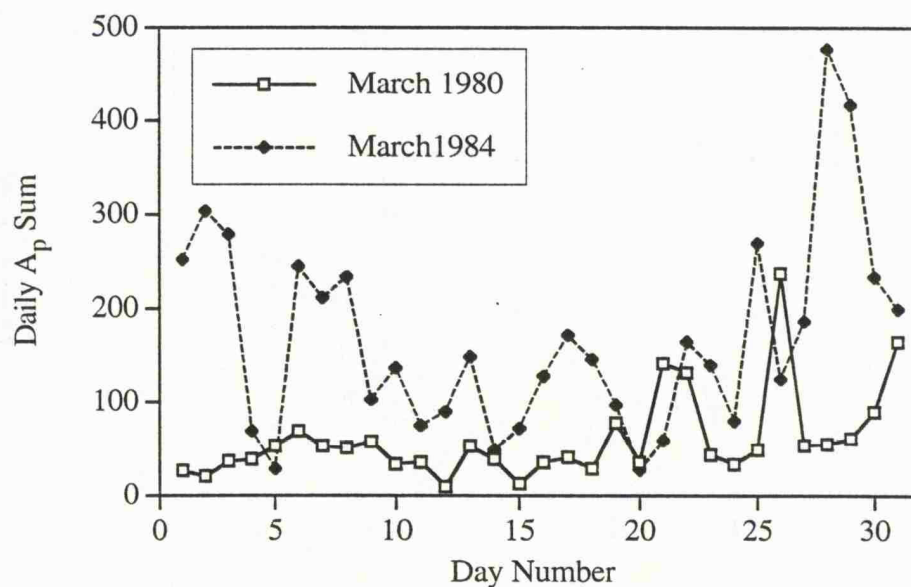


Figure 5.11: Variation of A_p summed over the day.

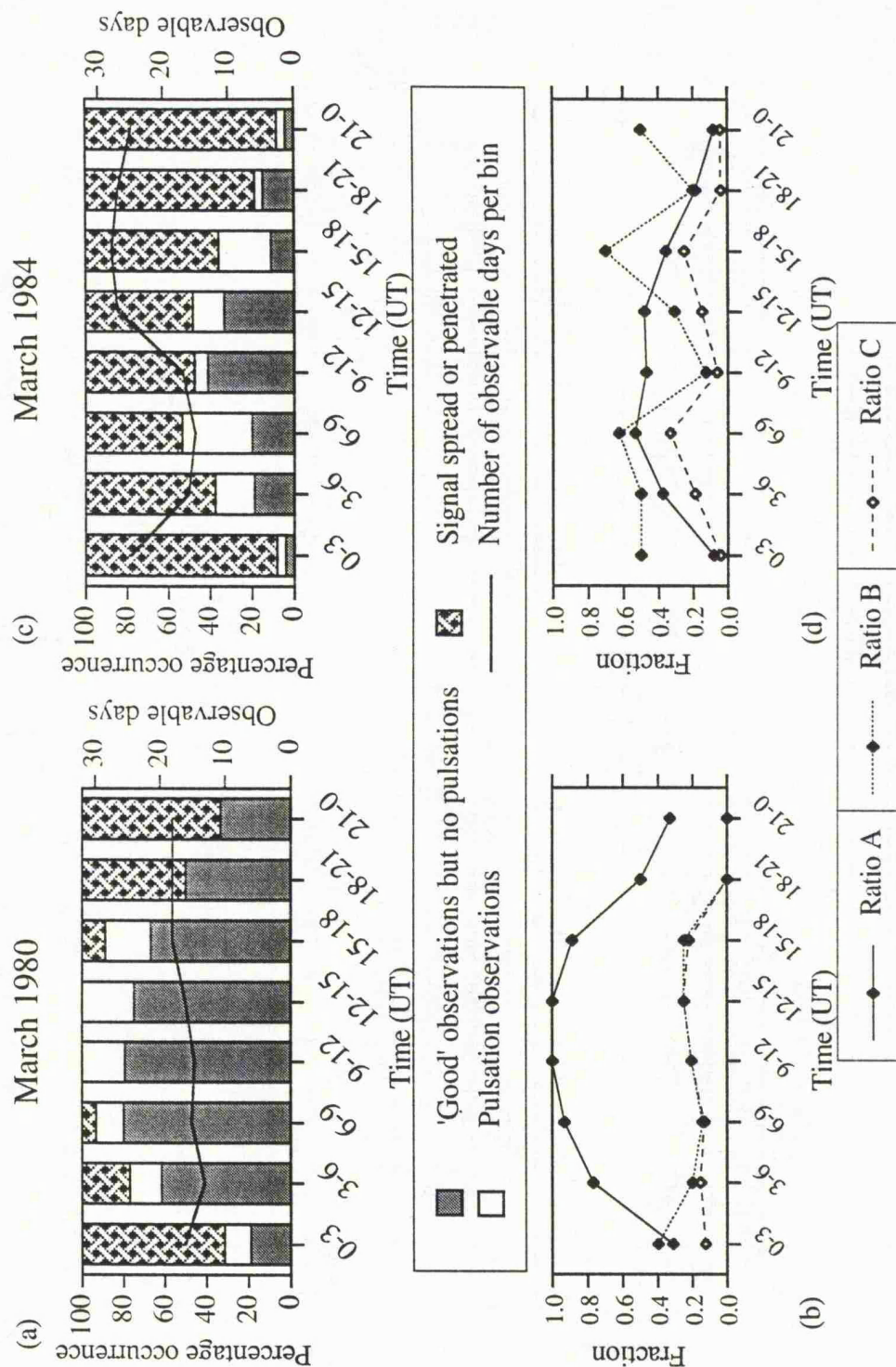


Figure 5.12: Pulsation occurrence plots for March 1980 (a,b) and March 1984 (c,d). The format is the same as that for figures 5.5 and 5.6.

but the intervals April 1981 and May 1983 were compared. The former interval had an average value of daily summed A_p of 28 and an average diurnal value of ratio B of 0.213 for the month. This compares to values of 22 and 0.165 respectively for the later interval. The geomagnetic activity control of ratio B, thus, remains consistent with the behaviour determined from the months of March 1980 and March 1984.

5.4 Discussion

5.4.1 Diurnal Occurrence Distributions

The diurnal variation of the ionospheric critical frequency (f_oF2) affects the ability of the Doppler system to observe ULF wave signatures throughout the day. Ratio A, illustrated in figure 5.3b, follows the same form as the f_oF2 curve of figure 5.4. As the f_oF2 decreases below the sounder frequency the signal penetrates the ionosphere and observations are impossible, leading to a corresponding decrease in ratio A. Also, the peak value of ratio A approximately coincides with the maximum diurnal value of f_oF2 . In order to evaluate the intrinsic ULF wave occurrence rate it is, then, important to consider the relative number of events which occur for conditions when good data, as defined earlier, are available (ratio B). Intervals of spread frequency or data absence due to penetration of the radio signal must be excluded. Ratio B, from this point of view, gives a better indication of the intrinsic distribution of occurrence of pulsation events than does ratio C.

The total data set (figure 5.2) for this study does not discriminate between particular types of wave in the Pc4 or Pc5 period range, hence, A- and R-class waves (section 2.2.4) with periods in the range 60-1000 seconds will be included. The data display a prenoon peak in ratio B together with a small postnoon peak (figure 5.3b). Events are nevertheless observed throughout all UT (LT for these results is equal to UT+2). The distribution of ratio B is consistent with the bimodal structure of A-class waves caused by field line resonances excited by the Kelvin Helmholtz instability on the dawn and dusk flanks of the magnetosphere or by an impulsive cavity mode oscillation. A similar variation with a bimodal asymmetrical occurrence distribution over local time is observed by high latitude ground based magnetometers (e.g. figure 2.10b) [Gupta (1973); Rao and Gupta (1978); Gupta and Niblett (1979); Ziesolleck and McDiarmid (1995)]. A similar result has been derived from measurements made by VHF radars such as STARE [Walker and Greenwald (1981)]. In addition, figure 2.10a indicates that there is

also an agreement with observations of A-class waves made by orbiting spacecraft [Anderson *et al.* (1990); Arthur and McPherron (1981); Kokubun (1985); Kokubun *et al.* (1989)]. The relative sizes of the dawn and dusk peaks in the present data set more closely resemble the spacecraft observations than those at the ground.

It is important to note that the form of ratio B may be modulated by changes in the sensitivity of the sounder which are a result of the diurnal variation of foF2 (see section 3.2.4). During intervals such as winter, where the peak daily foF2 is larger than the transmitted frequency, the sounder sensitivity would maximise in the morning and evening as foF2 passes close to the signal frequency and this could contribute to the diurnal variation of ratio B. However, an examination of figures 5.6a and 5.6b indicates that there is little difference between the shape of the diurnal distributions of ratio B at the spring equinox and the summer solstice, despite the fact that the diurnal foF2 response is much flatter in the summer (see figure 5.7). The bimodal distribution of ratio B is, however, more pronounced at the spring equinox than at the summer solstice suggesting that there is a genuine bimodal distribution in pulsation occurrence which is enhanced by Doppler sensitivity effects.

The previous ground based statistical studies mentioned above are of A-class waves. The distribution in figure 5.2 may well include a large number of storm or substorm related events occurring from 10 LT through until dusk as a result of R-class waves. Although ground magnetometers often do not resolve such waves [Kokubun (1985)] the Doppler sounder at Tromsø could have done so, as this instrument does not integrate information over such a large spatial area (see section 2.2.2). This system could potentially be sensitive to ionospheric oscillations with a very small horizontal scale length. Chapter 6 will investigate this spatial aspect in detail in the light of data provided by the new Doppler experiment, DOPE, and attempt to determine the extent to which occurrence observations are affected by it.

The diurnal distribution of ratio C in figure 5.3b (also figure 5.6) has a daytime peak which is broader than that for ratio A in all cases. It also has an amplitude which is lower than that for either ratio A or ratio B. This is a consequence of the fact that ratio C is a convolution of the other two. That is, ratio C includes information on both the intrinsic pulsation occurrence rate and the diurnal variation of foF2. It indicates that the effectiveness of the Doppler sounder for ULF wave observations under these conditions and at this sounder frequency is

restricted to the 03-18 UT interval and is maximum in the 06-09 UT (8-11 LT) range.

5.4.2 Seasonal Variations

Ratio A, illustrated in figure 5.6, is similar for both equinoxes and at the winter solstice but is different at the summer solstice, displaying a broader diurnal distribution at this time. This is a response to the seasonal change in the diurnal foF2 variation. As can be seen in figure 5.7, foF2 varies much less throughout the day in summer relative than in the winter. Thus, where foF2 is high enough for signal propagation, the signal will not penetrate so quickly in the evening or appear as suddenly in the morning.

An examination of figures 5.5 and 5.6 illustrates that for the present study the equinoxes provided the largest number of events relative to the available amount of good data (ratio B). At the winter solstice this ratio was higher than at the summer solstice. The intrinsic occurrence of ULF waves (figure 5.6) reaches a maximum at the autumn equinox and is minimum in summer. These results suggest that the Doppler observations are not inconsistent with those of the other authors, named in section 2.2.4, except Gupta (1973) and are in good agreement with the findings of Rao and Gupta (1978). Conditions for observing ULF waves and their signatures are at an optimum at the equinoxes because at these times the ionospheres of the two terrestrial hemispheres are nearest to being equal with similar ionospheric conductivities. At these times neither ionosphere is responsible for damping the wave more than the other [Southwood and Hughes (1983)] and as such the waves tend to persist for longer and are, as a result, observed more often. In addition, ratio C clearly demonstrates that the Doppler sounder operating at these frequencies is least effective at making high latitude ULF wave observations during the summer months.

5.4.3 Changes Throughout the Solar Cycle

Figure 5.8 illustrates the occurrence distributions for the intervals January-April 1980 and January-April 1984, respectively at solar maximum and near solar minimum. Ratio A, for the distributions in figure 5.8, is significantly higher in January-April 1980 than for that in January-April 1984. The sunspot number slowly, but strongly, modulates the diurnal change in foF2 (figure 5.10) and this, in turn, leads to the observed change in ratio A.

The diurnal distribution of ratio B does not change appreciably between the intervals in figure 5.8 and as such confirms the observation by Rao and Gupta

(1978) that the diurnal occurrence distribution changes little throughout a solar cycle. Despite the fact that the number of pulsation observations at the ground are generally expected to be higher at solar maximum (figure 2.14) [Gupta and Niblett (1979)], the amplitude of ratio B is higher (figure 5.8) for the 1984 interval than for that in 1980 and, therefore, does not follow the same response to the solar cycle variation demonstrated by ratio A. This fact is consistent with the suggestion, in section 5.3.4, that the intrinsic occurrence of ULF waves is controlled by the level of geomagnetic activity as reported by Gupta and Niblett (1979) and will be discussed further in section 5.4.4. Ratio C is roughly the same for each interval and this is not unexpected assuming that ratio C is a convolution of ratio A and ratio B. However, this fact demonstrates that the effectiveness of the Doppler sounder at observing ULF waves was the same for each interval. As there have been few investigations into the solar cycle effects on pulsation occurrence to date, this study has significantly added to the understanding of this relationship.

5.4.4 Geomagnetic Activity

As might be expected the work presented here is influenced by the level of geomagnetic activity. The data illustrated in figures 5.11 and 5.12 demonstrate that the value of ratio B for a given month is dependent on the level of geomagnetic activity and increases with the value of A_p . In section 5.4.1 it is suggested that ratio A is strongly dependent on the local foF2 which is related to the variation of sunspot number over an 11 year cycle. Geomagnetic activity, on the other hand, varies on a much shorter time scale and controls the form of ratio B. Thus, it is possible to separate out these two effects in the data set. The fact that ratio B is independent of phase of the solar cycle explains why the occurrence of ULF waves, observed over a solar cycle [Gupta and Niblett (1979)], varies so much around the general trend - the effects of activity are significant. The number of useful observations is smaller in March 1984 which is a consequence of the lower foF2 (figure 5.10), being nearer solar minimum, and also possibly because of disruption to signal propagation during the period of greater activity. Despite this fact, Ratio C indicates that the effectiveness of the Doppler sounder to observe ULF wave signatures increases (figure 5.12) considerably during a period of greater geomagnetic activity.

Although this work does not attempt to provide an in depth study of the relationship between event occurrence in the Doppler data and the level of A_p or K_p , it is still in agreement with the observations of Gupta (1973) and Walker and Greenwald (1981) who all found a linear increase in occurrence with K_p up to

around 4 or 5. These authors offer work on Pc5 waves, however. It is unclear how the Pc4 events, which are undoubtedly present in this data set, may affect this comparison. The review in chapter 2 has made it clear that different classes of waves have different dependencies on activity, so it is not appropriate to pursue this here. However, chapter 6 will provide evidence that there are three populations of waves in the data here with different activity dependence.

5.5 Summary

The statistical study presented here has characterised the occurrence of wave signatures, in the ULF range, in high latitude Doppler sounder data and the way in which prevailing ionospheric and magnetospheric conditions affect observations. The effects of season, solar cycle and level of geomagnetic activity on Doppler system sensitivity and pulsation occurrence are determined from a sizeable data set covering an interval of five years.

The relative number of useful observations (ratio A) made by the sounder during the period when data were recorded are strongly related to the diurnal, seasonal and solar cycle variations in the ionospheric critical frequency, foF2. The diurnal variation of ratio A consistently peaks before 12:00 UT and has a minimum around midnight. Bearing in mind that it has not been possible to subdivide the observed events into types according to suggested generation mechanisms, it is concluded that the intrinsic diurnal distribution of event occurrence when useful data are available (ratio B) is consistent with those reported earlier by other authors utilising alternative ground and space based instrumentation. The distribution is bimodal and suggests that a significant contribution to the observed signatures are related to field line resonances generated by the Kelvin-Helmholtz instability at the dawn and dusk magnetospheric flanks or impulsively at the sunward side of the magnetospheric cavity. Ratio B is controlled by the level of geomagnetic activity. It highlights the need for care when deconvolving the effects of solar cycle from those of geomagnetic activity. To date, there have been few studies into the relationship between solar cycle phase and ULF wave observations, and so this study adds significantly to current knowledge on the subject.

Ratio C is a measure of the effectiveness of the system for observing ULF waves. It demonstrates that a complex convolution of ionospheric and geomagnetic conditions ultimately controls the ability of a Doppler sounder to observe ULF wave signatures. Information on which conditions and times are likely to give the

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best results for such observations are provided by ratio C. Consequently, the results presented in this chapter have been important in the development of a new experiment, called DOPE, designed to investigate ULF waves at high latitudes. This will be discussed further in chapter 6.

Chapter 6

DOPE: High Latitude Doppler Sounder Observations of ULF Waves

6.1 Introduction

The Doppler sounder, described in Chapter 4, has been deployed in Norway and now continuously sounds the high latitude ionosphere at a frequency of 4.45 MHz. The system is intended to make measurements of ULF waves in conjunction with the European Incoherent Scatter (EISCAT) radar located in Tromsø, Norway. The EISCAT radar, has so far, only been utilised on a few occasions for ULF wave experiments [Crowley *et al.* (1985, 1987)]. However, the radar has a unique ability to determine the tristatic ionospheric drift velocity at a given altitude together with the ionospheric profiles of the electron density and the Hall and Pedersen conductivities. These measurements, in conjunction with the Doppler sounder and ground magnetometer data, could, for the first time, provide a complete determination of the electric and magnetic field signature in the ionosphere and of the mechanism through which the Doppler signature of the ULF wave is created. This information would enhance earlier studies of the ionospheric boundary conditions of MHD waves [Yeoman and Lester (1990); Yeoman *et al.* (1990, 1991)] and enable the verification of the modelling work of Poole *et al.* (1988), Sutcliffe and Poole (1989, 1990) and Sutcliffe (1994).

In this chapter the occurrence, structure and generation mechanisms of ULF waves at high latitudes are investigated from data collected by the new Doppler experiment and from ground magnetometers.

6.2 First Results from DOPE

A description of the DOPE Doppler sounder and the EISCAT experiment called SP-UK-DOPE is given in section 4.4. The DOPE sounder presently operates continuously and SP-UK-DOPE runs on a campaign basis when time is allocated on the EISCAT radar. Regrettably, DOPE has not yet provided a sufficient number of useful events to enable a detailed comparison with the tristatic measurements from EISCAT. There are two reasons for this. Firstly, there has been a shortage of accumulated experiment time on the EISCAT radar - only 20 hours (out of 35 awarded) up to May 1995, and secondly, during a large proportion of the time that EISCAT was running SP-UK-DOPE, the ionospheric conditions were poor from the point of view of the Doppler sounder. On these

occasions, the F-region critical frequency became too low to enable an ionospheric reflection of the HF diagnostic wave. EISCAT time is allocated in advance and it is difficult to change the experimental schedule. Despite this, DOPE can address a number of the questions it was designed to answer without concurrent EISCAT data. The DOPE experiment will continue in future and data will be collected simultaneously from DOPE, EISCAT and ground magnetometers.

The data which are about to be presented are derived from the Doppler sounder and from magnetometer stations located in Scandinavia. There are considerable archives of data available from IMAGE and SAMNET stations. The Doppler sounder has, in addition, been in operation continuously since early June 1995 and the number of useful events recorded are steadily increasing. There have been enough observations of ULF wave signatures by the sounder to be able to compile a small statistical data set of their occurrence, in addition to the investigation of individual events.

In the following sections the Doppler observations are compared with the magnetometer data. Two types of event are identified; those with a concurrent signature in data from surrounding magnetometers and those which do not correlate with a magnetometer signature, in the sense of there being no wave of the same frequency observed by the magnetometer. These observations will be discussed in the context of the statistical results of Chapter 5.

6.2.1 Ionospheric Signatures of ULF Waves

Most of the Doppler ULF wave signatures studied form part of a longer duration disturbance. A small section of the recording is utilised because one or both of the Doppler modes usually became noisy, which makes it difficult to ascertain the ULF wave frequency in that mode. In order to perform a frequency analysis on a time series from a Doppler sounder, the peak spectral component has to be extracted (section 3.2.4) from the signal. This can be difficult or impossible if the data are very noisy. For example, if there is an interfering signal being received along with the intended signal or if, say, the O-mode is beginning to penetrate the ionosphere as it approaches the F-region critical frequency. Thus, analysis is restricted to periods when only clear wave signatures are present. Also, due to considerations of relative phase, in general, only events observed in the Doppler which have a signature in both the O- and the X-mode are utilised in the case studies. However, this criterion was relaxed when compiling the general statistical overview of events. For these figures, the signal frequency shift (Doppler shift) is

plotted as a function of time. In some cases the data have been bandpass filtered to improve the quality. Accompanying X and Y component magnetometer data are plotted as the time variation of the field deflection of the from their mean values.

Two basic types of ULF wave signatures are observed by the sounder. Those which have a corresponding oscillation at the same frequency in the ground magnetometer data and those which do not. This latter type of wave is thought to be a true signature of ULF pulsations for the following reasons. Firstly, the waves are often seen as a series of sequential wave packets - indicative of pulsations categorised as “Pc” or continuous. Secondly, as previous work has suggested [Hughes and Southwood (1976a,b); Yeoman *et al.* (1992)], ULF waves may be invisible to a magnetometer on the ground due to screening by the ionosphere when the waves have a high enough azimuthal wave number, m . Evidence will be presented here which suggests that these “uncorrelated” waves are a distinct class of ULF waves at high latitude which may exhibit different characteristics to those which are observed simultaneously on the ground and in the F-region ionosphere. Possible causes of uncorrelated ULF wave signatures are discussed in detail in section 6.2.2.

HF Doppler and Ground Magnetometer ULF Wave Signatures

Figure 6.1 illustrates a pulsation event which occurred on 13/11/95. O- and X-mode data are presented, as a time series, along with unfiltered X and Y component Tromsø magnetometer data for comparison. The magnetometer and Doppler data have time resolutions of 10 and 12.8 seconds respectively. It is evident that three wave packets exist in the data. The packets commence at about 13:33 UT, 14:10 UT and 15:00 UT respectively. The O-mode trace is considerably noisier than that of the X-mode. There was an interfering signal which had a small offset from our own signal. It had a mean level somewhere below 2 Hz on this plot. However, by selectively plotting (section 3.2.4) the part of the spectrum in the range 1.5 - 4.5 Hz it was possible to improve the signal to noise ratio for the event. In chronological order, the three packets contain 9, 5 and 4 discernible wave cycles in the Doppler data respectively. Also presented on this plot are the unfiltered X and Y components of the Tromsø, Norway (TRO) and Sodankylä, Finland (SOD) IMAGE magnetometer stations. These stations are located at 69.66°N, 18.94°E and 67.37°N, 26.63°E respectively. Hence, they are geographically close and have a separation in longitude large enough to enable the calculation of the azimuthal wave number, m , of the ULF pulsations studied here. There is a clear wave signature in the magnetometer data at the same time as those

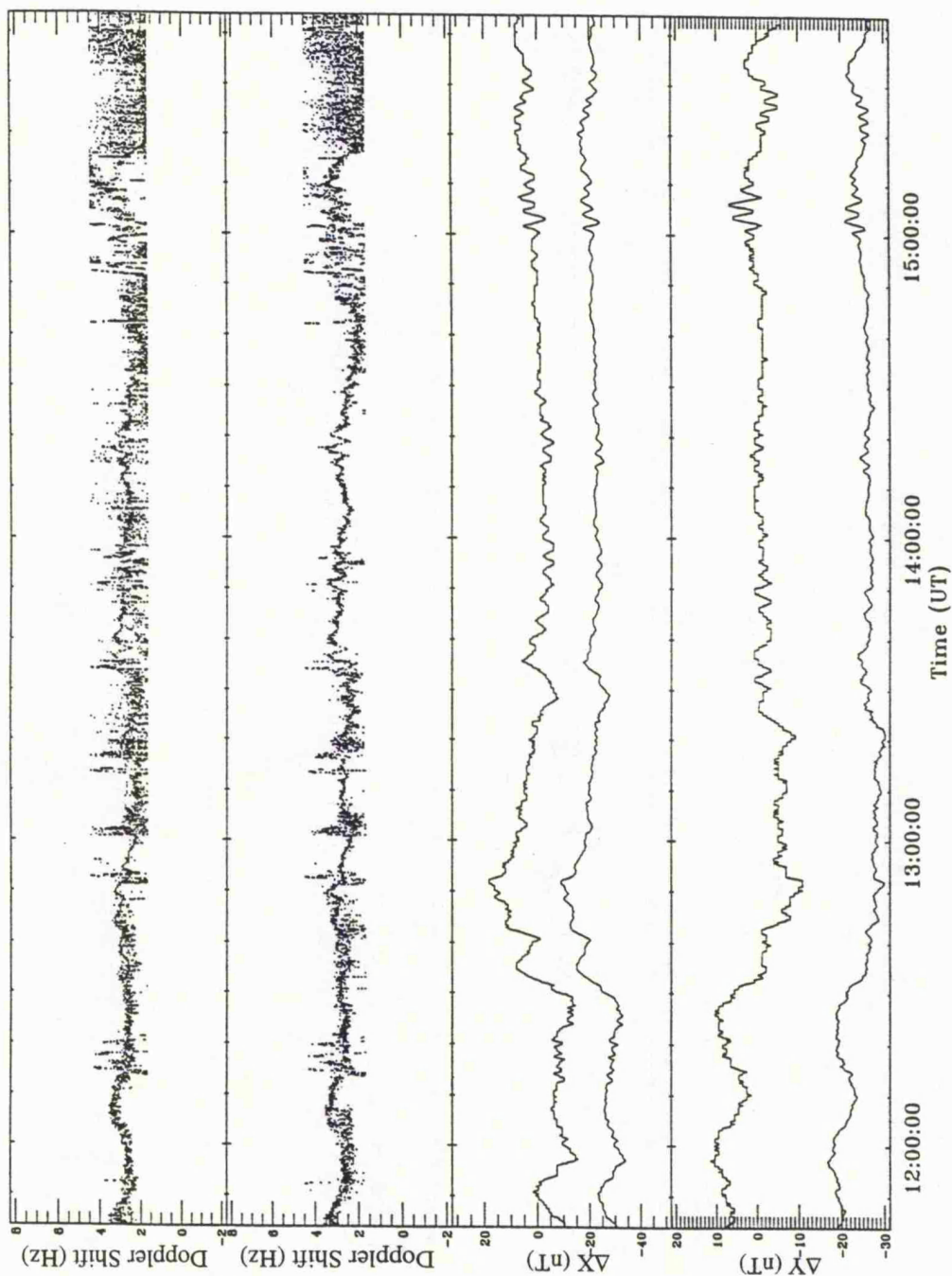


Figure 6.1: Doppler and magnetometer data for the correlated event on 13/11/95. The panels display (from the top down): Doppler O-mode frequency shift, X-mode frequency shift, TRO(upper trace) and SOD (lower trace) X component and Y component. The sampling interval of the Doppler data is 12.8 seconds and 10.0 seconds for that from the magnetometer.

in the Doppler data. The amplitude of the magnetometer signature is higher at TRO than at SOD. The Doppler wave has an amplitude of around 1 Hz peak-to-peak, which is equivalent to a Doppler velocity of 34 ms^{-1} at this sounding frequency (section 3.2.4), and there is a corresponding fluctuation in the magnetometer data with an amplitude of around 5 nT peak-to-peak. Figure 6.2 shows a section of this data which is filtered to include only those periods between 60 and 300 seconds. The interval 14:10 to 14:30 UT was examined because it had the clearest O-mode signature. The Doppler data here is the peak trace of the spectra plotted in figure 6.1. This is necessary in order to reject noise and to create a single component time series on which a frequency analysis is possible. The magnetometer data are both scaled by a factor of 0.2, that is their true amplitudes are 5 times larger than shown. All data have been filtered with a bandpass of 60-300 seconds (3.3-16.7 mHz). The short period cutoff is a method of smoothing out short period noise in the data. The TRO Y component phase leads all the other signatures, and there is a very good correlation between all four time series.

The data in the interval 14:10-14:30 UT (figure 6.2) were passed through a Fast Fourier Transform (FFT) and examples of the resulting spectra which have a frequency resolution of 0.83 mHz are given in figures 6.3a and 6.3b. A clear sharp peak exists in both Doppler and magnetometer spectra at a frequency of 5.8 mHz which corresponds to a period of 172 seconds and is in the frequency range of a Pc5 pulsation. Comparison of the Y component data of SOD and TRO reveals an azimuthal wave number of the order of 6.4 ± 2.7 . The Y component is selected to calculate m because the phase of the wave in the X component of two latitudinally separated magnetometers may vary considerably for a field line resonance (see section 2.2.3), and thus the Y component is more phase stable along lines of latitude. This is particularly important as TRO and SOD are latitudinally separated. A reasonable estimate of the error in the calculated value of m is derived from the time resolution of the magnetometer data, which is 10 seconds. Δm is the phase error of the measured wave, as a fraction of the wave period, divided by the longitudinal separation of the TRO and SOD stations. For this interval the X-mode signature leads the O-mode in phase by 5 degrees and the TRO Y component signature lead that of the TRO X component by 99 degrees. The TRO Y component also leads the Doppler O-mode signature by $90^\circ \pm 18^\circ$ *i.e.* the TRO X component is roughly in phase with the Doppler O-mode.

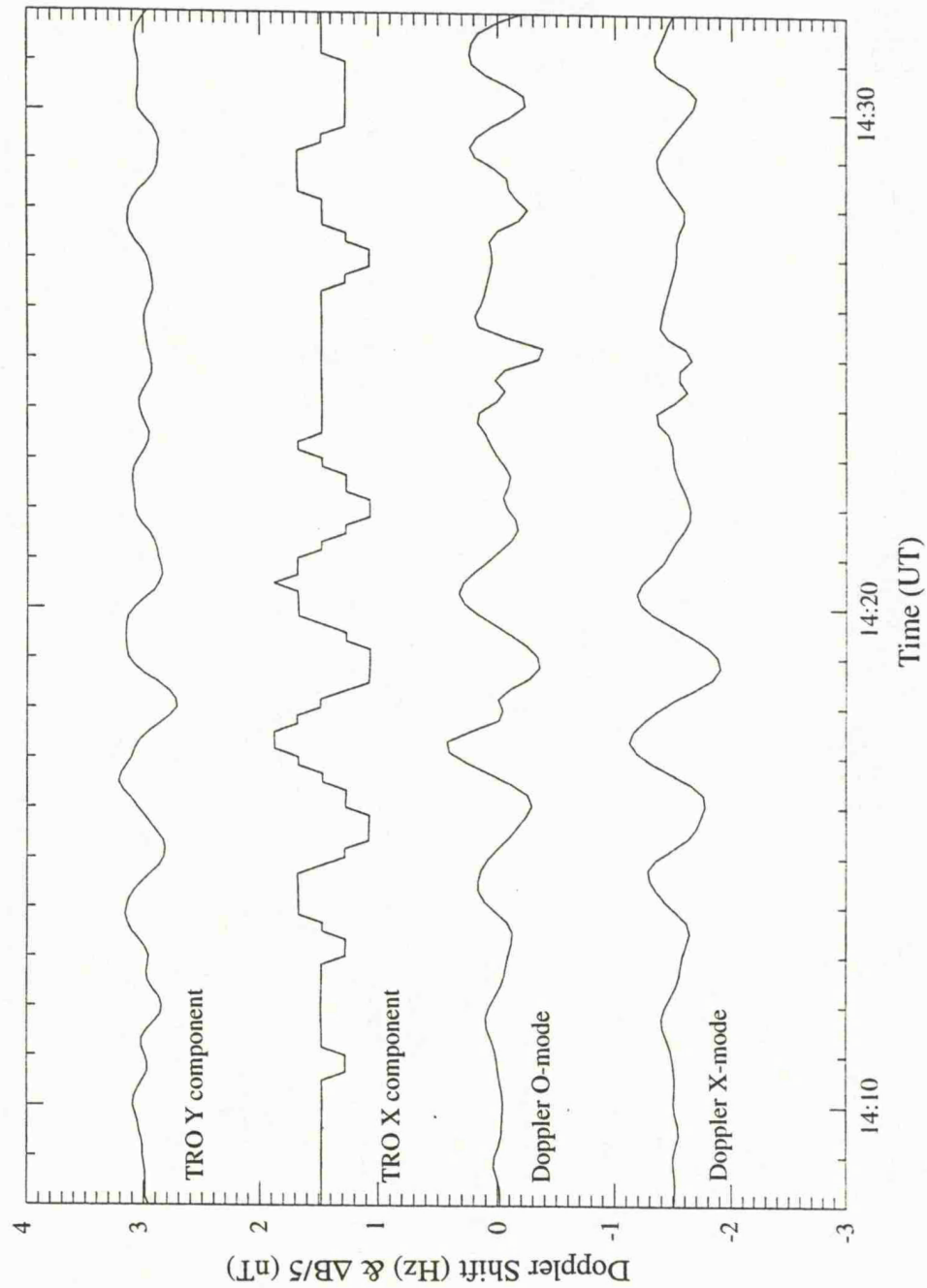


Figure 6.2: Time series of TRO magnetometer X and Y components and of peak traces for the Doppler O- and X-mode signatures for the interval 14:08 - 14:32 UT on 13/11/95. Data are filtered to exclude periods outside the range 60-300 seconds. Note that the Magnetometer component amplitude has been divided by 5 and that the ordinate axis is a relative scale with arbitrary offsets.

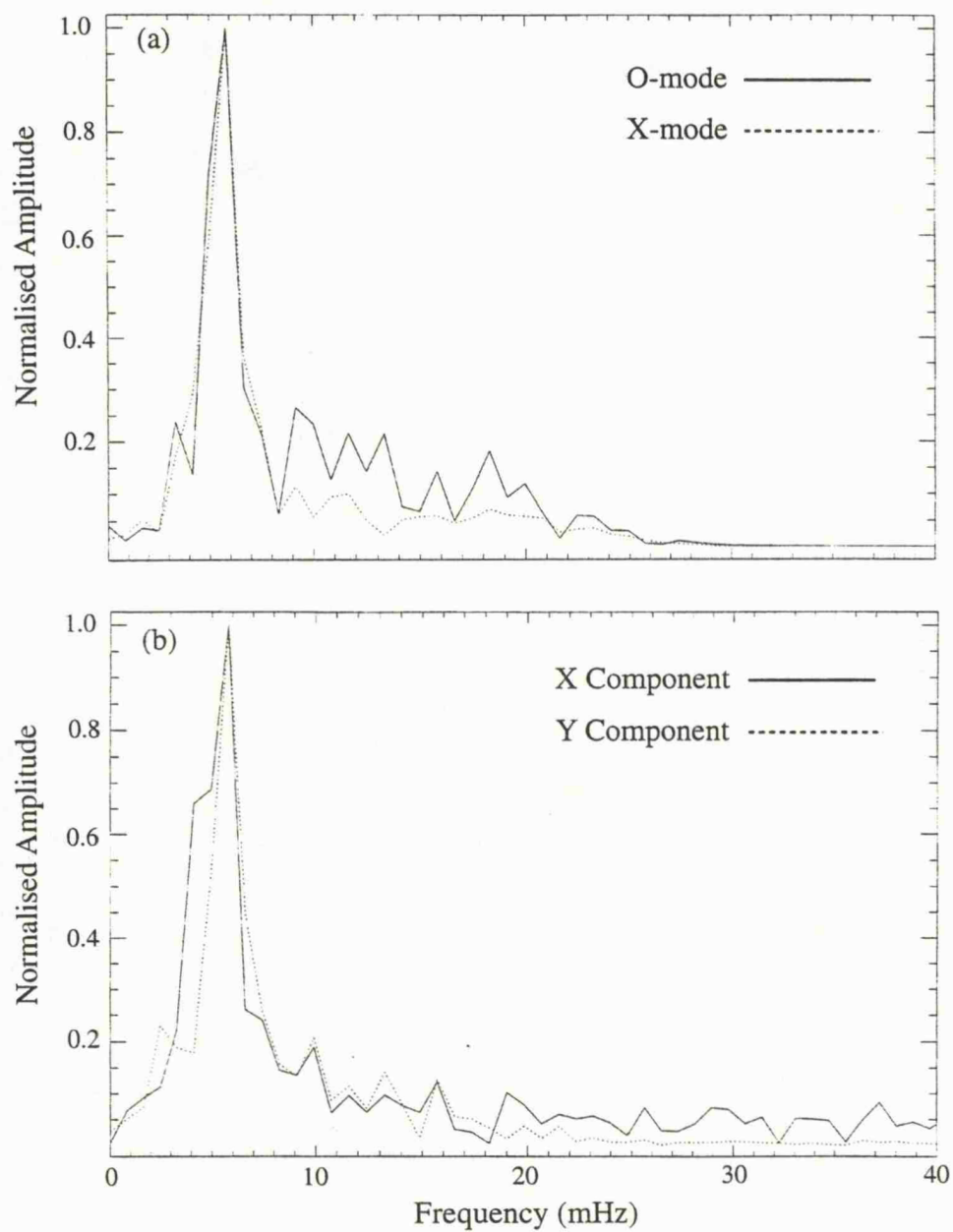


Figure 6.3: Frequency spectra of the time series of (a) Doppler 0- and X-mode traces and (b) Tromsø magnetometer (TRO) X and Y components for the interval 14:10 - 14:30 UT on 13/11/95 as illustrated in figure 6.2.

ULF Waves Observed in the F-region But Not on the Ground

A second type of event commonly occurred. Here, apparent ULF wave signatures in the Doppler records are not accompanied by a corresponding signature in the nearly collocated ground magnetometer. In other geomagnetically active intervals, a ULF wave signature was recorded on the magnetometer at the same time as the Doppler sounder but had a different frequency to that in the Doppler data. Figure 6.4 illustrates data of the first type. A number of wave packets of ULF activity were observed by the sounder at an F-region reflection point over Tromsø, commencing shortly before 04:00 UT on 2/9/95. Seventeen wave cycles are clearly defined in the X-mode data. The packet envelope amplitude modulation is particularly clear. Again, the O-mode data are a little more noisy in this plot but the earlier part of the wave is clear. A nearby interfering signal is just visible on the O-mode plot shortly before 05:00 UT at around 1 Hz. The rest of this noise has been removed. The packet structure of the wave and its short period make it the characteristic signature of a ULF wave. The Tromsø magnetometer data, on the other, hand shows no activity at all during the interval when the wave occurs. The X and Y component data primarily displayed 1 nT digitisation noise, with no wave signature present. The frequency of the wave observed in the Doppler trace has been determined to be 9.2 mHz (figure 6.5) which is in the frequency range of a Pc4.

Other Interesting Events in the Doppler Data

There are several instances where ULF waves observed in the Doppler data where a corresponding magnetometer oscillation has been present for only part of the interval. Two events of this kind will be presented.

Figure 6.6 depicts a particularly fine example of a Pc class pulsation signature in the Doppler data on 21/9/95. The significance of this data is that the wave, which commence at about 05:10 UT and persist for a duration of at least 3 hours, exists as a series of wave packets which is a characteristic of Pc type waves. In addition, the wave occurs at the Autumn equinox when ionospheric conditions for ULF wave occurrence are at an optimum (see section 2.2.2). Prior to the time of the wave commencement the signal strength was low and only noise, which is spread in frequency, was logged by the receiver. For most of the interval when the wave occurs, it is quite distinct in both O- and X- mode traces. However, there is little indication of the presence of this wave in the unfiltered Tromsø magnetometer data. Spectral analysis of this interval indicates that the main wave frequency component is 10.3 mHz and that this is absent from the magnetometer time series. Harmonics of this frequency were also absent from the magnetometer data.

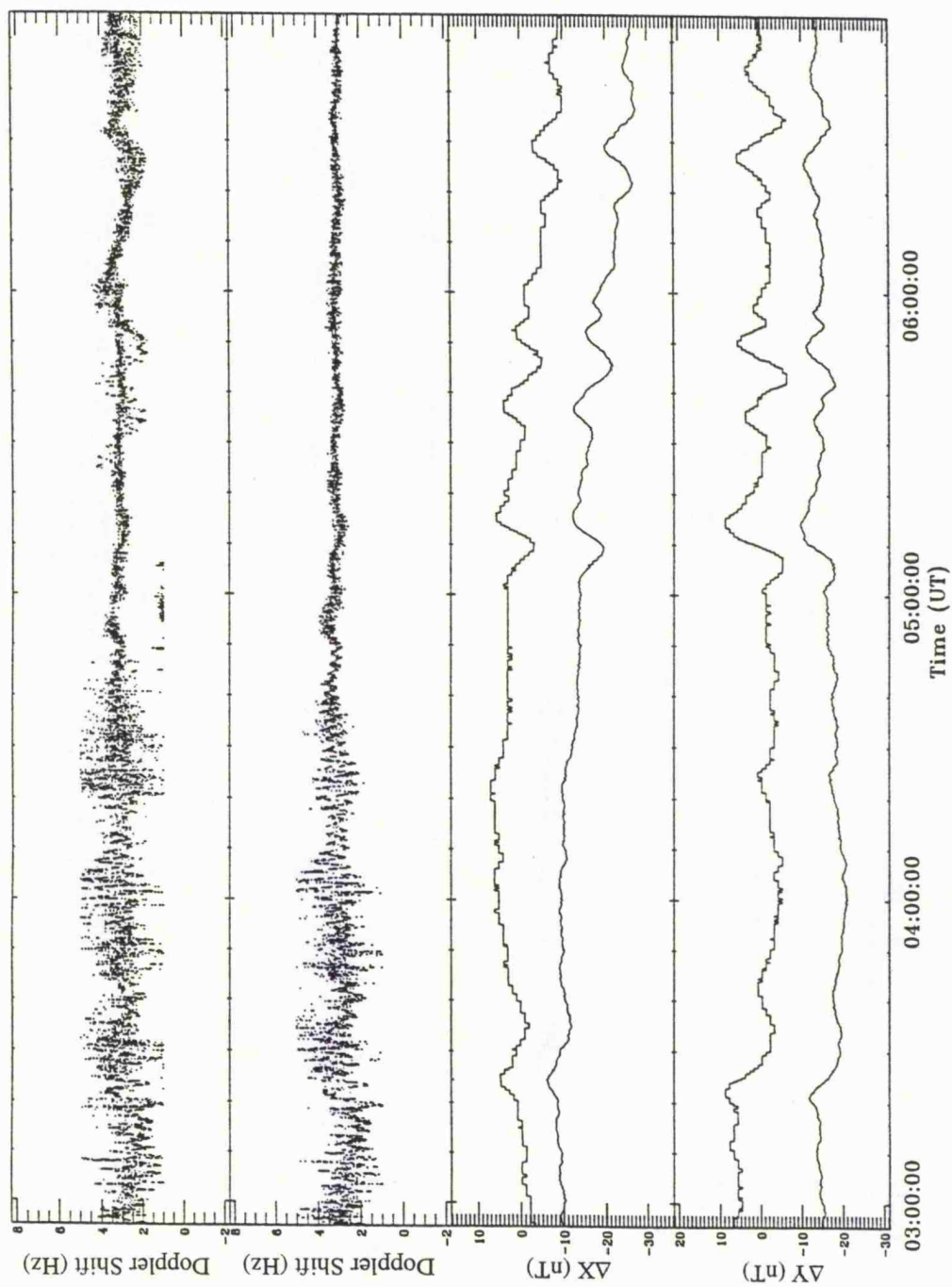


Figure 6.4: Doppler and magnetometer data for the uncorrelated event on 02/09/95. The panels are in the same format as those of figure 6.1.

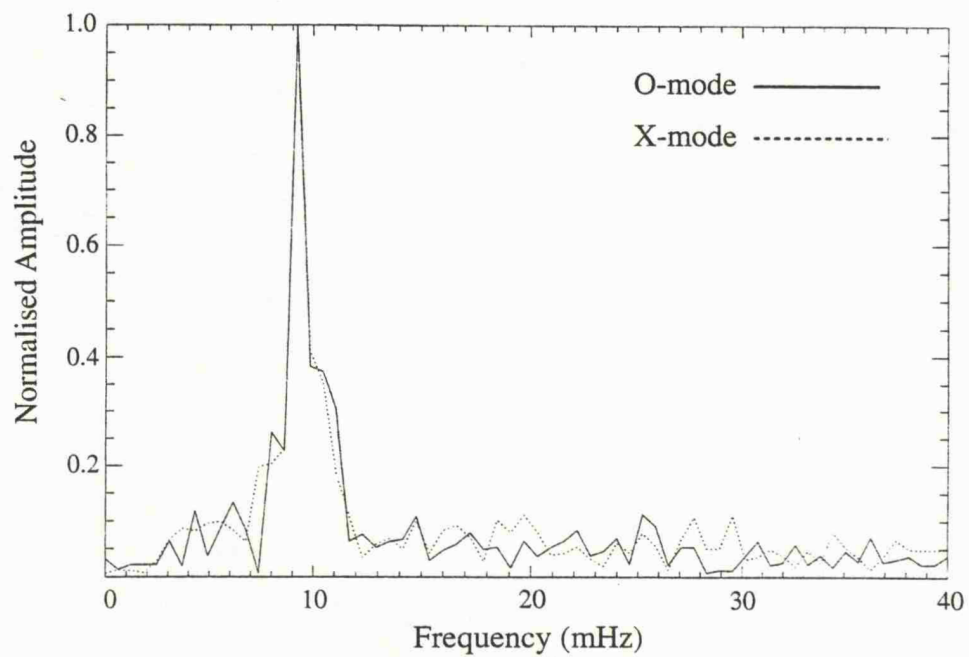


Figure 6.5: Frequency spectra of the Doppler O- and X-mode time series for the interval 03:55 - 04:22 UT on 02/09/95.

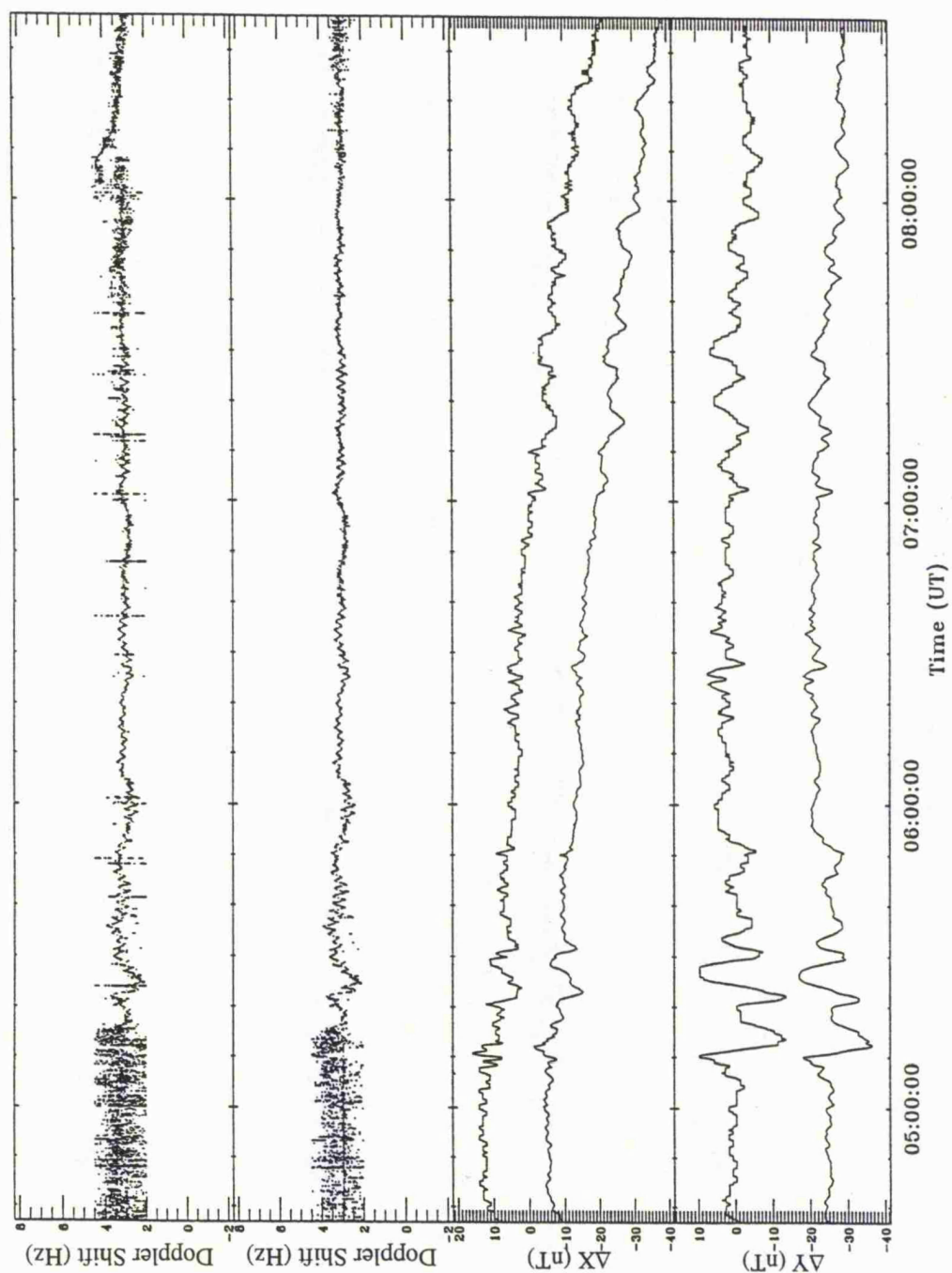


Figure 6.6: Doppler and magnetometer data for the uncorrelated event on 21/09/95. The panels are in the same format as those of figure 6.1. Note the packet structure of the wave signature in the Doppler data.

Chapter 6: High Latitude Doppler Sounder Observations of ULF Waves

The final case studied is another example of magnetometer wave activity of a different frequency to that in the Doppler data. Figure 6.7 portrays data from 12/9/95. There are two intervals of interest. First, there are the ten or so wave cycles starting at 12:25 which appear to have a corresponding oscillation in the magnetometer data, seen most clearly in the TRO Y component data. The data were filtered to the range 120-300 seconds (3.3 - 8.3 mHz). Spectral analysis of the various time series indicates a prominent 5 mHz wave signature in all. The azimuthal wave number was found to be 3.9 ± 2.3 for this interval.

This day is unusual in the fact that a second wave, exhibiting different characteristics, commenced about an hour after the first one ended. The wave may have started at around 14:00 UT but is clear to see from around 14:15 UT onwards. It is only apparent in the X-mode data - possibly due to the fact that the O-mode may have been on the verge of penetrating the ionosphere. However, this new wave has a much shorter period and has no apparent corresponding magnetometer signature. Instead, a wave of a similar period to the one occurring at the time of the first Doppler signature persists - indicating that some form of geomagnetic activity of a constant source may exist throughout the entire 3-4 hour period. It is likely that the longer period wave was the result of a resonant field line and the short period wave which subsequently commenced was a result of the evolution of a particle population in the magnetosphere associated with this source. These wave generation mechanisms will be discussed in great detail later in section 6.3. Spectral analysis demonstrates that the X-mode wave has a frequency of 13.3 mHz and the longer period magnetometer wave to be at around 4 mHz, which is different to that of the earlier ULF wave. Thus, one signature has a wave period which is over three times that of the other.

6.2.2 Characteristics of ULF Waves Derived from the DOPE Studies

In this section wave characteristics derived from the Doppler and magnetometer data sets are presented. The clearest events have been selected in order that the structure and the physical characteristics of the ULF waves, may be compared with the results of the statistical study in the previous chapter as well as with the work of others.

The total archive of Doppler data from the sounder at present extends from mid June 1995 for eight and a half months. In this time, 159 events have been identified. Of these 32 were waves with frequencies in the Pc4 range and the rest in the Pc5 range. Some were observed in both O- and X-mode data and some on one mode only. The clearest signatures have been studied quantitatively which

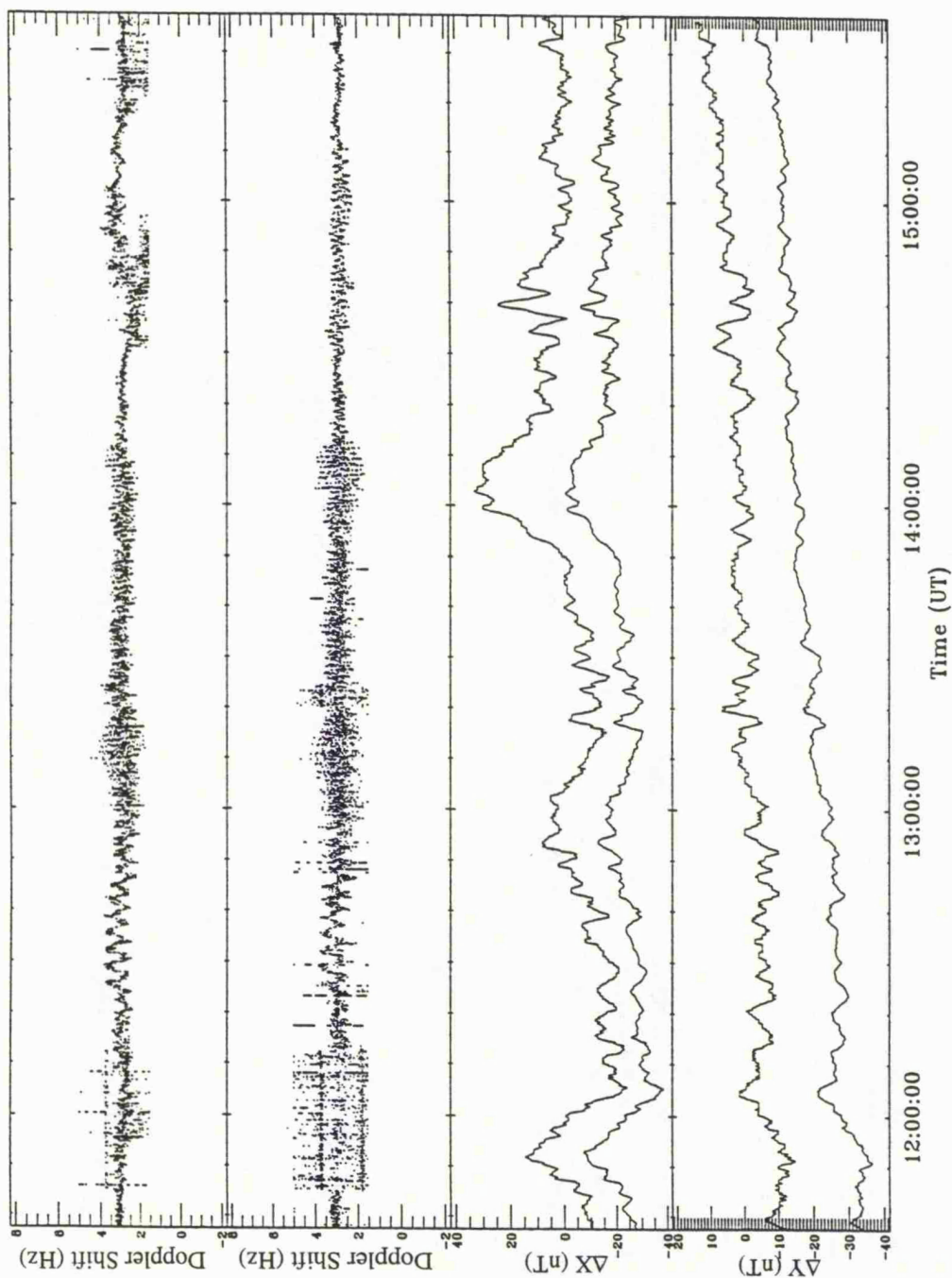


Figure 6.7: Doppler and magnetometer data for the ULF waves event on 12/09/95. The panels are in the same format as those of figure 6.1. A correlated wave packet occurs between 12:20 and 13:00 UT and an uncorrelated wave commences at around 14:15 UT.

include 10 events where the Doppler signal correlated with the Tromsø magnetometer signature and 11 events where the wave was not observed simultaneously at the ground. The four case studies described above are amongst these 21 events.

Two distinct populations of ULF waves have been identified by this new experiment. The diurnal occurrence distribution, frequency, amplitude and phase of the signatures in the O- and X-mode Doppler waves together with the ground magnetometer signatures have been investigated. From this an attempt has been made to specify the modes, types and generation mechanisms of the ULF waves.

Possible Causes of Short Period Doppler Signatures Not Related to Pulsations

In order to establish that the uncorrelated events observed in this experiment are signatures caused by incident magnetospheric ULF waves, other possible sources of Doppler wave signatures with periods in the ULF range must be considered.

Georges (1973) presented a detailed discussion of infrasonic waves which have periods in the range 2-5 minutes. These were briefly mentioned by Klostermeyer and Röttger (1976) as a possible cause of 2-4 minute oscillations apparent in their F-region HF Doppler observations. Such waves are generated in regions of convective storms and propagate vertically upwards with phase velocities of 500-600 ms⁻¹ [Georges (1973)] and lead to signatures in HF Doppler but not in ground magnetograms. Thus they are a possible source of uncorrelated waves. However, several characteristics of these waves and of the data presented in this thesis suggest that they are not responsible for the uncorrelated events observed by DOPE. Infrasonic waves appear to be restricted almost exclusively to occurrence in the evening whereas the uncorrelated events observed in this study occur at all times. Georges (1973) also stated that all significant observations of infrasonic waves have only occurred in the central United States of America. Unsuccessful attempts were made to detect them on the east coast of the USA in Florida. Furthermore, the phase velocity and frequency of the waves (typically 4 mHz) suggest a vertical wavelength of the order of 120 km. Thus, the relative phase between the signatures at the O- and X-mode reflection heights, which may have a vertical separation of up to 50 km when the sounding frequency is close to the critical frequency, would essentially be randomised due to the range of phase speeds and frequencies. However, the uncorrelated events in this study seem to mainly have zero O-X mode phase difference. It seems unlikely, therefore, that infrasonic waves have any bearing on the present observations.

Menk (1992) listed some possible ways that Doppler signatures, with frequencies in the ULF range, might be generated by a method other than a pulsation. It was suggested that multi-mode HF wave beating might occur between either multi-hop rays or between a ground wave and an ionospherically reflected wave. However, it seems unlikely that either of these effects are responsible for the Doppler signatures observed in the DOPE experiment. In addition, the suggestion by Menk (1992) that O- X mode polarisation interference might result in a beat at ULF wave frequencies can be dismissed because at high latitude such interference is negligible compared to the low latitudes where Menk (1992) made measurements [Toman (1967); Reddi and Rao (1967)].

Although it has previously been suggested that uncorrelated events of the type presented in this chapter may exist at mid-latitude [Klostermeyer and Röttger (1976)], this work provides the first confirmed observations, at high latitudes, of truly uncorrelated MHD waves with HF Doppler sounder signatures.

Diurnal Occurrence Distributions of Events

The overall set of 159 catalogued events have been plotted, in a similar manner to those in Chapter 5, in order to demonstrate their diurnal occurrence distribution (figure 6.8). Pc4 and Pc5 events have been separated on this graph. It is evident that the Pc5 events have a peak of occurrence in the 8-9 UT bin with a fairly broad distribution over the morning and prenoon sectors. The Pc4 distribution, on the other hand, seems to have a peak between 14-18 UT. However, events of this type do occur over all times between 2 and 18 UT. Note the lack of events in the dusk-midnight sectors. There are two possible reasons for this. The fact that the Doppler sounding ray will tend to penetrate the ionosphere more often during these times is an effect which will be convolved into the given distribution, as discussed in the previous chapter. Also, as discussed earlier (section 2.2.4) any ULF waves observed in this time sector are most likely to be of a different type - either a subset of Storm Time Pc5s or Pi2s, both of which are associated with geomagnetically active conditions in the Earth's geospace environment. Geomagnetic activity often leads to the disruption of HF signal propagation, for example, the increase in D-region absorption associated with a geomagnetic storm. All subsequent analysis is confined to the 21 events with clearest Doppler signatures in the O- and X-modes. These are divided into those correlated and those uncorrelated with ground magnetometer events.

Figures 6.9 and 6.10 (middle panels) include distributions of the diurnal event occurrence for the selected intervals for, respectively, the correlated and

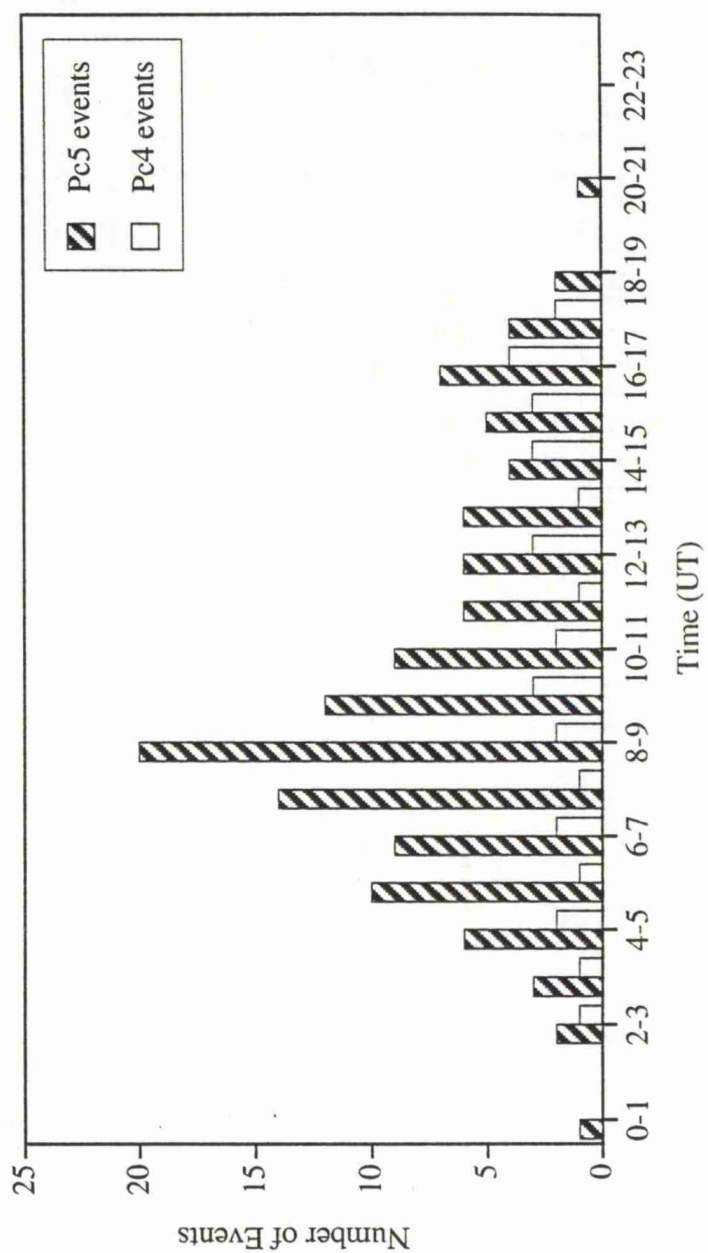


Figure 6.8: The diurnal occurrence distribution of ULF wave events in the Pc4 and Pc5 frequency range. The data for this plot were obtained by the DOPE sounder at Tromsø between June 1995 and February 1996.

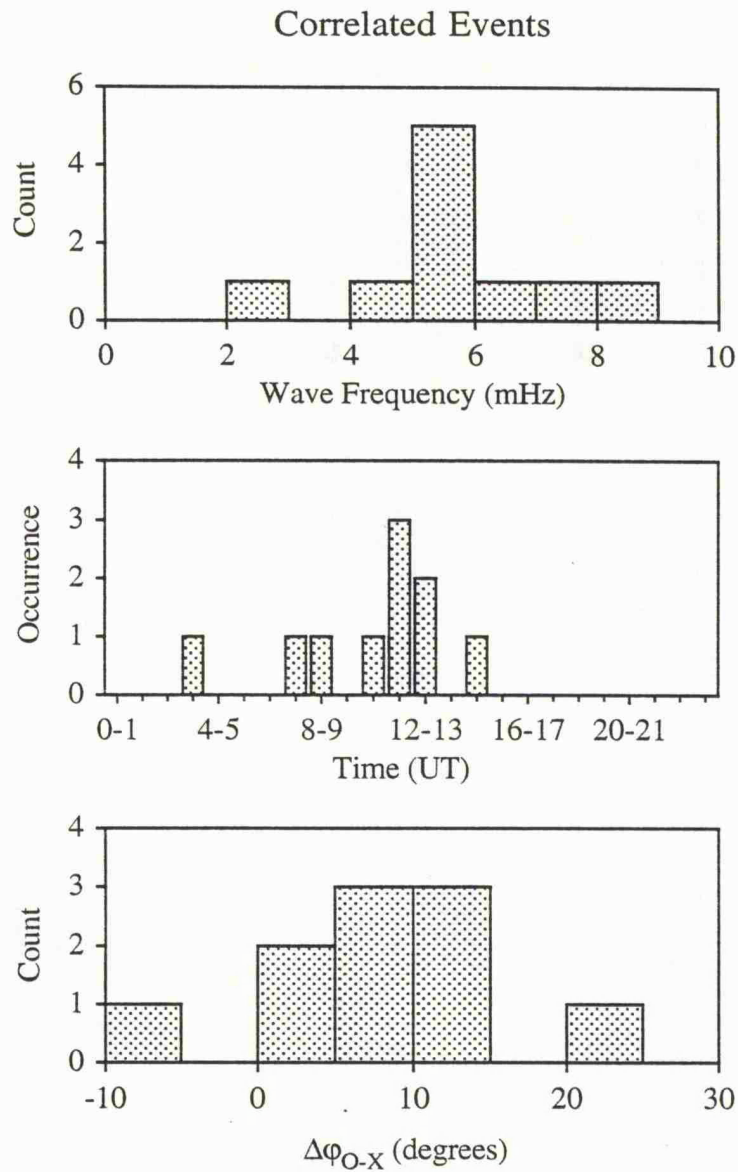


Figure 6.9: Distributions of ULF wave frequency (upper panel), diurnal occurrence (middle) and relative phase between the O- and X-mode Doppler signatures (lower) for the events where the Doppler signature correlated with oscillations in Tromsø magnetometer data. In the lower panel, negative relative phase indicates that the O-mode signature was leading in phase.

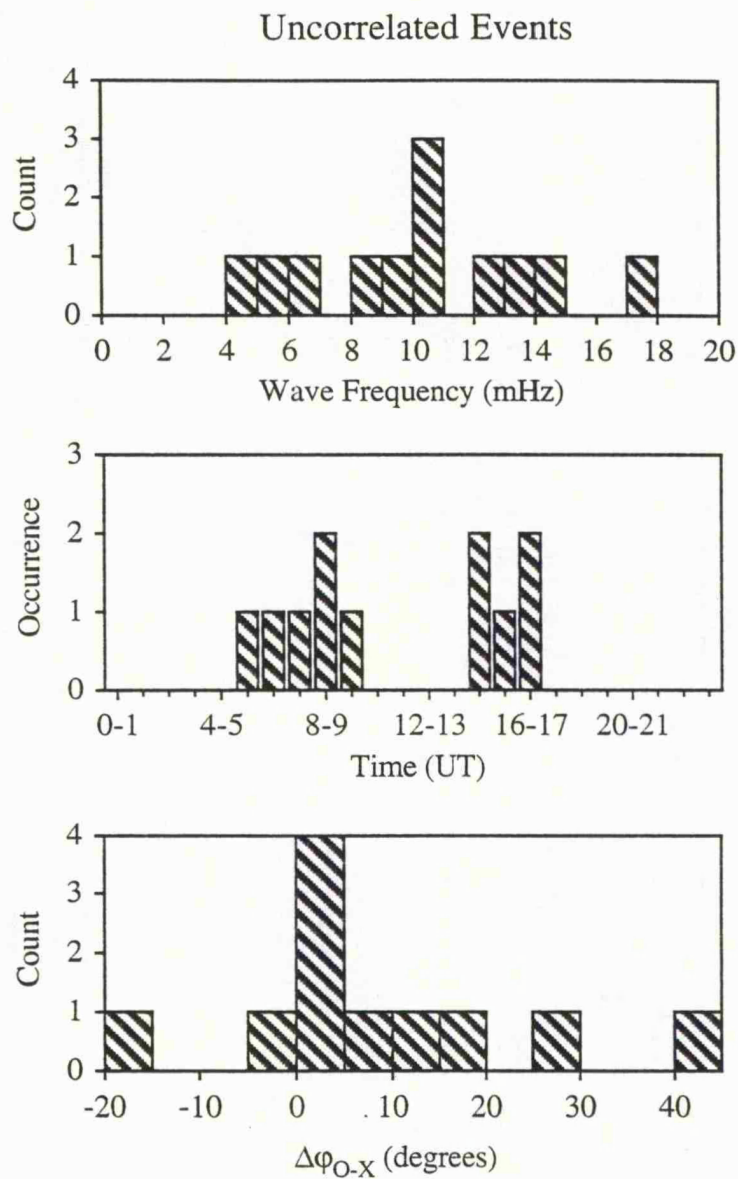


Figure 6.10: Distributions of ULF wave frequency (upper panel), diurnal occurrence (middle) and relative phase between the O- and X-mode Doppler signatures (lower) for the events where the Doppler signature did not correlate with oscillations in Tromsø magnetometer data. In the lower panel, negative relative phase indicates that the O-mode signature was leading in phase.

uncorrelated events respectively. The following differences are apparent: (a) the correlated events have a single peak in the 11-12 UT bin, whereas the other type have two obvious occurrence peaks; (b) the correlated events are mostly distributed over the range 7-15 UT, whereas the events which were not observed at the ground are concentrated into two sectors - one in the dawn/prenoon period and the other postnoon with none of the events identified around 12 UT.

Wave Characteristics Derived Directly from the Doppler Records

Also included in figures 6.9 and 6.10 are histograms representing the occurrence of ULF wave frequency and the phase difference ($\Delta\phi_{O-X}$) between the O- and X-mode wave signatures. A positive phase difference indicates that the X-mode was leading. Non-correlated events tend to have more widely and evenly distributed values of $\Delta\phi_{O-X}$. However, for such events a single narrow peak occurs around zero which is in contrast to correlated events, where the phase difference tends to be concentrated around small values in the range $5-15^\circ$. In both cases only one event was observed to have the O-mode leading the X. This phase difference is relevant when considering the vertical profile of the pulsation magnetic field perturbation, b , and the way in which the magnitude of the ionospheric response is affected. This will be discussed later with reference to the ionospheric coupling model of Poole *et al.* (1988) and Poole and Sutcliffe (1989).

The ULF wave frequency distributions in these figures indicate that the correlated event wave frequencies are below 10 mHz whereas the uncorrelated events range in frequency up to 18 mHz, which is an upper limit set by the temporal resolution of the Doppler data itself. The low frequency limit of about 2 mHz is equivalent to the longest periods of the Pc5 pulsation class. The majority of events observed without a ground signature are in the Pc4 range, in contrast to the ground correlated events in figure 6.9, which occur mostly with frequencies of 5-6 mHz (periods 165-200 seconds). Out of the 159 total events catalogued in the Doppler data set only 32 had frequencies in the Pc4 range.

Correlation of the Doppler and Ground Magnetic Signatures

This section is concerned solely with the 10 events which have been selected because of their simultaneous signature observation on the magnetometer and Doppler sounder. Figure 6.11 displays the Doppler shifts versus the X and Y magnetometer component perturbations for each of the correlated events. It indicates that a weak relationship may exist but the data are fairly spread. Examination of the magnitude of peak-to-peak Doppler shift (in Hz) of an event normalised to the magnitudes (in nT) of the X and Y component magnetometer

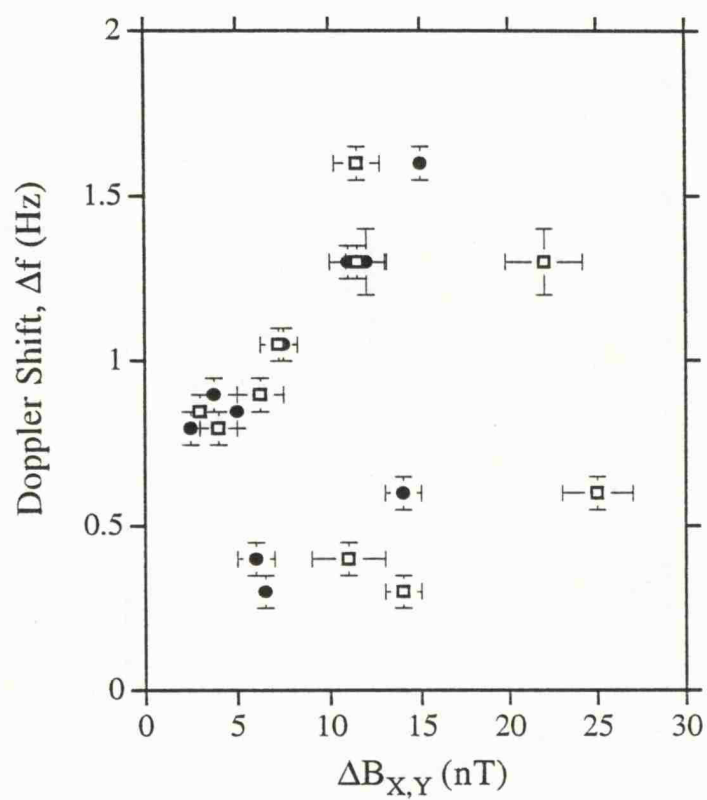


Figure 6.11: The O-mode peak to peak Doppler shift plotted as a function of X-component (squares) and Y-component (black circles) peak to peak deflections observed on the Tromsø magnetometer.

deflections indicates no obvious or simple relationship to m number. The values of $\Delta f/\Delta B_X$ and $\Delta f/\Delta B_Y$ are in the ranges 0.021-0.283 Hz nT⁻¹ (or 0.71-9.54 ms⁻¹ nT⁻¹ at 4.45 MHz) and 0.043-0.32 Hz nT⁻¹ (or 1.45-10.79 ms⁻¹ nT⁻¹ at 4.45 MHz) respectively. A ULF wave with larger magnetic perturbation might, to a first approximation, be expected to cause a larger frequency shift. However, since the Doppler sensitivity (see section 3.2.4) increases as the sounder frequency approaches the critical frequency then this may also influence these values to a large degree. Furthermore, as the m value of the wave increases then the amplitude of the ground magnetic signature tends to decrease (see section 2.2.2) which will make the calculated values deviate further from the expected relationship.

Phase Characteristics of the Correlated Wave Signatures

The relative phase between Doppler ULF wave signatures and those occurring simultaneously in magnetometer data has been of some interest [*e.g.* Menk (1992); Poole *et al.* (1988); Sutcliffe and Poole (1990)] with regards to the mechanisms which create an ionospheric change associated with the magnetospheric ULF wave. In this study the relative phase between Doppler O-mode and Y component magnetometer has been selected. The reason for selecting the O-mode ray is simply that this is the mode which has generally been used by previous authors whether modelling or presenting experimental data. The phase of the north-south (X) magnetic component of a field line resonance varies over 180° across the resonance region (see section 2.2.3), whereas the east-west (Y) component is related to the associated azimuthal wave number and is more stable in phase over a localised region. The Y component of the Tromsø magnetometer data has been chosen for this phase comparison.

The resulting distribution of B_Y - O-mode phase difference, $\Delta\phi_{YO}$, is displayed in figure 6.12. Values of $\Delta\phi_{YO}$ in the range 90-150 degrees occurred most frequently. In addition, examination of the relative phase of the ULF wave signatures in the O- and X-mode Doppler data demonstrates that phase shifts of around 0-20 degrees with the X-mode leading, in all but one case, occurs.

Azimuthal Wave Number Dependence of Wave Parameters For Correlated Events

Apart from magnitude and frequency, the azimuthal wave number, m , is an important parameter which can be measured from ground based observations of ULF waves. Therefore, data will now be examined to determine the significance of this parameter in the present results.

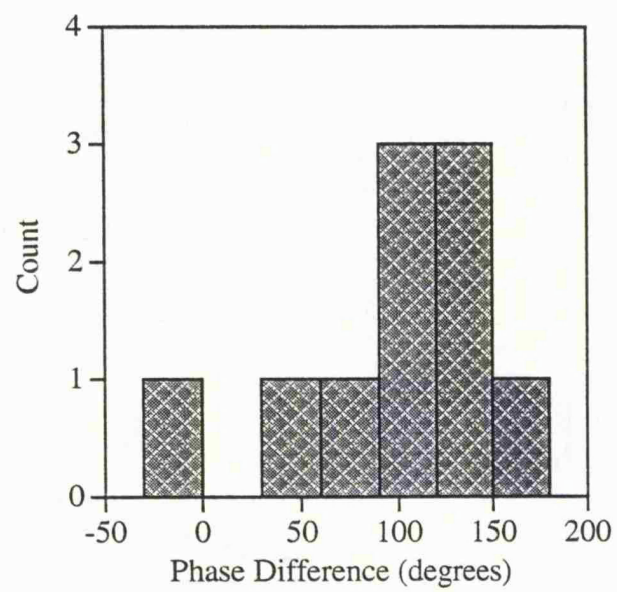


Figure 6.12: The occurrence of characteristic phase differences between the TRO Y component and the Doppler O-mode ULF waves signatures. Values have been counted in 30° bins. A positive phase difference indicates a leading B_Y signature.

For each of the correlated events, the azimuthal wave number, m , was determined from ULF wave signatures in magnetometer data from Tromsø (TRO) and Sodankylä (SOD). Figure 6.13 illustrates the derived dependence of ULF wave period with m . Note that the wave periods all lie within 100-400 seconds (2.5-10 mHz) and $3 \leq m \leq 8$. The observed periods are consistent with the findings of Poulter *et al.* (1984) who derived (see their figure 2) the periods associated with field line resonances as a function of geomagnetic latitude, by the STARE radar. The range of m values agrees with the observations of field line resonances determined from the SABRE radar by Yeoman *et al.* (1990).

The relative phase between the O- and X-mode signatures and between the TRO Y component and the O-mode signatures are plotted against m in figure 6.14. The O-X mode phase difference is concentrated in the 0-20° range (figure 6.9, lower panel) and indicates no obvious dependence on m . The relative phase between the TRO Y component wave and that in the O-mode data ranges, for these events, from about 60° to almost 180° and again has no definable relationship to m . However, waves with values of m between 3-5 only range between 90° and 150°.

6.3 Discussion

The following discussion will concentrate on the distinction between the correlated and uncorrelated events presented above. Specifically, the various derived parameters associated with the ULF waves demonstrate the difference between the likely types and sources of these waves.

The overall diurnal occurrence distribution (figure 6.8) of the 159 events looked at so far with this system is consistent with the results of the statistical study presented in chapter 5. In particular the prenoon occurrence peak is consistent with that observed in figure 5.2, the distribution for the whole data set in that study. The peak in the earlier Doppler data occurs a little later than for the recent data. Two facts may account for this difference. There are considerably fewer observations considered from the recent data set compared with that spanning 5 years in chapter 5. Furthermore, the data presented in chapter 5 are centred around solar maximum (1979-80) whereas the recent data represent conditions very close to sunspot minimum. It is likely that pulsation activity may have been at a higher level for the former. However, examination of figure 5.2 and consideration of ratio B and ratio C given, for the total data set, in figure 5.3b successfully allowed an optimum frequency for the DOPE sounder frequency to be selected so that the

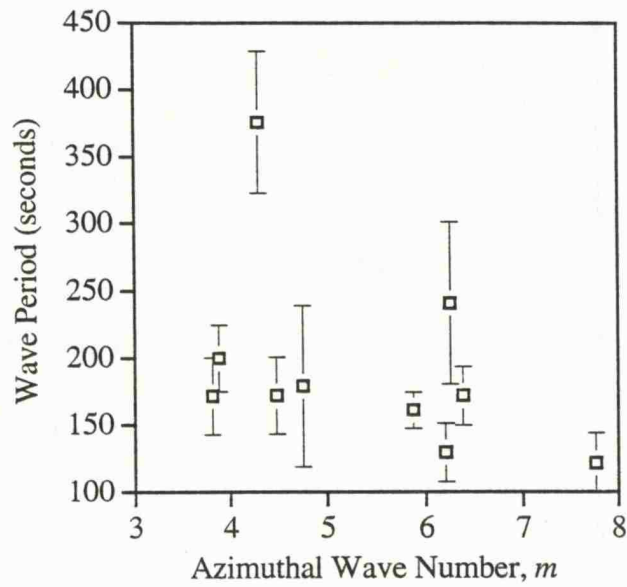


Figure 6.13: ULF wave period, derived from the Doppler data, for correlated events as a function of the azimuthal wave number, m (derived from magnetometer data).

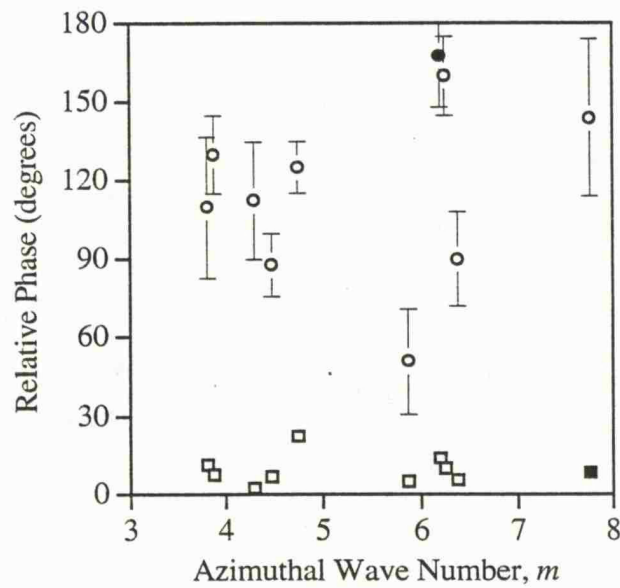


Figure 6.14: Azimuthal wave number (m) dependence of the relative phase between the O- and X-mode Doppler signatures (squares) and the relative phase between the TRO Y component and O-mode Doppler signature (circles). Black symbols indicate the X-mode or TRO Y component lagging in phase respectively.

number of observations could be maximised, and has been used in planning 3 EISCAT campaigns.

6.3.1 Correlated Wave Events

The correlated waves observed by the DOPE sounder occur in a UT range which is similar to those corresponding to conventional field line resonance events seen in other instrumentation. This will now be investigated further.

Diurnal Occurrence Distribution

The most important point to be made about the middle panels of figures 6.9 and 6.10 is that they demonstrate that the overall statistics (figure 6.8 and hence also figure 5.2) consist of two distinct populations. The middle panel of figure 6.9 indicates that correlated events, which are mostly Pc5s, have a peak occurrence in local time in the early afternoon with a few observations in the morning sector. The A-class waves observed at the ground [Gupta and Niblett (1979)] and in orbit [*e.g.* Kokubun (1985)] (figure 2.10) each demonstrate a bimodal distribution of occurrence with peaks in the dawn and dusk sectors. The distributions are asymmetric, where the spacecraft observations illustrate a significantly larger peak in the morning, peaking around 6-7 LT. The smaller afternoon peak has a maximum around 14-15 LT. In contrast the bimodal ground magnetometer occurrence distribution (figure 2.10b) has a slightly larger peak in the afternoon which occurs slightly later (15-17 UT) than for the observed satellite distribution. Both data sets have been associated with field line resonances generated at the dawn and dusk flanks of the magnetosphere by the Kelvin-Helmholtz instability. The observations in figure 6.9 (middle panel) represent some of the observations of FLRs which occur in the early afternoon. However, the data set illustrated in figure 6.9 is not large enough to fully represent the true occurrence distribution observed by the Doppler sounder.

Characteristic Wave Periods

The range of observed correlated wave periods, as illustrated in figure 6.13, is 100-400 seconds (2.5-10 mHz) and occur for $3 \leq m \leq 8$. The observed periods are consistent with the findings of Poulter *et al.* (1984) who presented (see their figure 2) the periods associated with field line resonances as a function of geomagnetic latitude derived from STARE radar observations. The range of periods associated with low m field line resonances at the latitude of Tromsø were about 200-590 seconds (equivalent to frequencies 1.7-5 mHz) - essentially the whole Pc5 range. This supports the hypothesis that the correlated events presented here are a result of such field line resonances. In addition, the range of m values

for these events agrees with the observations of field line resonances on the SABRE radar by Yeoman *et al.* (1990).

Phase Relationships

A characteristic feature of a field line resonance is that the phase of the wave changes by 180° at either side, in a magnetic meridian, of the resonance region [Southwood (1974)]. Also, the phase north of the resonant field line lags that to the south of it [*e.g.* Orr (1984)]. Due to their propagation characteristics the O- and X-mode signals of the Doppler sounder deviate north and south, respectively. The Tromsø magnetometer field of view will be somewhere between the reflection points of the two radio wave modes. Thus, for a correlated event, if they are field line resonances as suggested above, the X-mode signature phase should lead that of the O-mode and, similarly the O-mode signature should lag in phase relative to the magnetometer signature. Figure 6.9 (lower panel) supports this supposition, again indicating that correlated events are the result of such field line resonances.

6.3.2 The Uncorrelated Events

This second class of events recorded by DOPE at high latitude are very different from the correlated events. They do not exhibit the characteristics of field line resonances and are subdivided into two further types: those occurring in the morning and afternoon sectors respectively. All exhibit similarities to high m waves observed previously at the ground, in the ionosphere and by orbiting satellites. For the 11 events studied here there is no distinction between the morning and afternoon populations in terms of wave frequency or the relative phase between the O- and X-mode signatures.

Diurnal Occurrence Distributions

The diurnal occurrence distribution of the 11 selected uncorrelated events, which is given in figure 6.10 (middle panel), is concentrated into two groups. One in the morning between 5-10 UT and another in the interval 14-17 UT. None of the events are identified around 12 UT. This compares with the distribution for correlated waves (figure 6.9) where all events occur in one region which peaks just after local noon at a value higher than for either of the two uncorrelated groups.

Giant (Pg) pulsations occur most commonly in the morning sector in the 02-07 LT interval, peaking in the range 03-06 LT, [Green (1979); Chisham and Orr (1991)] with few observations in the afternoon. Drift waves in the quiet time ring current

have been suggested as the likely mechanism causing this type of ULF wave. Events have also been observed at geostationary orbit by the GOES 2 satellite (figure 2.10a) which did not have an associated ground magnetic signature. Kokubun (1985) reported that a subset of the A-class Pc5 waves observed were uncorrelated at the ground at the foot point of the satellite field line. The diurnal distribution of these events was also bimodal. The early morning peak in the data of Kokubun (1985) and the prenoon peak of the uncorrelated events presented in this thesis are both reminiscent of the distribution for giant pulsations. It is possible that the reason these waves were not observed on the ground is because they have high m numbers associated with them.

It is now widely accepted that a source of R-class type waves exists in drifting energetic particle fluxes. Particles of this type entering the Earth's near geospace from the geotail will undergo gradient curvature drift and, thus, move around the Earth constituting part of the global ring current. The drifting particles can drive MHD wave modes through wave-particle interactions, leading to perturbations in the electric and magnetic fields in the ionosphere [e.g. Hughes (1983)]. The $\mathbf{E} \times \mathbf{B}$ drift imposed on the plasma under these conditions is observed by VHF coherent radars, such as SABRE [e.g. Yeoman *et al.* (1992); figure 2.4]. This is believed to be the dominant mechanism which leads to detection of ULF wave signatures in the backscatter received by these systems in the dusk local time sector. Kokubun (1985) employed this particle driven mechanism to explain why so many R-class waves are observed after substorm onsets. The delay between the onset and the wave is caused by the time taken for the particles to drift from the midnight sector around to the time zone in which the observing instrument is located. The Storm time Pc5s seen in STARE data [Allan *et al.* (1983)] are R-class waves of high m number and period in the Pc5 range which are associated with the above source mechanism.

The diurnal distribution of the afternoon uncorrelated waves is consistent with the observed distributions for R-class waves at geostationary orbit, which has a maximum occurrence around 14-15 LT, (figure 2.11) and the storm time Pc5s observed on the STARE radar [Allan *et al.* (1983)], which occur in the 14-20 LT [e.g. Kremser *et al.* (1981)] interval, having peak occurrence around 17-18 LT. Both of these types of waves have been associated with ring current proton drifts. The afternoon peak in the ground uncorrelated A-class waves observed by Kokubun (1985) is similar to that for the uncorrelated waves in this study and those of the storm time Pc5s seen on the STARE radar. It is possible that the

reason these waves were not observed on the ground is because they have high m numbers associated with them [e.g. Allan *et al.* (1982, 1983)].

The Relative Phase of the O- and X-mode Signatures

Most of uncorrelated events exhibit little or no phase difference between the O- and X-mode Doppler signatures (figure 6.10, lower panel). This contrasts with the correlated events which were generally associated with a small O-X mode phase change with the X-mode signature leading (figure 6.9). Storm time Pc5s are non-resonant phenomena [e.g. Allan *et al.* (1982,1983)] with little latitudinal phase change (figure 2.13). However, Pg pulsations are known to have a latitudinal phase variation which is the same as that of a field line resonance in the H (north) component [Green (1979)]. However, the dominant Pg signal occurs in the D (azimuthal) component which has no latitudinal phase change (figure 2.12) [Green (1979); Chisham and Orr (1991)]. Thus, the O-X phase difference supports the hypothesis that the uncorrelated events are a type of event which is quite distinct from the correlated waves and that both the prenoon and postnoon events result from a mechanism involving particle driven field lines.

The Periods of the Uncorrelated Wave Signatures

The ULF wave frequency distribution in figure 6.10 (upper panel) suggests that the uncorrelated waves range in frequency from 4 to 18 mHz. The Pc4/5 boundary occurs at 6.67 mHz (150 seconds period) which indicates that the majority of events observed without a ground signature are in the Pc4 range. In contrast, the ground correlated events in figure 6.9 (upper panel) occur mostly with frequencies in the 5-6 mHz bin (periods 165-200 seconds) which are in the Pc5 range. Out of the 159 total events catalogued in the Doppler data set only 32 had Pc4 frequencies.

Allan *et al.* (1983) demonstrated that the “storm time” Pc5s observed with the STARE radar had frequencies which ranged from 2.4-5.7 mHz. Similarly, the equatorward propagating events seen in SABRE data [Yeoman *et al.* (1992)], associated with drifting energetic protons, were all in the Pc5 frequency range. Thus, particle driven waves of this type, which occur in the afternoon/dusk sectors are likely to account for some of the ground uncorrelated afternoon events in this study.

Chisham and Orr (1991) studied the characteristics of giant (Pg) pulsations observed on the EISCAT magnetometer cross chain and found that the wave periods were all in the range of Pc4 waves. Green (1979) studied Pgs observed at Tromsø and found that all the waves had periods in the range 50-130 seconds

(7.7-20 mHz). These waves have also been shown to have large m numbers. For example, the 34 Pg events studied by Chisham and Orr (1991) had an average m of 26. Thus again, this type of wave may be contributing to the observations of uncorrelated waves. The occurrence time as well as the long-lived, monochromatic nature of the wave presented in figure 6.4 is reminiscent of a Pg type wave. The uncorrelated events have a distribution in period similar to that for the Pgs. This fact will be dealt with further later in the discussion, where the theoretical relationship between period and m value is considered.

Associated D_{st} Measurements

D_{st} is a global index which is a measurement of the deviation from its mean value of the magnetic field associated with the equatorial ring current. The magnetic field associated with an injection of particles on the nightside, which subsequently drift around the Earth, opposes the Earth's own magnetic field. Hence, such an injection will have an associated depression in D_{st} . Figure 6.15 gives the results of a superposed epoch analysis of D_{st} magnitude around each of the 21 events. That is, the D_{st} values for 12 hours before and 6 hours after the start of each wave signature are averaged in one hour bins in order to determine the mean variation. The upper panel illustrates the D_{st} values around the correlated events and the middle and lower panels represent, respectively, the magnitude of the index associated with the uncorrelated events observed before 12 UT and after. D_{st} is moderately depressed during intervals when correlated events occur. However, there seems to be some difference in D_{st} between uncorrelated signatures which commence in the prenoon and postnoon sectors. The middle panel of this figure implies that the prenoon events occurred when geomagnetic activity was low or at least there were no significant plasma injections associated with these times. This supports the idea that these events may be associated with quiet-time [Green (1979)] giant (Pg) particle driven pulsations. The postnoon intervals, however, on average had larger changes in D_{st} around the times that the waves were observed. The changes in the index are larger here than for the times when correlated events occurred. This tends to support the likelihood that postnoon, but not prenoon, uncorrelated waves are associated with particle injections under geomagnetically active conditions and may be the same type of event as the storm time Pc5s observed with the STARE radar [Allan *et al.* (1983)] and the equatorward propagating events identified in SABRE radar data by Yeoman *et al.* (1992) (cf. their figure 11). Both of these types of VHF radar signature had high measured m values and were either attenuated on ground magnetometers or not observed at all.

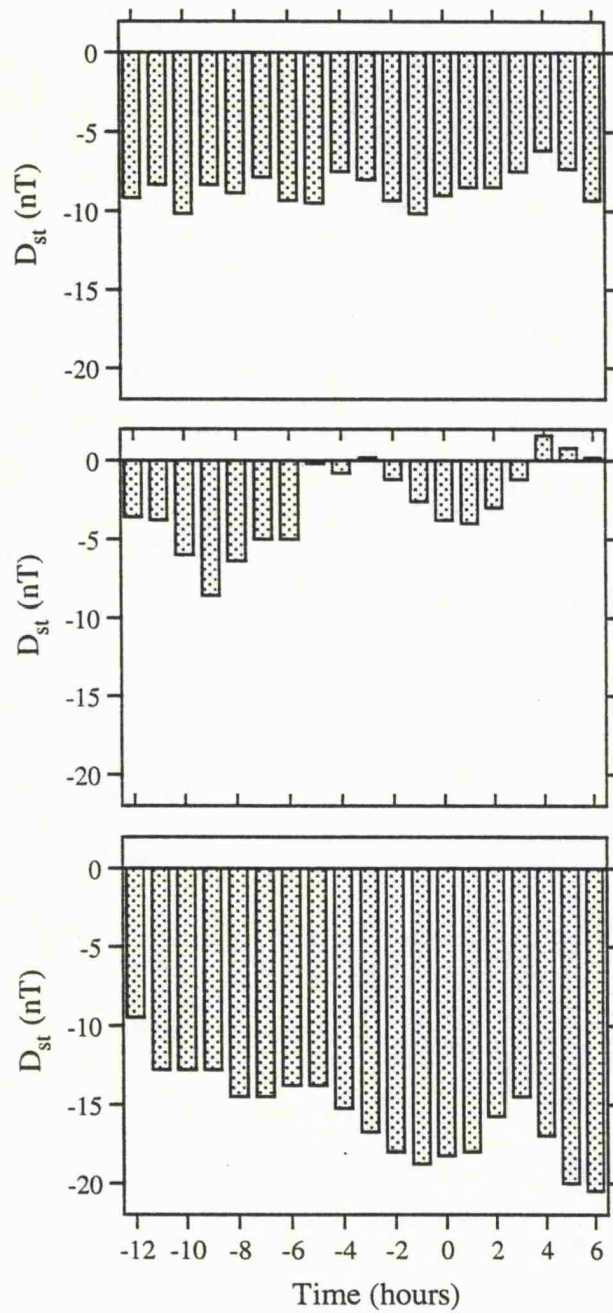


Figure 6.15: A superposed epoch analysis of the Dst index for 12 hours prior and 6 hours after the commencement of the observed ULF wave signatures. Panels illustrate results for correlated events (upper), uncorrelated events before 12 UT (middle) and uncorrelated events after 12 UT (lower).

ULF Waves with High Azimuthal Wave Numbers

It is probable that the ground magnetic signature of the uncorrelated events presented in this thesis were not observed by ground magnetometers because the spatial integration by these instruments causes phase mixing of waves with a large azimuthal wave number (see section 2.2.2). Ionospheric screening [Hughes and Southwood (1976a,b)] causes such waves to be attenuated so that the ground signature is weak. A good example of this effect is given in figure 2.4 [Yeoman *et al.* (1992)] where two pulsations with different m values, observed by the SABRE radar a short time apart, had very different ground magnetic signatures. The second wave, occurring between 20 and 21 UT, had larger m and was considerably more attenuated at the ground. The SABRE and STARE VHF radars, on the other hand, have range resolution of about 20 km [Nielsen *et al.* (1983); Greenwald *et al.* (1978)] and a Doppler sounder has a horizontal range integration of around 5 km. Thus, these instruments would be able to resolve high m wave signatures in the ionosphere. Assuming that the uncorrelated events presented here have large m values associated with them, then the range of measured wave frequencies given in figure 6.10, which are in agreement with those given by the authors above, support the hypothesis that at least a subset of these waves may be a result of a particle driven mechanism.

Estimations of the drift speed of protons in the equatorial plane have been made by Allan *et al.* (1982, 1983) using the observed period and m value for a given wave. Yeoman *et al.* (1992) gave an expression for this:

$$V_{eq} = \frac{2\pi LR_E}{m\tau}, \quad (6.1)$$

where V_{eq} is the drift velocity in the equatorial plane and τ is the wave period. L is the L -shell of the drifting particles, m is the azimuthal wave number and R_E is the radius of the Earth. Particle populations with drift speeds in the range 20-40 kms⁻¹ (consistent with the gradient curvature drift for protons with energies in the range 35-70 keV) were deduced to be the driving mechanism for the storm time Pc5s of Allan *et al.* (1982,1983) and also to be consistent with the equatorward propagating Pc5s observed by Yeoman *et al.* (1992). Assuming a value of V_{eq} of 30 km s⁻¹, $L=6.6$ for Tromsø and $R_E=6400$ km we obtain an expression relating the period of such waves to their expected m values,

$$m = \frac{8870}{\tau}. \quad (6.2)$$

The 11 uncorrelated events presented here have wave frequencies in the range 4.2-17.9 mHz. If a particle population of similar energy to that for storm time Pc5s is assumed to be the source for the uncorrelated events, the corresponding m values are, from equation 6.2, in the range, 37-159. These may be compared to

those given by Allan *et al.* (1982, 1983) for the storm-time Pc5s observed by the STARE radar, which ranged from 7-80, and for the SABRE observations of equatorward propagating Pc5s presented by Yeoman *et al.* (1992) where m ranged from 5-36 for the 26 events that they studied quantitatively. This supports the hypothesis that the uncorrelated waves presented in this thesis are a result of particle driven ULF waves. Furthermore, considering that ground magnetometers often do not observe high m waves ($m \geq 20$) then the above result suggests that higher m value waves may be observed with instruments which have highest spatial resolution (or integrate their data over the smallest area) such as Doppler sounders (~5 km) or coherent radars (~15-45 km) in contrast to ground magnetometers which integrate data over an area with a scale size of around 120 km.

6.3.3 Comparison of DOPE Results with Previous Observations and Modelling

Comparison is now made between the present data set and the model for relating Doppler ULF waves signatures to the incident wave field parameters described in detail in section 3.3.2 [Poole *et al.* (1988); Sutcliffe and Poole (1989, 1990); Sutcliffe (1994)] Included in this discussion will be previous experimental observations of such Doppler signatures and their correlation with waves detected on ground magnetometers.

Modelling Doppler ULF Wave Signatures

An ionospheric interpretation of relative phase between Doppler and ground magnetometer signatures is provided by the model of Sutcliffe and Poole (1990). It is important to note that the model profile employed for comparison in this study, as illustrated in figure 3.7, is not directly applicable and provides a qualitative comparison only. The ionospheric profile input into the model, taken from IRI 1979, in fact applies to a mid-latitude location at midday in summer at solar maximum, unlike the conditions of solar minimum at high latitudes which are appropriate for the present observations. The sounding frequency modelled is very close to the critical frequency of 7.3 MHz, however, and is likely to be a reasonable guide for the results in this thesis where the sounding frequency of 4.45 MHz is near to the critical frequency. Relative to the b_x and b_y components of the pulsation field which have a phase of 0° at the ground, components of the Doppler velocity due to the advection mechanism lagged by about 120° at F-region heights and those due to their compressional mechanism lead in phase by about 60° . The data for the correlated events (figure 6.12) indicate that a phase

shift, $\Delta\phi_{YO}$, in the range 90 - 150° occurred most often, with B_Y leading in phase. The model of Sutcliffe and Poole (1990), which is derived for an ionospherically reflected down-going Alfvén wave, implies that the “advection” mechanism dominates during these events and that field compression is small.

It is also important to note that, according to the model results of Sutcliffe and Poole (1990), there will be a phase difference between the O- and X-mode signatures as a result of the difference in their respective reflection heights (figure 3.8). As the sounding frequency approaches the F-region critical frequency (similar to the condition for this experiment), this phase difference, predicted by the model, is expected to lead in the O-mode rather than the X-mode signature and to be quite small (~ 10 - 20°). The phase of a FLR observed at the ground varies by 180° in the north-south direction across the resonance point. Thus, the effect of the height difference is expected to be dominated by that due to the north-south deviations when an FLR occurs. Figures 6.9 (lower panel) and 6.12 indicate that the X-mode signature leads in phase for correlated events, again suggesting that they are the result of field line resonances and, hence, that latitudinal effects may dominate those due to height separation of the HF wave modes. For uncorrelated waves the O-X mode phase difference, $\Delta\phi_{O-X}$, is most often around zero. Thus, either these waves are not the result of a field line resonance or the height related phase difference is more important.

The amplitude of the Doppler oscillations relative to the peak-to-peak magnitude of the magnetometer signature in the north-south (X) component for the correlated events in this study are in the range 0.021 - 0.283 Hz nT⁻¹ (0.71 - 9.54 ms⁻¹ nT⁻¹ at 4.45 MHz). These values are considerably larger than those predicted by the model which, at F-region heights, are expected to be less than 1 ms⁻¹ nT⁻¹. The value is expected to be somewhat nearer to the critical frequency however.

Comparison with Previous Observations

Menk (1992) stated that at low latitudes the Doppler signature of daytime events was often in phase with the ground magnetic signature but that the phase frequently drifted around as time progressed which made it difficult to infer any general relationship. He suggested that this was due to phase mixing in the magnetometer signatures from contributions from adjacent regions of the ionosphere. For Pi2 observations in the same data set, no systematic phase relationship could be deduced for waves with periods less than 90 seconds. However, waves with periods 90-300 seconds in the Doppler data were generally either directly in or out of phase with ground magnetometer signatures. Menk

(1992) demonstrated that the daytime events had values of $\Delta f/\Delta H$ in the range 0-0.1 Hz nT⁻¹ (0-6.52 ms⁻¹ nT⁻¹ at 2.3 MHz) with those for the nighttime Pi2s having somewhat smaller values. This is compared to the range of 0.021-0.283 Hz nT⁻¹ (0.71-9.54 ms⁻¹ nT⁻¹ at 4.45 MHz) which is observed for the 10 correlated events studied here.

The present observations, along with those of Menk (1992) and Al'perovich *et al.* (1991), are consistently larger than the expected values derived from the model of Sutcliffe and Poole (1990). Menk (1992) suggested that the reason for the discrepancy might be due to the fact that the model employs a horizontal scale length which may in fact be too long for the types of events observed by sounders. A reduction in scale size would reduce the amount of phase mixing imposed on the signature and might increase its amplitude correspondingly. In addition, it is worth considering that any particle precipitation associated with an incident ULF wave at high latitudes might conceivably cause large amplitude signatures due to an increased electric field in the F-region ionosphere and, hence, an increase in the magnitude of the $\mathbf{E} \times \mathbf{B}$ drift. This could explain why the observations in the present study have larger amplitudes compared to those of the other authors whose measurements were made at low or mid-latitudes.

6.4 Summary

The DOPE system, optimised through the results determined from previous Doppler observations (chapter 5), has successfully observed the ionospheric signatures of magnetospheric ULF waves. Clear correlation has been achieved between some of the events and ground magnetometer data. However, so-called uncorrelated event signatures have also been observed where no associated ground magnetic signature was found. Thus, the observations in chapter 5 indicate two distinct populations of ULF waves.

The correlated events have been linked, through previous observations on the ground, in the ionosphere and in the magnetosphere to the signatures of resonant field lines with low m values. Comparison with modelling work supports this idea since the experimental data display relative phases between the Doppler and ground magnetometer signatures which are predicted by the model for an incident Alfvén wave.

In contrast, the uncorrelated events are related to waves with high values of azimuthal wave number, m . It seems likely that these phenomena are a result of

Chapter 6: High Latitude Doppler Sounder Observations of ULF Waves

two types of wave. The afternoon events are consistent with a storm time particle driven generation mechanism whereas those in the morning sector have features which suggest that they may be related to quiet time particle driven giant pulsations. D_{st} data support the conclusion that the afternoon waves are similar to the Pc5 events observed on the STARE and SABRE VHF radars, which have been related to drift bounce waves. The morning waves have associated D_{st} values which suggest that they occur during quiet times in a similar manner to giant pulsations.

The development and deployment of the DOPE system provides a link between ground based and satellite borne measurements of ULF waves, allowing routine observations from the ground which are not limited by the spatial integration of the instrument. The small integration area provided by a HF sounder (~5 km), effectively gives a point measurement in the ionosphere.

Chapter 7

Conclusions and Future Work

7.1 Introduction

A study of ULF wave occurrence at high latitudes has been undertaken by the re-examination of a Doppler sounder data set originally recorded over 10 years ago. The results of this study indicated the need for a new Doppler sounder which could record the effects of ULF waves in the ionosphere and be operated in conjunction with other instruments such as ground magnetometers and the EISCAT radar. A new sounder has been constructed and deployed near Tromsø, Norway. It has already identified two distinct types of waves and enabled the characteristics of these waves to be determined. Possible future studies are discussed in the light of the new results.

7.2 The Early Tromsø Doppler Sounder

Doppler data measured at a high latitudes over an interval of five years, from 1979 to 1984 has been examined for the presence of ULF wave signatures. A quantitative analysis has been undertaken in terms of three ratios (see table 5.2), *i.e.* the relative number of useful observations made by the sounder during the period when data were recorded (ratio A); the intrinsic diurnal distribution of ULF wave occurrence when useful data are available (ratio B) and the relative number of ULF wave observations made when data were recorded (ratio C). Ratio A is strongly dependent on ionospheric propagation *i.e.* on factors such as foF2, and thus to the seasonal and solar cycle changes. Ratio B is found to be strongly dependent on geomagnetic activity and its changes are consistent with similar results reported by other workers. The third ratio provides a measure of the effectiveness of the sounder for observing ULF wave signatures and is a convolution of ratios A and B.

The outcome of this study demonstrates that ULF wave activity shows variations which are similar to those reported by other authors employing different instrumentation. The data indicate when ULF wave activity is most likely to be observed by a Doppler sounder and this has enabled coordinated experiments (such as DOPE with EISCAT and ground magnetometers) to be optimised. In addition, the investigation has allowed the generation processes of the observed ULF waves to be identified and this has been related to the work of other investigators.

7.3 The New DOPE Sounder

A new HF Doppler sounder has been built at Leicester and deployed near Tromsø for ULF wave observations and forms part of the Doppler Pulsation Experiment (DOPE), a multi-instrument campaign involving radars and magnetometers. The data from the Doppler sounder are digitally sampled and stored by a control PC linked to the receiver. A major feature of this equipment is the fact that both the transmitter and receiver may run completely unattended for several weeks in a remote environment. The sounder receiver resolves O- and X-mode signal components which are reflected from spatially separated (both in height and range) positions. This enables the phase changes in the pulsation signature to be determined in the meridian plane, a fact which demonstrates that the Doppler signatures are the result of magnetospheric ULF waves rather than infrasonic waves or interference.

A series of innovative hardware and software measures have lead to a cost effective approach in the development of this system. In particular, the timing and receiver attenuation control were made possible by means of small modifications to already existing PC and receiver hardware and the design of dedicated software to manipulate low level processes in the PC. The UPS external power supply is monitored by the computer which allows complete data management by the system even when the external power fails. The QNX operating system for the PC provides a multi-tasking environment which enables intercommunication between independent control processes, the utilisation of “shell” script in addition to ‘C’ language software and enables various tasks to be driven, for example a real time data display, while the system continually logs data. The whole system has the flexibility for new experiments and future development.

7.4 Results from DOPE

A number of ionospheric signatures of magnetospheric ULF waves have been successfully observed with DOPE. The overall distribution of these events is similar to that derived from the data base provided by the earlier sounder. The diurnal distribution of occurrence in each case is reasonably broad and peaks shortly before 12 UT. A minimum in occurrence around midnight is related to the diurnal variation of foF2 as described above. Thus, recent measurements confirm and extend the existing statistical study.

Chapter 7: Conclusions and Future Work

Case studies clearly indicate that ULF wave signatures are distinct and distinguishable from the transient effects of other wave types such as acoustic-gravity waves. They also clearly demonstrate that two distinct types of wave are present in the new data set. Clear correlation has been achieved between one type of event and ULF waves recorded in ground magnetometer data; these have been termed “correlated” events. However, the second type, so-called “uncorrelated” event signatures, have also been observed, where no associated ground magnetic signature was found. A quantitative analysis has been performed on the 10 clearest correlated events and the 11 clearest uncorrelated events.

The correlated events signatures exhibit wave periods in the range 100-400 seconds and azimuthal wave numbers in the range $3 \leq m \leq 8$ (figure 6.13). This is consistent with previous observations on the ground, in the ionosphere and in the magnetosphere of the signatures associated with field line resonances with low m values. In addition, the relative phases between the O- and X-mode Doppler signatures and between the Doppler signatures and the wave occurring on ground magnetometers is indicative of the latitudinal phase profile of a field line resonance. These phase measurements contribute towards the verification of a model of the conversion mechanisms between the magnetospheric pulsation electric and magnetic field perturbations of an incident Alfvén wave and its ionospheric signature in a Doppler sounder [Poole *et al.* (1988); Sutcliffe and Poole (1989, 1990)].

In contrast, the uncorrelated events are thought to be related to waves with high azimuthal wave number, m . These phenomena are subdivided into two types of wave. The afternoon events (figure 6.10) are consistent with a particle driven generation mechanism during active conditions. D_{st} data support the belief that the afternoon waves are similar to the Pc5 events observed on the STARE and SABRE VHF radars, which have been related to drift bounce waves. The Doppler signatures occurring in the morning sector have features which are reminiscent of those exhibited by giant pulsations. D_{st} values suggest that these events occur during quiet times in a similar manner to this type of ULF wave. Thus, moderate geomagnetic conditions are optimum for the observation of correlated waves but giant pulsation signatures in the morning and those due to storm time waves in the afternoon sector occur when conditions are quiet and active respectively.

The development and deployment of the DOPE system allows routine observations from the ground which are not limited by spatial integration such as occurs with ground magnetometers. The 5 km integration area provided by a HF sounder effectively gives a point measurement in the ionosphere which makes the

system more sensitive to small scale structures than a ground magnetometer. It is waves at these small scale lengths which have lead to the observations of “uncorrelated” pulsations. The point measurements of the DOPE system thus provides a link between ground based and satellite borne *in situ* measurements of magnetospheric ULF waves.

7.5 Future Work

The DOPE sounder is in continuous operation in the Norwegian Arctic and is expected to collect data over a period of several years. As the data set increases, the statistics of ULF wave occurrence will improve providing more information regarding the different populations of waves. There already exists a limited data base of EISCAT measurements from the SP-UK-DOPE program which will also increase as more time is allocated on the radar in the future. The opportunity should arise for multi-instrument studies, which include ground magnetometers, ground based HF and VHF radars, other sounders and satellites. Comparison of these sensors will allow the characteristics of the two populations of ULF waves to be investigated further.

There is an urgent need to collect sufficient data to verify the model of Poole *et al.* (1988) and Sutcliffe and Poole (1989, 1990). Application of the model should enable the determination of which mechanisms contribute the most to the ionospheric changes which are observed by the Doppler sounder and under what conditions these contributions occur. The model must be run with input parameters and profiles closer to those appropriate for the present level of solar activity and for high latitude conditions. Data obtained during runs of SP-UK-DOPE will provide measurements of ion flows and E-region conductivities in the ionosphere. These can be input to the model to investigate the evolution of an incident ULF wave in the ionosphere and the boundary conditions associated with it. The evolution of the ULF wave signatures and the reflection and damping of ULF waves (section 2.2.2) have been the subject of some previous modelling studies. Unfortunately these have been poorly tested experimentally due to the small number of observations (section 3.3.2) and the difficulty in making appropriate measurements. The development of modelling studies and their verification by comparison with experimental data is regarded as a high priority for future studies.

The separation of the O- and X-mode waves recorded by DOPE enable the combined height and latitude variation of the phase of the pulsation electric and

Chapter 7: Conclusions and Future Work

magnetic fields to be determined. In order to enhance this capability a series of spatially separated sounders operating at different frequencies, and, therefore, reflecting at different altitudes, would provide a three dimensional picture of the wave structure in the ionosphere. Such observations would enable the conditions under which the “advection” and “compression” mechanisms dominate the signature observed on a Doppler sounder to be established. Furthermore, the differences between the ionospheric effect of incident Alfvén and fast mode waves can be addressed. Ultimately, the data can be utilised as input for future modelling work in an attempt to generate more accurate predictions of the coupling processes between the ionosphere and magnetosphere for ULF waves.

The work described in this thesis illustrates the desirability of combining ground and space based observations to investigate the magnetospheric and ionospheric signatures of ULF waves. In the near future, the number of available ground and space based instruments and their sophistication will increase significantly. This will result in more extensive studies into the nature of magnetohydrodynamic waves and the ionospheric response to them. HF Doppler sounders will play an important role in these future observations.

References

References

Allan, W. and Poulter, E. M.; "ULF waves - their relationship to the structure of the Earth's magnetosphere"; Rep. Prog. Phys., 55, p533, 1992.

Allan, W., Poulter, E. M. and Nielsen, E.; "STARE Observations of a Pc5 Pulsation with Large Azimuthal Wave Number"; J. Geophys. Res., 87(A8), p6163, August 1982.

Allan, W., Poulter, E. M. and Nielsen, E.; "Pc5 Pulsations Associated with Ring Current Proton Drifts: STARE Radar Observations"; Planet. Space Sci. 31(11), p1279, 1983.

Allan, W., White, S. P. and Poulter, E. M.; "Impulse excited hydromagnetic cavity and field line resonances in the magnetosphere."; Planet. Space Sci., 34, p371, 1986.

Al'perovich, L. S., Fedorov, E. N., Volgin, A. V., Pilipenko, V. A. and Pokhil'ko, S. N.; "Doppler sounding as a tool for the study of the MHD wave structure in the magnetosphere."; J. Atmos. Terr. Phys., 53(6/7), p581, 1991.

Anderson, B. J., Engebretson, M. J. and Rounds, S. P.; "A Statistical Study of Pc3-5 Pulsations Observed by the AMPTE/CCE Magnetic Fields Experiment - 1. Occurrence Distributions"; J. Geophys. Res., 95(A7), p10495, July 1990.

Annexstad, J. O. and Wilson, C. R.; "Characteristics of Pg micropulsations at conjugate points."; J. Geophys. Res., 73, p1805, 1968.

Appleton, E. V.; "The propagation of radio waves over the Earth"; Nature, 115, p382, 1925.

Appleton, E. V. and Barnett, M. A. F.; "Local reflection of wireless waves from the upper atmosphere."; Nature, 115, p333, 1925a.

Appleton, E. V. and Barnett, M. A. F.; "On some direct evidence for downward atmospheric reflection of electric rays."; Proc. Royal Soc., 190, p621, 1925b.

References

Appleton, E. V. and Builder, G.; "The ionosphere as a doubly-refracting medium."; *Proc. Physical Soc.*, 45, p208, 1932.

Arthur, C. W. and McPherron, R. L.; "The Statistical Character of Pc4 Magnetic Pulsations at Synchronous Orbit"; *J. Geophys. Res.*, 86(A3), p1325, March 1981.

Baker, D. N., Higbie, P. R. and Belian, R. D.; "Multispacecraft Observations of Energetic Electron Flux Pulsations at $6.6 R_E$ "; *J. Geophys. Res.*, 85(A12), p6709, December 1980.

Barry, G. H.; "A low power vertical incidence ionosonde."; *IEEE Trans.*, GE-9, p86, 1971.

Breit, G. and Tuve, M. A.; "A radio method of estimating the height of the conducting layer."; *Nature*, 116, p357, 1925.

Breit, G. and Tuve, M. A.; "A test of the evidence of the existence of the conducting layer."; *Phys. Rev.*, 28, p554, 1926.

Brown, W. L., Cahill, L. J., Davis, L. R. McIlwain, C. E. and Roberts, C. S.; "Acceleration of trapped particles during a magnetic storm on April 18, 1965."; *J. Geophys. Res.*, 73, p153, 1968.

Chan, K. L., Kanellakos, D. P. and Villard, O. G.; "Correlation of short-period fluctuations of the Earth's magnetic field and instantaneous frequency measurements"; *J. Geophys. Res.*, 67(5), p2066, 1962.

Chapman, P. J.; "HF Doppler System: Technical Report"; internal technical report; Radio and Space Plasma Physics group, Leicester University, UK; 1996.

Chapman, S.; "The absorption and dissociative or ionising effect of monochromatic radiation in the atmosphere on a rotating Earth."; *Proc. Phys. Soc.*, 43, p26, 1931.

Chen, L. and Hasegawa, A.; "A Theory of Long Period Magnetic Pulsations, 1. Steady State Excitation of Field Line Resonances"; *J. Geophys. Res.*, 79, p1024, 1974.

Chisham, G. and Orr, D.; "Statistical studies of giant pulsations (Pgs): harmonic mode."; *Planet. Space Sci.*, 39(7), p999, 1991.

References

Crowley, G., Wade, N., Waldock, J. A., Robinson, T. R., Jones, T. B.; "High time resolution observations of periodic frictional heating associated with a Pc5 micropulsation."; *Nature*, 316, p528, 1985.

Crowley, G., Hughes, W. J., Jones, T. B.; "Observational evidence of cavity modes in the Earth's magnetosphere."; *J. Geophys. Res.*, 92, p12233, 1987.

Cummings, W. D., Mason, F. and Coleman, P. J.; "Some Characteristics of Low Frequency Oscillations Observed at ATS-1"; *J. Geophys. Res.*, 77, p748, 1972.

Davies, K.; "Ionospheric Radio Waves."; Blaisdell Publishing Company; 1969.

Davies, K.; "Ionospheric Radio."; IEE Electromagnetic Waves series 31, Peter Peregrinus Ltd. publishers, 1990.

Dungey, J. W.; Penn. State Univ. Ionos. Res. Lab. Sci., report no. 69; 1954.

Dungey, J. W.; "Cosmic Electrodynamics."; Cambridge University Press; 1958.

Dungey, J. W.; "Interplanetary magnetic field and the auroral zones."; *Phys. Rev. Lett.*, 6, p47, 1961.

Fenwick, R. C. and Villard, O. G.; "Continuous recordings of frequency variation of the WWV-20 signal after propagation over a 4000 km path."; *J. Geophys. Res.*, 67, p3249, 1960.

Foppiano, A. J. and Bradley, P. A.; "Prediction of auroral absorption of high frequency waves at oblique incidence."; *Telecom. J.*, 50, p547, 1983.

Foppiano, A. J. and Bradley, P. A.; "Morphology of background auroral absorption."; *J. Atmos. Terr. Phys.*, 47, p663, 1985.

Georges, T. M.; "Ionospheric effects of atmospheric waves"; E. S. S. A. technical report; Institute for Environmental Research (Boulder, Colorado), I. E. R. 57 - I. T. S. A. 54; October 1967.

Georges, T. M.; "Infrasound from convective storms: examining the evidence."; *Rev. Geophys. Space Phys.*, 11(3), p571, 1973.

References

Green, C. A.; "Observations of Pg pulsations in the northern auroral zone and at lower latitude conjugate regions."; *Planet. Space Sci.*, 27, p63, 1979.

Greenwald, R. A., Weiss, W., Nielsen, E. and Thomson, N. P.; "STARE: A new radar auroral backscatter experiment in northern Scandinavia"; *Radio Sci.*, 13, p1021, 1978.

Gupta, J. C.; "Occurrence studies of Geomagnetic Micropulsations Pc5 at High Latitudes"; *J. Atmos. Terr. Phys.*, 35, p2217, 1973.

Gupta, J. C. and Niblett, E. R.; "On the Quiet-time Pc5 Pulsation Events (Spacequakes)"; *Planet. Space Sci.*, 27, p131, 1979.

Hargreaves, J. K.; "The upper atmosphere and solar terrestrial relations."; The Nostrand Reinhold Company, New York; 1979.

Hargreaves, J. K., Feeney, M. T., Ranta, H. and Ranta, A.; "On the prediction of auroral radio absorption on the equatorial side of the absorption zone."; *J. Atmos. Terr. Phys.*, 49, p259, 1987.

Heaviside, O.; "Telegraphy: Theory."; *Encyclopedia Britannica*, 33, p215, 1902.

Hines, C. O.; "Internal atmospheric gravity waves at ionospheric heights"; *Can. J. Phys.*, 38, p1441; 1960.

Hughes, W. J.; "Hydromagnetic waves in the magnetosphere."; *Solar Terrestrial Physics* (edited by Carovillano, R. L. and Forbes, J. M.); Reidel, Dordrecht; 1983.

Hughes, W. J. and Southwood, D. J.; "The Screening of Micropulsation Signals by the Atmosphere and Ionosphere"; *J. Geophys. Res.*, 81(19), p3234, 1976a.

Hughes, W. J. and Southwood, D. J.; "An Illustration of Modification of Geomagnetic Pulsation Structure by the Ionosphere"; *J. Geophys. Res.*, 81(19), p3241, 1976b.

Hughes, W. J., McPherron, R. L., Barfield, J. N. and Mauk, B. H.; "A compressional Pc4 pulsation observed by three satellites in geostationary orbit near local midnight."; *Planet. Space Sci.*, 27, p821, 1979.

References

Hunsucker, R. D.; "Radio techniques for probing the terrestrial ionosphere."; Springer-Verlag, New York; 1990.

Jacobs, J. A., Kato, Y., Matsushita, S. and Troitskaya, V. A.; "Classification of Geomagnetic Micropulsations"; J. Geophys. Res., 69, p180, 1964.

Jacobs, J. A. and Watanabe, T.; "Doppler frequency changes in radio waves propagating through a moving ionosphere."; Radio Sci., 1(3), p257, 1966.

Junginger, H., Geiger, G., Haerendel, G., Melzner, F., Amata, E. and Higel, B.; "A Statistical Study of Dayside Electric Field Fluctuations with Periods Between 150 and 600 s"; J. Geophys. Res., 89, p5495, 1984.

Kennelly, A. E.; Electrical World, 39, p473, 1902.

Kivelson, M. G., Etcheto, J. and Trotignon, J. G.; "Global compressional oscillations of the terrestrial magnetosphere: the evidence and a model."; J. Geophys. Res., 89(11), p9851, 1984.

Kivelson, M. G. and Southwood, D. J.; "Resonant ULF waves: a new interpretation"; Geophys. Res. Lett., 12(1), p49, 1985.

Kivelson, M. G. and Southwood, D. J.; "Hydromagnetic waves and the ionosphere."; Geophys. Res. Lett., 15(11), p1271, 1988.

Klostermeyer, J. and Röttger, J.; "Simultaneous geomagnetic and ionospheric oscillations caused by hydromagnetic waves."; Planet. Space. Sci., 24, p1065, 1976.

Kokubun, S.; "Statistical Characteristics of Pc5 Waves at Geostationary Orbit"; J. Geomag. Geoelectr., 37, p759, 1985.

Kokubun, S., Erickson, K. N., Fritz, T. A. and McPherron, R. L.; "Local Time Asymmetry of Pc4-5 Pulsations and Associated Particle Modulations at Synchronous Orbit"; J. Geophys. Res., 94, p6607, 1989.

References

- Kremser, G., Korth, A., Fejer, J. A., Wilken, B., Gurevich, A. V., Amata, E.; "Observations of Quasi-periodic Flux Variations of Energetic Ions and Electrons Associated with Pc5 Geomagnetic Pulsations"; *J. Geophys. Res.*, **86**, p3345, 1981.
- Mao Tian, Yeoman, T. K., Lester, M. and Jones, T. B.; "Statistics of Pc5 Pulsation Events Observed by SABRE"; *Planet. Space Sci.*, **39**(9), p1239, 1991.
- McDiarmid, D. R., Yeoman, T. K., Grant, I. F. and Allan, W.; "Simultaneous Observation of a Travelling Vortex Structure in the Morning Sector and a Field Line Resonance in the Postnoon Sector"; *J. Geophys. Res.*, **99**(A5), p8891, May 1994.
- Menk, F. W.; "Characterization of ionospheric Doppler oscillations in the Pc3-4 and Pi2 pulsation frequency range."; *Planet. Space Sci.*, **40**(4), p495, 1992.
- Menk, F. W., Cole, K. D. and Devlin, J. C.; "Associated geomagnetic and ionospheric variations."; *Planet. Space Sci.*, **31**(5), p569, 1983.
- Milan, S.; "Observations of HF radiowaves propagated over high latitude paths."; Ph. D. thesis, University of Leicester, UK; October 1994.
- Nichols, H. W. and Schelleng, J. C.; "The propagation of radio waves over the Earth"; *Nature*, **115**, p334, 1925.
- Nielsen, E., Guttler, W., Thomas, E. C., Stewart, C. P., Jones, T. B., and Hedburg, A.; "SABRE a new radar auroral backscatter experiment."; *Nature*, **304**, p712, 1983.
- Orr, D.; "Magnetospheric hydrodynamic waves: their eigenperiods, amplitudes and phase variations; a tutorial introduction."; *J. Geophys.*, **55**, p76, 1984.
- Poole, A. W. V., Sutcliffe, P. R. and Walker, A. D. M.; "The relationship between ULF geomagnetic pulsations and ionospheric Doppler oscillations: derivation of a model."; *J. Geophys. Res.*, **93**(A12), p14656, 1988.
- Poulter, E. M., Allan, W., Keys, J. G., and Nielsen, E.; "Plasmatrough ion mass densities determined from ULF pulsation eigen periods."; *Planet. Space Sci.*, **32**(9), p1069, 1984.

References

- QNX Software Systems Ltd; "QNX: system architecture."; 1995.
- Rao, D. R. K. and Gupta, J. C.; "Some Features of Pc5 Pulsations During a Solar Cycle"; *Planet. Space Sci.*, 26, p1, 1978.
- Reddi, C. R. and Rao, B. R.; "Anomalous variations in phase path records."; *J. Atmos. Terr. Phys.*, 29, p1063, 1967.
- Reeves, G. D., Fritz, T. A., Cayton, T. E. and Belian, R. D.; "Multi-satellite measurements of the substorm injection region."; *Geophys. Res. Lett.*, 17(11), p2015, 1990.
- Reid, G. C.; "Ionospheric disturbances" in "Physics of geomagnetic phenomena"; Academic Press, New York; 1967.
- Rishbeth, H. and Garriot, O. K.; "Introduction to ionospheric physics."; *International Geophysics Series*, 14, Academic Press (New York and London) publishers, 1964.
- Robinson, T. R.; "Modification of the high latitude ionosphere by high power radio waves."; Ph. D. thesis, University of Leicester, UK; June 1983.
- Robinson, T. R.; "The heating of the high latitude ionosphere by high power radio waves."; *Phys. Rep.*, 179(2&3), p79, 1989.
- Robinson, T. R. and Jones, T. B.; "A Preliminary Report on the Tromsø Doppler Experiment"; *Ionospheric Physics Group Internal Technical Report*, No. 25; January 1980.
- Southwood, D. J.; "Some features of field line resonances in the magnetosphere."; *Planet. Space Sci.*, 22, p483, 1974.
- Southwood, D. J. and Hughes, W. J.; "Theory of hydromagnetic waves in the magnetosphere."; *Space Sci. Rev.*, 35, p301, 1983.
- Stewart, B.; "On the great magnetic disturbance which extended from August 2 to September 7, 1859 as recorded by photography at the Kew Observatory."; *Phil. Trans. Roy. Soc. Lond.*, 151, p423, 1861.

References

Sutcliffe, P. R.; "Modelling the ionospheric signatures of geomagnetic pulsations."; J. Geomag. Geoelectr., 46, p1011, 1994.

Sutcliffe, P. R. and Poole, A. W. V.; "Ionospheric Doppler and electron velocities in the presence of ULF waves."; J. Geophys. Res., 94(A10), p13505, 1989.

Sutcliffe, P. R. and Poole, A. W. V.; "The relationship between ULF geomagnetic pulsations and ionospheric Doppler oscillations: model predictions."; Planet. Space Sci., 38(12), p1581, 1990.

Takahashi, K. and Anderson, B. J.; "Distribution of ULF Energy ($f < 80$ mHz) in the Inner Magnetosphere: A Statistical Analysis of AMPTE CCE Magnetic Field Data"; J. Geophys. Res., 97(A7), p10751, July 1992.

Taylor, J. R.; "The cause of magnetic disturbances in the Earth's ionosphere."; Ph. D. thesis, University of Leicester, UK; 1994.

Toman, K.; "Ionospheric phase- and group-path."; J. Atmos. Terr. Phys., 29, p1019, 1967.

Walker, A. D. M.; "Theory of magnetospheric standing hydromagnetic waves with large azimuthal wave number. 3. Particle resonance and instability."; J. Geophys. Res., 99(A6), p11105, 1994.

Walker, A. D. M. and Greenwald, R. A.; "Statistics of Occurrence of Hydromagnetic Oscillations in the Pc5 Range Observed by the STARE Auroral Radar"; Planet. Space Sci., 29, p293, 1981.

Walker, A. D. M., Ruohoniemi, J. M., Baker, K. B., Greenwald, R. A. and Samson, J. C.; "Spatial and Temporal Behaviour of ULF Pulsations Observed by the Goose Bay HF Radar"; J. Geophys. Res., 97(A8), p12187, 1992.

Watermann, J.; "Observation of correlated ULF fluctuations in the geomagnetic field and in the phase path of ionospheric soundings"; J. Geophys., 61, p39, 1987.

Watts, J. M. and Davies, K.; "Rapid frequency analysis of fading radio signals"; J. Geophys. Res., 65, p2295-2301; 1960.

References

Wright, D. M.; "A HF Radio Doppler Diagnostic: User Guide"; internal technical report no. 62; Radio and Space Plasma Physics group, Leicester University, UK; 1996a.

Wright, D. M.; "Software Guide to the HF Doppler Diagnostic"; internal technical report; Radio and Space Plasma Physics group, Leicester University, UK; 1996b.

Wright, J. W. and Pitteway, M. L. V.; "Data processing for the dynasonde."; J. Geophys. Res., 87, p1589, 1982.

Yeoman, T. K. and Lester, M.; "Characteristics of MHD waves associated with storm sudden commencements observed by SABRE and ground magnetometers."; Planet. Space Sci., 38, p603, 1990.

Yeoman, T. K., Lester, M., Orr, D. and Lühr, H.; "Ionospheric boundary conditions of hydromagnetic waves: the dependence on azimuthal wave number and a case study."; Planet. Space Sci., 38, p1315, 1990.

Yeoman, T. K., Lester, M., Milling, D. K. and Orr, D.; "Polarisation, propagation and MHD modes of Pi2 pulsations: SABRE/SAMNET results."; Planet. Space Sci., 39, p983, 1991.

Yeoman, T. K., Mao Tian, Lester, M. and Jones T. B.; "A study of Pc5 hydromagnetic waves with equatorward phase propagation."; Planet. Space Sci., 40(6), p797, 1992.

Yeoman, T. K., Freeman, M. P., Reeves, G. D., Lester, M. and Orr, D.; "A comparison of mid latitude Pi2 pulsations and geostationary orbit injections as substorm indicators."; J. Geophys. Res., 99(A3), p4085, 1994.

Yumoto, K., Takahashi, K., Ogawa, T. and Watanabe, T.; "Sc- and Si-associated ULF and HF-Doppler oscillations during the great storm of February 1986."; J. Geomag. Geoelectr., 41, p871, 1989.

Ziesolleck, C. W. S. and McDiarmid, D. R.; "Statistical Survey of Auroral Latitude Pc5 Spectral and Polarization Characteristics"; J. Geophys. Res., 100(A10), p19299, October 1995.