Studies of nightside spectral width behaviour from coherent high frequency radars

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For Mum and Dad
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Abstract

Studies of nightside spectral width behaviour from coherent high frequency radars

Emma Elizabeth Woodfield

The work presented in this thesis is aimed at improving our understanding of the HF Doppler spectral width parameter and how it can be used to identify ionospheric and magnetospheric boundaries, specifically the use of the frequently observed gradient between high (>200 m s\(^{-1}\)) and low (<200 m s\(^{-1}\)) spectral width. Locating the boundaries between regions is important to the study of how the magnetosphere responds to the solar wind and interplanetary magnetic field conditions. Three case studies and a statistical investigation are presented herein which investigate the nature of these regions. Data from the Co-operative U.K. Twin Located Auroral Sounding System (CUTLASS) HF radars and the European Incoherent SCATter (EISCAT) radars form the primary observations. The cases presented show that high spectral width can be observed both on open and closed magnetic field lines, and that there is a relationship between elevated electron temperature and high spectral width (although the reverse is not true) which appears to be restricted to the post 0300 MLT nightside region. The data also show that high spectral widths can be associated with both single- and multiple-peak HF spectra. The statistical study compares three years of data from the CUTLASS radars and the Syowa East radar (part of the Super Dual Auroral Radar Network, SuperDARN), magnetically conjugate to Iceland East. It is found that the mean spectral width is dependent on latitude, magnetic local time (MLT) and season. The data from the two hemispheres show similar dependence on these factors, although the Syowa East spectral widths are larger in general (instrumental variations are discounted). These results suggest that the physical mechanism(s) creating the high spectral widths must work both on open and closed field lines, be dependent upon latitude and MLT, and be less prevalent (or attenuated) in summer months.
Declarations

The research undertaken during the course of this doctoral programme has led to the publication of the following scientific papers in refereed journals:


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CHAPTER 1

An introduction to the solar-terrestrial environment

This thesis presents work pertaining to the monitoring of the dynamics of the Earth's magnetic plasma environment, namely the ionosphere and magnetosphere. The interaction between the Sun and the Earth is conspicuous in its control of the dynamics of the Earth's magnetic plasma and it is therefore useful to give a brief introduction to the solar-terrestrial interaction. For a more detailed description of the following sections the reader is referred in the first instance to Kivelson and Russell [1995] and Hargreaves [1995] and references therein. Chapters 2 and 3 will provide a detailed background to the work presented in this thesis.

1.1 The Sun

The Sun is the source of energy that sustains life on Earth, it is also a highly dynamic object with many processes yet to be understood. Figure 1.1 shows the major regions thought to exist in the Sun, superposed on an image of the Sun at X-ray wavelengths. The source of the Sun's energy is the nuclear fusion reactions occurring in the core of the star. The visible layers of the Sun begin at the photosphere which is at a radius of approximately $7 \times 10^5$ km and has a temperature equivalent to a black body at ~6000 K. The chromosphere is a thin (~2000 km) layer about ten times hotter than the photosphere. The corona is the very outermost layer, which extends into space at over a million degrees Kelvin. Both the chromosphere and parts of the corona can be viewed from Earth during solar eclipses.

There are many periodicities associated with the Sun, firstly it rotates around its own axis approximately once every 27 days, although the period of rotation is dependent upon latitude. Of particular importance to the solar-terrestrial interaction is the 11 or 22 year cycle in solar activity (determined by the number of sunspots and magnetic field orientation). This cycle consists of an 11 year period in the sunspot number and a reversal
Figure 1.1. An image of the sun taken at X-ray wavelengths with elements of the structure superimposed. This image is from 1992. (The solar x-ray image is from the Yohkoh mission of ISAS, Japan. The x-ray telescope was prepared by the Lockheed Palo Alto Research Laboratory, the National Astronomical Observatory of Japan, and the University of Tokyo with the support of NASA and ISAS.)
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in the Sun's magnetic polarity after 11 years making the whole cycle 22 years. Sunspots are relatively small (1000 to 100 000 km in diameter) dark features visible from the Earth (with no magnification), which are a result of magnetically disturbed conditions in the photosphere. They are cooler than their surroundings at ~3800 K, grow over a few days and can last from days to months. Sunspots have been observed for many centuries and the 11 year cycle is well established, although it varies in magnitude.

Other dark features on the Sun are the large coronal holes, the absence of electromagnetic radiation from these holes is most marked in the X-ray wavelengths. The magnetic field lines are said to be open in coronal holes, that is they extend out into space and have only one footprint on the Sun (the field lines in sunspots are closed). During the sunspot minima of the 11 year solar cycle coronal holes are confined to the polar regions of the Sun. The converse of coronal holes are coronal helmet streamers which have closed magnetic field lines and emit copious electromagnetic radiation.

The Sun can behave violently releasing huge quantities of electromagnetic radiation and/or particles in comparatively short amounts of time. Solar flares typically release ~10^{25} J of both light and particles on timescales of minutes to hours. Coronal mass ejections (CME), as the name suggests, are huge eruptions of matter into space, sometimes towards Earth. CMEs are about five times more likely to occur during solar maximum (of the 22 year cycle), and are often a trigger for geomagnetic storms at the Earth.

1.2 The solar wind and interplanetary magnetic field

It was thought until the 1950's that the solar corona was in hydrostatic equilibrium, but work by L. Biermann in 1951 studying the tails of comets showed that radiation pressure alone could not account for the bending of the tails away from the Sun. He proposed that there was a stream of particles originating from the Sun with a speed of ~500 km s^{-1}. S. Chapman and E. N. Parker then showed theoretically that the solar corona is not in hydrostatic equilibrium, but expands continuously out into space. This stream of particles is known as the solar wind and consists mainly of protons with some (5 to 20 %) alpha particles and ~0.5 % heavier, positively charged ions. The typical number density
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of positive ions in the solar wind is 3 to 10 cm\(^3\) at 1 A.U. with a similar number of
electrons present giving bulk neutrality. The solar wind plasma streams past the Earth
travelling at superAlfvénic speeds between 200 and 800 km s\(^{-1}\).

The Sun’s magnetic field is extended into the interplanetary medium by the solar
wind plasma due to a condition known as *frozen in flow*. In this part of space the Sun's
magnetic field is called the *interplanetary magnetic field (IMF)*. The plasma that forms
the solar wind has a very high conductivity and is therefore *frozen* to magnetic field lines
of the IMF. A simplified version of the proof of this theorem follows here. If the
displacement current is neglected then two of Maxwell’s equations become

\[
\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (1.1) \\
\n\nabla \times \mathbf{B} = \mu_0 \mathbf{J} \quad (1.2)
\]

where \(\mathbf{E}\) is the electric field strength, \(\mathbf{B}\) is the magnetic field strength, and \(\mathbf{J}\) is the current
density. Ohm’s law can be stated as:

\[
\mathbf{J} = \sigma (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \quad (1.3)
\]

where \(\sigma\) is the conductivity and \(\mathbf{v}\) is the velocity. The conductivity in the solar wind is
very high and allowing it to tend to infinity it follows that:

\[
\mathbf{E} + \mathbf{v} \times \mathbf{B} = 0 \quad (1.4)
\]

Thus from Equation 1.1 the *frozen in flow* equation is found:

\[
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) \quad (1.5)
\]

The energy balance between the kinetic energy of the plasma and the magnetic
field pressure

\[
\frac{nmv^2}{2} > \frac{B_{\text{Sun}}^2}{2\mu_0} \quad (1.6)
\]

(where \(n\) is the number density of particles, \(m\) is the particle mass, \(v\) is the solar wind
velocity and \(B_{\text{Sun}}\) is the IMF flux density) determines whether the plasma follows the
motion of the magnetic field or vice versa. In the case of the solar wind the kinetic energy is about eight times the magnetic contribution.

The solar wind streams out radially from the Sun. However the Sun is continuously rotating and the magnetic field is forced to spiral outwards in a manner often compared to water from a garden hose being spun in a circle. A representation of this is shown in Figure 1.2. The IMF is also observed to contain sectors where the field direction is either towards or away from the Sun. This is explained using the ‘Ballerina’s skirt’ model of a current sheet approximately in the equatorial plane of the Sun, Figure 1.3. The current sheet is formed in the region between the oppositely directed magnetic fields.

The speed of the solar wind is partly dependent upon where the particles originated from in the outer layers of the sun, the solar wind from coronal holes is known as the fast solar wind where speeds exceed 700 km s\(^{-1}\). This often creates shocks and discontinuities in the solar wind, where fast streams catch up with slow particles.

1.3 The magnetosphere

When the solar wind and IMF arrive in the vicinity of the Earth a number of phenomena occur. Firstly the solar wind is superAlfvénic in the rest frame of the Earth and encounters a stationary regime of plasma, therefore a collisionless shock is formed known as the bow shock, Figure 1.4. The now slower solar wind plasma in the region called the magnetosheath then tries to impinge further upon the obstacle in its path. However, since the IMF is frozen into the solar wind plasma, and similarly the Earth’s plasma is frozen to the geomagnetic field, the IMF is effectively separated from the region of the terrestrial magnetic field. This results in a stand-off between the two magnetic plasma systems, and a cavity in the solar wind and the IMF is formed around the Earth. This cavity is known as the magnetosphere. The size of the cavity created is a balance between the solar wind kinetic pressure and the pressure exerted outwards by the terrestrial magnetic field. The boundary between the solar wind plasma and the terrestrial plasma is called the magnetopause. The shape of the magnetosphere is much like that of the debris around a comet, a short nose and an extended tail.
Figure 1.2. The Parker Spiral of the interplanetary magnetic field being pulled away from the Sun by the solar wind. (Kivelson and Russell, [1995])

Figure 1.3. The Ballerina's skirt model of the sector structure of the interplanetary magnetic field.
Figure 1.4. The structure of the magnetosphere.

Figure 1.5. A schematic of reconnection at the magnetopause. (Kivelson and Russell, [1995])
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The frozen in flow condition breaks down where the two magnetoplasma systems meet and a current sheet forms in response to the close proximity of different magnetic orientations at the magnetopause. The solar and terrestrial magnetic fields may join under these circumstances in a process known as reconnection. This is an important process in all kinds of magnetic plasmas from astrophysical plasmas to fusion reactors. Figure 1.5 shows schematically how reconnection occurs. The two magnetic fields of opposite orientation diffuse across the current sheet where the magnetic field lines snap only to be joined to each other. The magnetic tension in these newly formed and highly kinked magnetic field lines accelerates them away from the reconnection site. This situation can occur at the sub-solar magnetopause when the IMF is directed oppositely to the Earth’s magnetic field, i.e. the IMF points southwards. The situation that follows is depicted in Figure 1.6. The Earth’s magnetic field line (1) that has undergone reconnection is now connected to the IMF directly (and is termed ‘open’), but the IMF is still being dragged past the Earth by the solar wind. Thus the open field line is pulled tailward (2, 3, 4, 5) which moves the plasma stuck to the magnetic field line (Figure 1.6 inset). At some point in the tail of the magnetosphere suitable conditions for reconnection are found, where the north and south open field lines come very close to each other and a current sheet in the tail is formed (6). Here the Earth’s magnetic field lines are reconnected to themselves and are now said to be ‘closed’, that is with both feet in the Earth’s magnetic field. Once again the kinked field lines are accelerated, this time towards the Earth and the plasma on those field lines is accelerated with them. The joining of the terrestrial and interplanetary magnetic fields by reconnection facilitates the exchange of particles from one regime to the other such that magnetospheric particles can enter the magnetosheath and solar wind particles can enter the magnetosphere. The cycle is completed when the original field line returns to the front of the magnetosphere ready to start all over again. This situation will continue as long as the IMF is directed southwards. It is thought that reconnection can occur at sites removed from the sub-solar region when the IMF is directed northwards.

Reconnection rates are often not steady and it is possible for the amount of open flux in the magnetosphere to build up or decrease. The build up of open flux is often released in a process known as a magnetospheric substorm. There are various phenomena associated with substorms, an increase in auroral activity in the ionosphere was the earliest observed of these. Occasionally the Earth’s geomagnetic environment becomes
Figure 1.6. Convection driven by reconnection at the sub-solar magnetopause when the interplanetary magnetic field is directed southwards. (Kivelson and Russell, [1995])
extremely disturbed for several days. These are geomagnetic storms and they are often triggered by the arrival of a CME at the magnetosphere, or other shocks in the solar wind. Geomagnetic storms have serious consequences for spacecraft, astronauts, and also for electrical systems and radio communications on the Earth (particularly at high latitudes).

1.4 The ionosphere

The magnetosphere is bounded at its lower edge by the ionosphere. This is the region of plasma closest to the Earth and it is generated by the ionising action of ultraviolet light on the gases of the Earth's atmosphere. It extends in altitude from approximately 60 km to over a 1000 km. At the lower altitudes where the density of the neutrals is sufficient for collisions between the electrons and neutrals and ions and neutrals to be reasonably frequent, the chemistry of the plasma becomes important. Unlike the solar wind, the Earth's low altitude plasma environment contains many negative ions. Traditionally the ionosphere is split into a number of horizontally stratified layers termed the D, E and F-regions defined by peaks in the electron concentration, Figure 1.7. The electron concentration in these regions varies diurnally as well as with the 11 year solar cycle and due to the dynamics of the plasma and magnetic field lines. During the daytime in the summer months two peaks of electron concentration occur in the F-region, named the F1 and F2 regions.

Many particles precipitate into the ionosphere, particularly in the high latitude regions. Precipitating particles of sufficient energy may create beautiful light displays known as the aurora. The aurora are generated through collisions with various species of atom and molecule in the ionosphere. Part of the kinetic energy of the precipitating particle can be transferred to an electron of the atom or molecule creating excited states. These states can then decay through the emission of a photon of a particular wavelength. The aurora cover the electromagnetic spectrum from ultraviolet to infrared, although the most commonly observed wavelengths are 630.0 nm and 557.7 nm (red and green respectively). Both of these are due to atomic oxygen energy transitions. The aurorae have the highest probability of occurring within the regions known as the auroral ovals, one around each magnetic pole [e.g. Feldstein, 1963; Holzworth and Meng, 1975]. Aurorae can also occur within the polar cap, a phenomenon often referred to as the Theta
Figure 1.7. The structure of the ionosphere with altitude at mid-latitudes. (After W. Swider, Wallchart *Aerospace Environment*, US Air Force Geophysics Laboratory).

Figure 1.8. The northern auroral oval as seen by satellite imaging. M is the magnetic north pole, and N is the geographic north pole. This image is from 23rd November 1981. (Image taken by the Spin-Scan Auroral Imaging Instrument on board Dynamics Explorer - 1. Courtesy L. Frank, the University of Iowa, and NASA.)
aurora where a sun-aligned arc forms. An example of the auroral oval is presented in Figure 1.8, this is satellite imagery of the northern oval taken by the Dynamic Explorer I spacecraft. The bright region on the left of the picture is scattered sunlight. It can be seen from this picture that the auroral oval is highly structured and this reflects the dynamics of the Earth's plasma environment.

The ionosphere is vital to high frequency (HF) radio communications which use the refractive properties of the plasma to bounce radio waves around the Earth. The electron concentration and stratification in the ionosphere has an enormous effect upon the success of HF communications. If the electron concentration is too high in the D-region for example, the signal may be totally absorbed in places. HF radio waves can also be used as a diagnostic tool for looking at the ionosphere, HF radars form the major data resource for this thesis.
CHAPTER 2

High Frequency radars and their spectra

The principle instruments used in this thesis are the coherent High Frequency (HF) radars of the Super Dual Auroral Radar Network (SuperDARN). It is crucial to understand the principles on which these radars work to draw valid conclusions from the work presented in the following chapters. This chapter covers the physical principles of HF radio propagation and how the data from the SuperDARN network is processed with emphasis on the spectral width parameter.

2.1 Radio waves in the ionosphere

The magnetised, collisional plasma that forms the ionosphere has an important effect upon radio waves propagating within it. Just as visible light is refracted at the glass/air interface of a prism, radio waves are refracted in the presence of the magnetised plasma of the ionosphere. The ionosphere can be considered to be horizontally stratified in electron density when the wavelength of the incident radiation is such that the properties of the medium vary little over a few wavelengths. Thus radio waves incident on the ionosphere are continually refracted throughout their journey through a slowly varying ionosphere. The amount of refraction depends on ionospheric parameters and the frequency of the radio waves (just as blue light is bent more by a prism than red light). The relationship that governs the refractive index of the ionosphere is called the Altar-Appleton-Hartree relation and is given by

\[
n^2 = (\mu - i\chi)^2 = 1 - \frac{X}{1 - iZ - \frac{Y^2 \sin^2 \theta}{2(1 - X - iZ)} \pm \left[ \frac{Y^4 \sin^4 \theta}{4(1 - X - iZ)^2} + Y^2 \cos^2 \theta \right]^{1/2}} \tag{2.1}
\]
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Where,

\[ X = \frac{\omega_p^2}{\omega^2} = \frac{N_e e^2}{\varepsilon_0 m_e \omega^2} \] 

(2.2)

\[ Y = \frac{\omega_H}{\omega} = \frac{eB}{m_e \omega} \] 

(2.3)

\[ Z = \frac{v}{\omega} \] 

(2.4)

\( \omega_H \) is the angular electron gyrofrequency, \( \omega_p \) is the angular plasma frequency, \( \omega \) is the angular wave frequency, \( e \) is the electric charge on an electron, \( m_e \) is the mass of an electron, \( \varepsilon_0 \) is the permittivity of free space, \( N_e \) is the plasma electron density, \( B \) is the external magnetic field magnitude, \( v \) is the collision frequency between electrons and all other particles, \( \theta \) is the angle between the direction of wave phase propagation and the external magnetic field. A full derivation of the Altar-Appleton-Hartree relation can be found in Ratcliffe [1959].

This is a complicated formula, but there are special conditions that can simplify it dramatically. Neglecting the collision frequency and magnetic field simplifies the refractive index to:

\[ n^2 = 1 - X = 1 - \frac{\omega_e^2}{\omega^2} \] 

(2.5)

If a wave with an angular frequency less than the plasma frequency \( (\omega < \omega_p) \) is vertically incident upon such an ionosphere then the wave will be reflected (since \( n \) will then be purely imaginary and the wave evanescent). The reflection point occurs where the angular frequency of the wave is equal to the plasma frequency which is dependent on the electron number density for a normally incident wave.

If the presence of a magnetic field is now assumed there will be two values for the refractive index as in Equation 2.6 and the ionosphere becomes birefringent.

\[ n^2 = 1 - \frac{X}{1 - \frac{Y^2 \sin^2 \theta}{2(1 - X)} \pm \left[ \frac{Y^4 \sin^4 \theta}{4(1 - X)^2} + Y^2 \cos^2 \theta \right]^{1/2}} \] 

(2.6)
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The two characteristic waves are termed the ordinary (O) and extraordinary (X) modes. These modes have different propagation characteristics in the ionosphere and the effects are easily observed with an ionosonde for example, which uses radio waves sent vertically into the ionosphere to assess the structure.

HF radio waves (3 to 30 MHz) are of a suitable wavelength (100 to 10 m) to consider the ionosphere to be slowly varying and therefore horizontally stratified. This assumption allows us to treat the propagation path of the radio wave in the following way. Suppose an HF radio signal is transmitted at an angle $\theta_0$ to the zenith as in Figure 2.1, once it starts to encounter the ionosphere the signal will be refracted by each layer in turn. Snell’s law of refraction may be applied (equation 2.7) at each boundary until the angle to the zenith is $\pi/2$ and total internal reflection occurs.

\[
\sin(\theta_0) = n_1 \sin(\theta_1) \\
\sin(\theta_1) = n_2 \sin(\theta_2) \\
\vdots \\
\sin(\theta_{(r-1)}) = n_r \sin(\pi/2)
\]

This will occur since $n$ becomes smaller with height as a consequence of the increase with height of the electron number density. The radio signal propagates horizontally where

\[
\sin(\theta_0) = n_r \sin(\pi/2)
\]

The refraction then continues and bends the signal back towards the ground. The path will be symmetric if the ionosphere is horizontally uniform. Substitution into the simplified version of the Altar-Appleton-Hartree equation (2.5) indicates the radio wave will be reflected when $\omega_n = \omega \cos(\theta_0)$. This idea is the most basic form of ray tracing, if the magnetic field, collisions and more complicated ionospheric models are included then the ray tracing is best performed by computers.

2.2 Instabilities, irregularities and HF radars

HF radars require scattering targets just as any other form of radar does. In the ionosphere there are targets that will scatter HF radio waves, a hindrance to radio communications, but useful for studying plasma conditions. These targets are like the
Figure 2.1. The refraction of radio waves in a horizontally stratified ionosphere.
atomic planes of the crystals used in X-ray scattering. Just as the Bragg condition for
reflection is obtained in crystals where the atomic planes are separated by distances of the
order of half the X-ray wavelength, so there are periodic structures in the electron number
density of the ionosphere from which radio waves may be reflected. These ionospheric
targets are known as irregularities and are to be found parallel to the magnetic field
(hence the frequently used term field-aligned irregularities). Two mechanisms for
forming such irregularities are generally put forward, the two-stream (or Farley-
Bunemann) instability and the gradient-drift instability. Although instability processes
can produce irregularities that are parallel to the magnetic field, the rapid expansion of the
irregularities along the magnetic field is a result of the ease with which particles can move
along the magnetic field direction and the plasma pressure build up within the
irregularities.

2.2.1 The two-stream or Farley-Buneman instability

This instability forms as a result of the interaction of streams of ions and electrons
when the speeds of the two species differ by more than the ion-acoustic speed [Farley,
1963; Buneman, 1963]. There is a threshold value of the relative drift speed of the ions
and electrons below which this instability will not occur, the value of which is dependent
on the ion and electron collision and gyro-frequencies, the angle between the wave vector
and the magnetic field, $\alpha$, and the ion-acoustic speed. The value of $\alpha$ has a critical effect
upon the threshold where for normal propagation ($\alpha = 90^\circ$) the threshold is reasonably
attainable with typical drift speeds in the ionosphere. However the threshold increases
rapidly as $\alpha$ moves away from 90°. Hence electrostatic waves generated by the two-
stream mechanism will tend to travel perpendicular to the magnetic field. The growth rate
is dependent on wavelength and the instability grows more rapidly at shorter wavelengths.

In the E-region, above 85 km the electrons exhibit Hall drift perpendicular to the
electric field, while the ions Pedersen drift parallel to it. As a result the electrons stream
through the ions, exciting the two-stream instability. In the F-region, the ions and
electrons both drift with the Hall velocity, so their relative drift speed is essentially zero,
and the instability cannot occur.
2.2.2 The gradient-drift instability

The gradient-drift instability [e.g. Keskinen and Ossakow, 1983] is an example of the Rayleigh-Taylor instability where a reduction in the total energy is achieved by interchanging two elements of a fluid, for example where a high density fluid lies above a lower density one. The gradient-drift instability is a common mechanism for breaking down large, irregular F-region structures into smaller periodic structures, some of which are on a scale where HF radars can detect them (10s of metres).

This instability is set off by a small perturbation where ions move slightly relative to the electrons on the edge of a region of enhanced plasma density. This causes a charge separation to take place as in Figure 2.2. This charge separation produces a small polarization electric field which increases the disturbance by creating ExB drift due to the polarization electric field and the background magnetic field. This mechanism also generates irregularities that are parallel to the magnetic field and is thought to be active in both the E and F-regions. In the F-region it is the dominant mechanism since the plasma conditions are not suitable for the two-stream instability to occur.

2.3 SuperDARN HF radars

The SuperDARN network of HF radars covers a large part of the northern and southern auroral ovals [Greenwald et al., 1995]. The radars are run by several different nations in cooperation to obtain global measurements of ionospheric plasma flow related to ionospheric, magnetospheric and solar processes. The locations of the radars currently in operation are shown in Figure 2.3 in conjunction with Table 2.1 which gives the radar name codes and coordinates.

The radars normally scan through 16 beams arranged symmetrically about the radar bore site. In the standard operating mode the dwell time on each beam is typically 7 seconds and the scan starts every two minutes in standard common mode operation. Each beam is separated into 70 or 75 range gates depending on the radar. In standard common mode these range gates are 45 km in length with a distance to the first gate of 180 km. The radars can operate at frequencies between 8 and 20 MHz. The fields of view of several of the radars overlap to facilitate bistatic velocity measurements. The radar fields of view...
2. The charge separation introduces a polarisation electric field to $\mathbf{E} \times \mathbf{B}$. 

3. The plasma drifts due to polarisation electric field.

1. Ions drift relative to electrons creating charge separation.

Figure 2.2. Two densities of plasma interacting via the gradient drift instability mechanism. $\mathbf{k}$ is the wave vector of the gradient drift wave, $\delta N$ indicates the direction of increase in plasma density, $\mathbf{B}_0$ and $\mathbf{E}_0$ are the background magnetic and electric fields. (Adapted from Chen [1984]).
Figure 2.3. The SuperDARN network of HF radars in the northern and southern hemispheres, the letters for each radar are referred to in Table 2.1.
(Map from JHU/APL)
<table>
<thead>
<tr>
<th>Radar</th>
<th>Letter code</th>
<th>Institution</th>
<th>Latitude (geographic) (AACGM)</th>
<th>Longitude (geographic) (AACGM)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Northern Hemisphere</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>King Salmon</td>
<td>C</td>
<td>Communications Research Laboratory in Japan.</td>
<td>58.68 °N</td>
<td>156.65 °W</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>57.43 °N</td>
<td>100.51 °E</td>
</tr>
<tr>
<td>Kodiak</td>
<td>A</td>
<td>Geophysical Institute, UAF in the USA.</td>
<td>57.60 °N</td>
<td>152.20 °W</td>
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<td></td>
<td></td>
<td>57.17 °N</td>
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<td>Prince George</td>
<td>B</td>
<td>Univ. of Saskatchewan in Canada.</td>
<td>53.98 °N</td>
<td>122.59 °W</td>
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<td>59.88 °N</td>
<td>65.67 °W</td>
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<td>Saskatoon</td>
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<td>52.16 °N</td>
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<td></td>
<td>61.34 °N</td>
<td>45.26 °W</td>
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<td>Kapuskasing</td>
<td>K</td>
<td>JHU/APL in the USA.</td>
<td>49.39 °N</td>
<td>82.32 °W</td>
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<td></td>
<td>60.06 °N</td>
<td>9.22 °W</td>
</tr>
<tr>
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<td>G</td>
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<td>53.32 °N</td>
<td>60.46 °W</td>
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<td>61.94 °N</td>
<td>23.02 °E</td>
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<tr>
<td>Stokkseyri</td>
<td>W</td>
<td>CNRS/LPCE in France. [Also known as Iceland West]</td>
<td>63.86 °N</td>
<td>22.02 °W</td>
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<td></td>
<td></td>
<td></td>
<td>65.04 °N</td>
<td>67.33 °E</td>
</tr>
<tr>
<td>Æykkvibær</td>
<td>E</td>
<td>Radio and Space Plasma Physics Group, Univ. of</td>
<td>63.86 °N</td>
<td>19.20 °W</td>
</tr>
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<td></td>
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<td>64.59 °N</td>
<td>69.65 °E</td>
</tr>
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<td>Hankasalmi</td>
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<td><strong>Southern Hemisphere</strong></td>
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<td>Halley</td>
<td>H</td>
<td>British Antarctic Survey in the UK.</td>
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<td>26.63 °W</td>
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<tr>
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<td></td>
<td>Also known as the Southern Hemisphere Auroral Radar</td>
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<td>28.92 °E</td>
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<td></td>
<td></td>
<td>Experiment [SHARE].</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SNAE</td>
<td>D</td>
<td>Univ. of Natal and the PUCHE in the Republic of South Africa.</td>
<td>71.68 °S</td>
<td>2.85 °W</td>
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<td></td>
<td></td>
<td>61.52 °S</td>
<td>43.18 °E</td>
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<td>J</td>
<td>National Institute of Polar Research in Japan.</td>
<td>69.00 °S</td>
<td>39.58 °E</td>
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<td></td>
<td></td>
<td>55.25 °S</td>
<td>23.00 °E</td>
</tr>
<tr>
<td>Syowa East</td>
<td>N</td>
<td>National Institute of Polar Research in Japan.</td>
<td>69.01 °S</td>
<td>39.61 °E</td>
</tr>
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<td></td>
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<td>22.98 °E</td>
</tr>
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<td>Kerguelen</td>
<td>P</td>
<td>CNRS/LPCE in France.</td>
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<td>70.26 °E</td>
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<td>122.14 °E</td>
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<tr>
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<td>R</td>
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<td>43.38 °S</td>
<td>147.23 °E</td>
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<td></td>
<td></td>
<td>55.31 °S</td>
<td>133.36 °W</td>
</tr>
</tbody>
</table>

Table 2.1. The SuperDARN radars, the letter codes refer to Figure 2.3.
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High Frequency radars and their spectra

cover some \(4 \times 10^6\) km\(^2\) each, although often only a proportion of this area produces ionospheric backscatter. There are two reasons for this, the first being that HF radio propagation in the ionosphere does not uniformly illuminate the region. Secondly, if there are no field-aligned irregularities then there will be no targets to scatter from and hence no backscatter. Therefore care is required in deducing geophysical data from boundaries of backscatter, since the edge may be due to the end of the region illuminated by the radar and not the edge of the location of field-aligned irregularities [Milan et al., 1998].

2.3.1 Radar operations

The antennas which are fed by this system are Log Periodic Arrays of dipoles that are large as illustrated in Figure 2.4 to accommodate the wavelengths used (~15 to 37 m, for a frequency of 8 to 20 MHz). The beam separation is 3.25°, although the beam width varies with frequency between 2° and 12°. The beam also has several low power sidelobes, including some to the rear of the radar. An example of the horizontal beam pattern is given in Figure 2.5 for a frequency of 10 MHz.

Radio signals can be transmitted either continuously or in pulses. A single long pulse could be transmitted where the length of the pulse would need to approximate the decorrelation time of the plasma. Long pulses have the disadvantage of containing no range information because they sample the entire range at the same time. A sequence of repeated short pulses may be used instead, with each pulse preceding a sample of the received signal. The spatial resolution of this method is determined by the length of the transmitted pulses. This method has its own drawback that scatter from different ranges may be received simultaneously.

The transmission of two short pulses is shown in Figure 2.6. \(P_1\) and \(P_2\) in Equations 2.9a and 2.9b are the signals received from the first and second pulse respectively, scattering from the same target which has a Doppler frequency of \(\omega_0\).

\[
P_1 = A e^{i\phi} \quad (2.9a)
\]
\[
P_2 = A e^{i(\phi + \omega_0 T)} \quad (2.9b)
\]
Figure 2.4. The Iceland East CUTLASS and SuperDARN radar. The long row of antennas is the main array and the four antennas to the right of the picture are the interferometer array.
Figure 2.5. Beam patterns at 10.0 MHz with no tapering applied. The power is normalised to the maximum power.
Figure 2.6. Double pulse schematic. The first pulse is received at time $t_0$, the second pulse is received from the same target at time $t_0 + \tau$. 

The first term for $P_1$ is the received signal from pulse 2 at range 1 and the second term for $P_2$ is the received signal from pulse 1 at range 2. The log1 ACT term is then
The separation of the two pulses is \( \tau \) and the phase at the target due to its position and any random phase contribution is \( \phi \). If the same sequence is transmitted again shortly afterwards

\[
P_1' = A'e^{i\phi'} \
\]
\[
P_2' = A'e^{i(\phi + \phi' + \phi_{oh}\tau)} \
\]

where \( P_1' \) and \( P_2' \) are the signals from the first and second pulse of the second pulse sequence. The two received signals cannot be summed because of the unknown difference between \( \phi \) and \( \phi' \). However an auto-correlation function (ACF) can be assembled from the pulse information by calculating the value of the ACF at various 'lags'. 'Lags' are essentially a quantised measure of time, each one formed by pairs of pulses separated by different time intervals. In the two pulse case, two lags can be formed, the zero lag (lag0) and the first lag (lag1). The ACF at lag0, \( R_{lag0} \), is formed by multiplying the signal from pulse 1 by its complex conjugate, as in Equation 2.11. Similarly, lag1 is calculated using the signal from pulse 2 and the complex conjugate of the signal from pulse 1.

\[
R_{lag0} = P_1P_1^* \quad (2.11)
\]
\[
R_{lag1} = P_2P_1^* = (Ae^{i\phi})e^{i\phi_{oh}\tau} + Be^{i\phi_{oh}\tau} \quad (2.12)
\]

The ACFs for different pulse sequences can be summed since the terms involving \( \phi \) and \( \phi' \) are no longer present. For pulse sequences with more than two pulses, a similarly useful result is obtained.

Range aliasing can be a problem with signals received from two different ranges at the same time. If the first pulse produces scatter from two ranges (amplitudes \( A \) and \( B \)) then the received signal from pulse two can be mixed with the other range scattering pulse one as in Equation 2.13, with \( P_1 \) remaining as in Equation 2.9a.

\[
P_2 = Ae^{i(\phi + \phi_{oh}\tau)} + Be^{i\phi} \quad (2.13)
\]

The first term for \( P_2 \) is the received signal from pulse 2 at range 1 and the second term for \( P_2 \) is the received signal from pulse 1 at range 2. The lag1 ACF term is then:

\[
R_{lag1} = P_2P_1^* = A^2e^{i\phi_{oh}\tau} + ABe^{i(\phi - \phi')} \quad (2.14)
\]
To remove the range aliasing the second term in the lag1 part of the ACF must cancel out over the integration of several pulse sequences. Range aliasing is a particular problem in pulse schemes where two ranges are regularly sampled at the same time (in which case that lag is generally ignored). The general form of an ACF lag from one pulse sequence with some form of range aliasing is

$$R = A^2 e^{i\phi} + AB e^{\text{random phase}}$$  \hspace{1cm} (2.15)$$

which over N pulse sequences becomes

$$R = A^2 e^{i\phi} + \frac{AB}{\sqrt{N}}$$  \hspace{1cm} (2.16)$$

If the signal received from range B is particularly strong it will contaminate the final ACF even with the reduction due to several pulse sequences being used.

In the SuperDARN radars a multiple pulse scheme is used (multipulse transmission is discussed in Farley [1972]). In this multiple pulse scheme the pulses are of the same length and are separated by different multiples of some basic lag separation time. Care is required when assembling a pulse scheme to consider the number of lags with no inherent ambiguity in the range but also to minimise the number of missing lags. The range ambiguity arises from more than one pair of pulses giving a particular lag. Four is the maximum number of pulses that can be used with no ambiguity in the range and no missing lags. The pulse scheme currently employed by the SuperDARN HF radars involves seven pulses (Figure 2.7) with some missing lags, but no range ambiguity. The first pulse of the sequence is usually separated from the next pulse by a large number of the basic lag separation to avoid contamination of lag0. Lag0 is especially important in the estimation of the received power. The normal pulse length is 300 µs (giving a range resolution of 45 km) with the lag separation set at 2400 µs. The 7-pulse pattern is transmitted in a 100 ms window. A dwell time of 1 s in a particular look direction allows 10 pulse sequences to be transmitted which is usually sufficient to remove the cross terms in the equivalent of Equation 2.16. The multipulse technique does have disadvantages, notably an increase in the background noise due to uncorrelated scatter from other ranges and also a number of lags where no data can be received because a pulse is being transmitted when those lags are sampled. Although there is up to lag 27 available from the 7-pulse scheme, only the first 18 (where the power is generally not too
Figure 2.7. The 7-pulse transmitting scheme used by SuperDARN radars showing how the different lags are calculated. Pulse length is 300 μs and the lag time, $\tau$, is normally 2400 μs.
2.3.2 The complex ACF

The ACF is formed automatically at the radar sites and stored as 'raw' data (.dat files) and also used as an input for the FITACF software which fits standard parameters to the ACF without the need to perform a Fourier transform on it first. The complex ACF consists of the lags calculated as described in the previous section. Figure 2.8(a) shows an example of an ACF, the power is in arbitrary units and is shown versus the lag number. The '*' and '+' data points indicate good data, and the 'o' and '□' indicate 'bad lags'. Bad lags can arise in a number of different ways. The easiest to identify are lags which cannot be determined due to a transmit/receive conflict within the radar, and also the missing lag (16 in this case) due to the multipulse sequence used. Individual lags can also suffer from range aliasing as mentioned earlier, and also any random spikes in the noise (either internally from the radar system or from external sources, HF interference for example).

An ACF that is characterised by a single Doppler frequency should have maximum power at the zero lag with the power in each successive lag less than the last one. A small increase due to noise is allowed, but large increases in the power beyond lag0 are taken to signify a bad lag. This assumption neglects the fact that the ACF could be the result of more than one Doppler frequency. Bad lags are also identified if the power in a lag is less than a noise level determined from the clear frequency search performed before each scan. Data is also disregarded if the power of a returned signal is much lower than simultaneous returns from another range gate.

The phase of the two outputs of the receiver is important for the determination of the Doppler velocity of the scattering target. This is shown for this example in Figure 2.8(b). The phase measurement is restricted to between $\pm \pi$ which causes the data to jump every so often.
Figure 2.8. An example of an ACF, (a) with no interpolation over the bad lags, (b) the residual phase, This example is taken from CUTLASS Finland, beam 14, 23/11/1999, 04:02:07, range 40. * or + indicate good lags, squares or diamonds indicate bad lags.

Figure 2.9. (a) the result of linear interpolation on the ACF from Figure 2.8(a), and (b) the Fourier transform of the interpolated ACF with a spectrum produced from the fitted parameters overlaid (dotted line).
2.3.3 FITACF

There are several standard parameters produced by high frequency (HF) radars, the most commonly used ones are backscatter power, line-of-sight velocity and Doppler spectral width. The SuperDARN radars use software called 'FITACF' to produce the parameters directly from the ACF without the need to produce a power spectrum. Fitting the parameters directly to the ACF reduces the errors in the estimation. For example, estimating the line-of-sight velocity from the peak of the spectrum is subject to the resolution of the spectrum and also the interpolation used to fill over the badlags in the ACF before doing the FFT whereas the straight line fitting applied directly to the phase of the ACF uses all the points to find the velocity. FITACF assumes that the ACF is characterised by a single Doppler frequency. The decorrelation of the ACF is modelled in two ways:

\[
\text{Power} \propto e^{-\lambda_l} \quad (2.17a)
\]

\[
\text{Power} \propto e^{-\sigma_l^2} \quad (2.17b)
\]

termed the exponential (or lambda) fit and the Gaussian (or sigma) fit respectively. The Gaussian form would be expected if the decorrelation was due to multiple scatterers in the presence of velocity turbulence. The exponential form would be expected from the growth and decay of irregularities with little velocity turbulence. Thus for every ACF obtained two possible sets of parameters are produced (although the line-of-sight velocity is the same for both models).

The backscatter power parameter can be obtained from the signal to noise ratio of the lag0 power or from the intercept of the lambda or sigma fits at lag0. The line-of-sight velocity is estimated from the true phase at each lag, assuming that the lag0 phase is 0°. The true phase is the phase between the real and imaginary parts of the ACF but not restricted to a range of ±π. Reconstructing the true phase is not a simple process in the presence of noise and bad lags. A process of iteration is used to generate the true phase which in the ideal case would be a straight line. The Doppler frequency, \(\omega_0\), is then found from:

\[
\text{truephase} = \omega_0 \tau \quad (2.18)
\]

where \(\tau\) is the basic lag separation, using a weighted least squares fit.
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High Frequency radars and their spectra

The Doppler spectral width is obtained from the $\lambda$ and $\sigma$ parameters of the decorrelation models assumed. To estimate the width from these models the Fourier transform of the models is required. The Fourier transform of the exponential decorrelation model is given by

$$\bar{R}(\omega) = \int_{-\infty}^{\infty} e^{i\omega t} e^{-\lambda t} e^{-i\omega t} dt$$ (2.19)

The imaginary part of Equation 2.19 is an odd function and therefore over the limits will integrate to zero. The real part is an even function and the integral can therefore be calculated from zero to infinity and the result doubled as in Equation 2.20

$$\bar{R}(\omega) = 2\Re \left[ \int_{0}^{\infty} e^{-\lambda t + i(\omega - \omega_b) t} dt \right] = \frac{2\lambda}{\lambda^2 + (\omega - \omega_b)^2}$$ (2.20)

The values of $\omega$ which are at half the maximum power are:

$$\omega = \omega_b \pm \lambda$$ (2.21)

Thus the full spectral width at half maximum is $2\lambda$.

For the Gaussian decorrelation model the Fourier transform is given by:

$$\bar{R}(\omega) = \int_{-\infty}^{\infty} e^{-\sigma^2 t^2 + i(\omega - \omega_b) t} dt$$ (2.22)

rearranging the quadratic in $t$ gives

$$\bar{R}(\omega) = \int_{-\infty}^{\infty} e^{-i(\omega - \omega_b) t} e^{{-\sigma^2 t^2}} dt$$ (2.23)

where

$$q = \frac{i(\omega_b - \omega)}{2\sigma}$$ (2.24)

then substitute

$$x = \sigma t - q$$ (2.25)

$$\bar{R}(\omega) = e^{i\omega} \int_{-\infty}^{\infty} e^{-x^2} \frac{dx}{\sigma}$$ (2.26)

and hence
Chapter 2

High Frequency radars and their spectra

\[ \overline{R}(\omega) = \frac{\pi}{\sigma} e^{-(\omega_0 - \omega)^2 / 4\sigma^2} \] (2.27)

The full width at half maximum for the Gaussian form is therefore \( 4\sigma\sqrt{\ln 2} \).

To convert the Doppler shift frequency to a velocity one must bear in mind that a reflection from a moving target is involved, thus a factor of two is introduced:

\[ \frac{\Delta f}{f} = \frac{2v}{c} \] (2.28)

which becomes the following when considering that the \( \Delta f \) measured is actually the angular frequency \( \omega_0 \):

\[ v = \frac{c}{4\pi f} \omega_0 \] (2.29)

where \( f \) is the transmitted radar frequency. The same conversion factor is applied to the measurements of spectral width:

\[ W_x = \frac{c}{4\pi f} \cdot 2\lambda \] (2.30a)

\[ W_\sigma = \frac{c}{4\pi f} \cdot 4\sigma\sqrt{\ln 2} \] (2.30b)

Why are the parameters not calculated from the power spectrum? The power spectrum is the Fourier transform of the complex ACF (using the convolution theorem). There are problems in using the spectrum, firstly power leakage, this occurs if the frequency measured is not an exact value occurring in the discrete Fourier transform so that other points in the fast Fourier transform (FFT) will take power from the central peak thus affecting the power, velocity and width. Bad and missing lags are more of a problem to the FFT process, since a regularly spaced array is required. To produce a spectrum some kind of interpolation must be performed over the bad and missing lags which may lead to an inaccurate spectrum whereas the ACF fitting process requires no interpolation since the bad lags are just ignored. Nevertheless the backscatter power, line of sight velocity and spectral width can be estimated from the spectrum using the zeroth, first and second moments defined as follows:
The zeroth moment is the total backscattered power and therefore the area under the
spectrum. The velocity is simply related to the mean Doppler shift given by the first
moment. The second moment gives the mean square width of the spectrum.

In order to Fourier transform the ACF the bad lags must be removed and are
replaced by a simple linear interpolation between the surrounding good lags. Figure
2.9(a) shows the result of interpolating the 'raw' ACF from Figure 2.8(a). This is a good
example with few bad lags. ACFs containing more than a permissible number of bad lags
are rejected since the spectrum produced would be unreliable.

To correctly transform the ACF to the power spectrum some processing is
required, this involves taking the complex conjugate of the ACF and reflecting it about
the zero time point generating a symmetrical ACF. To avoid 'ringing' in the spectrum a
window is then applied to the ACF to tail the ends to zero. The power spectrum, as in
Figure 2.9(b) is then plotted as the absolute value of the Fourier transform of the
processed ACF. Overlaid as the dotted line in Figure 2.9(b) is the result of using Equation
2.26 to plot the spectrum given by the fitted parameters.

2.3.4 Ground scatter and elevation angle

As well as receiving scatter from irregularities in the ionosphere HF radars are
capable of receiving scatter from the ground. Figure 2.10 shows various possible
scattering points for HF radio waves in the E-region of the ionosphere (assuming the
ionospheric plasma density is sufficient to totally reflect the wave). The 'hop' terminology
indicates how many ground reflections have occurred. A similar terminology is
applicable to F-region reflections although the path will in general be more complicated
(the amount of refraction is dependent upon the plasma density which typically varies as
in Figure 1.7). Reflections from the ground are often easily distinguishable from
Figure 2.10. A schematic showing 1/2 hop, groundscatter and 1 1/2 hop scatter from an HF signal in the E-region. The shape of the propagation path is dependent on ionospheric conditions.
Chapter 2 High Frequency radars and their spectra

Ionospheric scatter. The Doppler shift of the ground should be small and precise with a long correlation time - hence a small spectral width. The ground scatter algorithm works by finding the difference between the velocity estimate and its error, and also the exponential width estimate and its error. If the following condition is true then the scatter is marked as ground scatter:

\[ \left| |v| - v_{\text{err}} \right| < 30 \text{ m s}^{-1} \quad \text{AND} \quad \left| |w| - w_{\text{lerr}} \right| < 35 \text{ m s}^{-1} \]

In general this works well but some high velocity and/or high width ionospheric scatter where the errors are also large may be regarded as ground scatter. Although clearly these types of echo would not be ground scatter they would be less reliable ionospheric scatter.

The height of scatter can be estimated using a parameter called the elevation angle. This is only possible at radar sites where there is a second, 'interferometer' array of four antennas slightly displaced (\(~100\text{m as in Figure 2.4}\) from the main array such that phase differences in the arriving signals can be determined. The CUTLASS radars have such a feature as do several other SuperDARN radars. A description of the calculations involved can be found in Milan et al. [1997b]. The elevation angle is useful in estimating which region of the ionosphere is scattering the signal and also if the scatter is being received from the rear lobe of the radar pattern Milan et al. [1997b].
Chapter 3

A review of the use of the HF spectral width parameter

The work presented in this thesis is aimed at improving our understanding of the HF spectral width parameter and how it can be used to identify ionospheric and magnetospheric regions and processes, specifically the use of the frequently observed spectral width gradient between high (>200 m s\(^{-1}\)) and low (<200 m s\(^{-1}\)) values. There has been much investigation of the behaviour of spectral width on the dayside, particularly around the cusp. Similar features are observed in the spectral width parameter on the nightside to those seen in the region of the low altitude cusp. This thesis extends the exploration of the spectral width parameter to the nightside where much less investigation has been performed. This chapter describes the work that has already been done regarding the spectral width parameter in the F-region.

3.1 The Cusp

3.1.1 Observations of the cusp

In the open model of the magnetosphere (section 1.3) the cusp is the neutral point where the magnetic field lines change from closed to open. In general though, the cusp is often defined as the location in the magnetosphere where magnetosheath particles have the most direct access. Newell and Meng [1992] found the average location of the ionospheric footprint of the cusp (and other dayside magnetospheric regions) using many passes of the DMSP satellites, the resulting statistical map of magnetospheric regions is shown in Figure 3.1. These authors identified the cusp using a neural network method to find magnetosheath particles at the altitude of the DMSP satellites (~830 km).

The location of the boundary between open and closed field lines is of particular importance to the study of reconnection (described in section 1.3) and how this process is affected by the solar wind and interplanetary magnetic field (IMF) conditions. The region of open field lines over the poles is known as the polar cap and the size of this area is
Figure 3.1. The statistical map of dayside magnetospheric regions as found from DMSP measurements (from Newell and Meng [1992]).
Chapter 3 Review of the use of HF spectral width
related to the balance between dayside and nightside reconnection [Cowley and Lockwood, 1992]. Reconnection at the dayside low-latitude magnetopause is prevalent during periods when the IMF has a southward component (with respect to the magnetic poles of the Earth). This orientation of the IMF (as Figures 1.5 and 1.6 show) provides the oppositely directed IMF and terrestrial magnetic fields which are needed for reconnection to occur in the subsolar region. Northward directed IMF is thought to allow reconnection to occur at other sites.

The cusp has been the subject of many investigations, both from the ground and with satellites. The in-situ measurements show that the cusp is characterised by electron and ion precipitation of < 1 keV and < 10 keV, respectively [Smith and Lockwood, 1996]. In particular, the ions show a dispersed signature, sometimes exhibiting steps [Lockwood and Smith, 1992]. The cusp has also been found to be characterized by the onset of broadband electrostatic noise [Curtis et al., 1982; Maynard, 1985] measured by low-altitude satellites. Maynard [1985] also observed strong, narrow DC field structures near the equatorial boundary of the cusp for IMF southward conditions. Higher altitude satellites have found intense wave activity in the cusp. For example, EXOS-D observations [Matsuoka et al., 1993] at ~10000 km found strong electric field oscillations in conjunction with soft particle precipitation and they suggested that the waves were generated at the magnetopause where ions and electrons are injected into the magnetosphere from the magnetosheath. The sharp increase in low frequency wave activity (0.1-10 Hz) [Erlandson and Anderson, 1996; Matsuoka et al., 1993], can be attributed to two causes: electric and magnetic field variations arising from FACs (the static explanation), and also to up and down travelling Alfvén waves which are generated at the dayside magnetopause (either during reconnection processes or by upgoing accelerated ions at the poleward edge of the cusp [e.g. Dyrud et al., 1997]). The amplitude of the observed waves is large enough (a few mV m⁻¹) to modulate the large-scale plasma velocity field.

The question of where the OCFLB and FRB lie in relation to the particle signatures used by Newell and Meng [e.g. 1992] is treated for example by Lockwood [1997]. Figure 1a of Lockwood [1997] shows the situation that may be expected from a closed magnetosphere model, with the OCFLB and FRB in the same place as the
boundary between the cusp and LLBL. Conversely Figure 1b of Lockwood [1997] shows the situation more likely from the open magnetosphere model with reconnection occurring at the dayside magnetopause which has the OCFLB equatorward of both the FRB and the boundary between the cusp and LLBL. In this picture the FRB is somewhere within the open field lines in the LLBL. Thus locating the OCFLB on the dayside is not a simple procedure.

Many ground signatures associated with the satellite signatures have also been observed in the low-altitude cusp and this region is an excellent example of multiple ionospheric proxies. For example, optical observations find the equatorward edge of the 630.0 nm optical emission indicates the equatorward edge of the cusp [e.g. Eather et al., 1979; Moen et al., 2001]. This is related to the presence of a magnetosheath population of particles. This optical proxy for the open/closed field line boundary (OCFLB) on the dayside is displaced poleward from the true image of the OCFLB by an amount that depends on the distance the cusp particles convect between injection and impact on the ionosphere [e.g. Rodger, 2000].

High and variable HF radar spectral width has been associated with the cusp and more general cleft region for sometime. The term cleft is used here to describe the dayside ionosphere where relatively intense soft electron precipitation is observed. The addition of ion precipitation indicates that the satellite is in the cusp proper rather than the larger region known as the cleft. Later papers restrict the high and variable width signature to the cusp rather than the whole cleft once a clear distinction was made between the two. Baker et al. [1986] made observations of the cleft using the HF radar at Goose Bay in Canada [Greenwald et al., 1985] in conjunction with the HILAT satellite [Fremouw and Wittwer, 1984]. Geomagnetic conditions were becoming increasingly disturbed on the afternoon in question (1300 to 1700 UT, 28th November 1983), the Kp index was approximately 4. Unfortunately the IMP8 spacecraft suffered a data gap during the interval and hence there are no upstream IMF measurements although data either side of the gap (1438 to 2000 UT) indicate southward $B_z$. The HILAT measurements are consistent with an upward flowing FAC surrounded on the poleward and equatorward sides by downward flowing currents. Baker and co-workers suggested that this could be a weak, afternoon region 2 FAC flowing into the ionosphere on the equatorward side, with
a strong region one current flowing away from the ionosphere in the middle and a cusp region current flowing into the ionosphere on the poleward side. Ray tracing analysis was performed using data from the HILAT satellite to construct a model ionosphere. Most of the rays were perpendicular to the magnetic field lines at or below 300 km and the field-aligned irregularities that form targets for the HF rays will stretch along the field line even if they were lower in altitude than this. The ray tracing also showed that the radar was sensitive to the region from 900 km to 1800 km horizontal range, which is much greater than the 200 km wide range where the backscatter was observed, indicating that the limits of the backscatter are geophysical rather than instrumental. The difference between the assumed free space path and the ionospheric path is \( \sim 20 \) km, i.e. of the order of one range gate. Baker et al. [1986] found very high spectral widths 700 - 1500 m s\(^{-1}\) in the region of the cleft and although they mention the possibility of the changing velocity within the region being the cause of the high widths, the required magnitude of change to give these widths is unfeasible given the flow patterns. They were of the opinion that the variable electric fields observed in the cusp by satellites [Egeland et al., 1982] were responsible for the high spectral widths observed.

Baker et al. [1990] published a case study where the DMSP F9 spacecraft [Hardy et al., 1985; Greenspan et al., 1986] passed over the field-of-view of the PACE (Polar Anglo-American Conjugate Experiment) Halley HF radar situated on Antarctica [Baker et al., 1989b] as part of the Geospace Environment Modelling (GEM) program. The DMSP satellites orbit at an altitude of \( \sim 830 \) km in a sun synchronous, approximately polar orbit. This conjunction of the DMSP spacecraft over the radar field of view specifically covered the cusp, the cusp being identified by both electron and ion precipitation signatures in the satellite data. The DMSP cusp and LLBL signatures [Newell and Meng, 1988; Newell and Meng, 1989; Newell et al., 1989] are primarily the ion precipitation (< 10 keV) and electron precipitation (<1 keV). The conditions during the interval studied (1200 to 1500 UT, on 10\(^{th}\) October 1998) were disturbed with \( B_z \) negative and therefore conditions were conducive to sub-solar reconnection for the entire interval (which had a Kp of \( \sim 7 \)). They note that typical HF Doppler spectra have a width of around 100 m s\(^{-1}\) whereas the widths observed in this case were much higher, 150 m s\(^{-1}\) to over 750 m s\(^{-1}\). The drift meter on the DMSP F9 spacecraft indicated large variations in the velocity from which large electric field turbulence was inferred. Baker et al. [1990] linked this to observations of
the electric field variability in the cusp [e.g. Dyson and Winningham, 1974] and that other observations of the cusp/cleft region have indicated unusually wide spectra [Baker et al., 1986]. They also note that the cusp is often a significant region of backscatter indicating that this region is a good source of ionospheric irregularities.

Baker et al. [1995] made use of the DMSP satellites and SuperDARN (Halley and Goose Bay) HF radars to identify more conclusively a radar signature for the cusp and low-latitude boundary layer (LLBL). They found that the cusp is indeed characterised by high spectral widths and that these widths originate from wide, multiple-peak spectra. They also found that the LLBL is dominated by single component spectra. A total of eight cusp and eight LLBL events were employed in their investigation. The authors found that the distribution of spectral widths from the cusp is approximately Gaussian in shape with the mode at \(\sim 220 \text{ m s}^{-1}\). Figure 3.2 shows two examples of spectral width distributions from Baker et al. [1995], panel (a) depicts the distribution found in the cusp and panel (b) that observed in the LLBL. The LLBL distribution is more exponential in shape than that from the cusp. There are a few cases in the LLBL where the spectra are very similar to those observed in the cusp, and the width distribution reflects this as a mixture of the exponential and Gaussian-like forms. The spectral width distribution plots were compiled from the average over the +/- 10 minutes either side of the pass and within the latitude bounds found by DMSP and within +/- 30 minutes of MLT. In the more exponential LLBL distributions the authors note there is a secondary peak at \(\sim 225 \text{ m s}^{-1}\) (as in Figure 3.2b).

Also in 1995 Pinnock et al. reported high spatial (15 km) and temporal (10 s) measurements of the cusp and LLBL using the Halley HF radar. The interval studied here was for 3 hours from around magnetic noon (~1500 UT) on 5th February 1994. These authors were primarily interested in the radar signatures of flux transfer events (FTEs) which are thought to be the result of non-steady reconnection [Cowley et al., 1991; Smith et al., 1992]. The poleward moving radar auroral forms (PMRAFs) in this interval are typical of many observations in the cusp region. The PMRAFs are seen as diagonal striping of high spectral width and velocity on latitude-time plots as in Figure 3.3. The temporal evolution of reconnection is a hot topic. The data in this interval show that the HF cusp signature is present in a continuous way but that the poleward component of
Figure 3.2(a) distribution of spectral widths for all cusp events listed in Table 1 of Baker et al. [1995] and (b) all LLBL events listed in Table 2 of Baker et al. [1995]. Data were selected from a UT time range of +/- 10 m of the satellite pass. Only data from the latitude range identified as the cusp or LLBL were included and only the data from the MLT time range within +/- 30 m of the satellite pass.
Figure 3.3. HF radar signatures of flus transfer events (from Pinnock et al. [1995])
plasma flow in the LLBL is continuously pulsed. The authors suggest that the FTE type features in the spectral width which extend quite a way equatorward could be the origin of the 'contamination' of LLBL spectra in the Baker et al. [1995] paper.

Many other authors have published work using HF radars in the cusp region [e.g. Rodger et al., 1995; Rodger and Pinnock, 1997; Yeoman et al., 1997; Milan et al., 1999; Rodger, 2000; Chisham et al., 2001; Milan and Lester, 2001; Moen et al., 2001]. Having established that the high spectral width and highly variable velocity region can be used as a locator for the low altitude cusp, the main thrust of subsequent research has been to determine the reconnection rate and electric field by monitoring the spectral width boundary on the dayside [Baker et al., 1997; Pinnock et al., 1999; Pinnock and Rodger, 2001]. Milan et al. [2002] have used the spectral width on the dayside as one of a multitude of complimentary methods to locate the polar cap boundary (PCB) on both the day and nightside. They then used the location of the PCB to monitor the opening and closing of magnetospheric flux during negative and positive $B_z$ and two substorm cycles.

Very recent work by Chisham et al. [2002] will go a long way to improving current estimates of the spectral width boundary location within the cusp, allowing it to be done automatically and far more reliably than before using a system of spatial and temporal median filtering. These authors have assessed the effect of applying various threshold algorithms to a simulated cusp-region spectral width distribution. The results indicate that the simple algorithms used previously (such as searching for the first data point above a threshold for a given time and beam, and then checking that the data is still above the threshold for one range gate poleward of the first data point) correctly identify the spectral width boundary at best 50% of the time. The effect of smoothing the spectral width data both temporally and spatially before applying the threshold algorithm significantly improves the success rate to more than 95%. The algorithms tested have also been applied to a year of data from the Halley radar. Different threshold levels were tested on the data and it was found that in the cusp region the spectral width threshold value had little effect on the latitude of the high spectral width region identified. However, this was not found to be the case on the dayside away from the cusp region, the location of the spectral width boundary was found to be highly dependent on the threshold value chosen. Further testing of these properties is required on the nightside.
3.1.2 What causes the high spectral width in the cusp?

Baker et al. [1995] noted that the high and variable spectral width in the cusp was associated with HF power spectra containing many powerful peaks and they suspected the characteristics observed were a result of the variability of the electric field. There are two main factors which influence the spectral width, (i) how the irregularities form and decay, and (ii) the variation of the velocity of the irregularities. The dominating factor will determine which model will fit the ACF best, the first factor leading to an exponential decorrelation of the ACF and the second to the Gaussian decorrelation. Baker et al. [1990] demonstrated that the region identified as the cusp from the strong particle precipitation corresponded to the region of strong horizontal drift turbulence seen by the satellite (DMSP F9). They also compared the radar velocity to the drift measurements from DMSP to confirm that the radar velocities are indeed representative of the overall flow and not subject to distortion from the multi-component spectra. The region of wide spectra often continues poleward of the cusp into the mantle region. Hanuise et al. [1991] point out that a continuous, turbulent distribution of velocities would be expected to produce a smooth radar spectrum, either Gaussian if the coherence time is large (compared to an ACF), or Lorentzian is the coherence time is short. Thus the observed multi-component spectra could indicate that the cusp is characterised by strong variations, either temporal or spatial, that have a discrete nature. They suggest velocity shears or sudden changes in velocity as possible candidates. They also note that there is a large variation in the velocities as well as the widths.

There is a limit to the frequency of changes in plasma flow that the radar can pick up. It is possible that the multiple-peak spectra are a result of undersampling, and therefore the extra peaks would not have any physical meaning. This proposal was investigated by André et al. [1999; 2000a; 2000b] in the light of satellite (see section 3.1.1) and ground magnetometer measurements [Menk et al., 1992] of wave activity in the Pc1/Pc2 (0.1 to 5 Hz) frequency band. André et al. [1999] simulated 500 monochromatic sources with a Gaussian distribution based on a mean value and a definite bandwidth, a uniform distribution of phases and a common amplitude. They concluded that all the characteristics of cusp spectra can be explained by the presence of a broadband wave in the Pc1/Pc2 frequency band. This short paper was expanded in André et al.
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[2000a] and they demonstrated that even a monochromatic electric field variation can cause apparently turbulent behaviour, including large widths and apparent multiple components. The simulations also demonstrated that low amplitude waves are sufficient if the frequency of the electric field variations is high enough. Figure 3.4 demonstrates that an onset frequency for large widths is displayed for a fixed amplitude wave. The spectral width value is colour coded for different combinations of wave amplitude and frequency. They found, as did Baker et al. [1990], that the background velocity measurement is not strongly affected by the presence of these waves. André et al. [2000a] show that due to the non-linear nature of the phase of the ACF under such conditions, large errors in the velocity fitting routine will occur under these conditions. Figure 3.5 shows both the existence of an onset frequency for a given wave amplitude and also the increase in the variability of the velocity and width once this onset frequency is passed. This is the source of the variability in the velocity. When the spectrum contains several components, FITACF is less reliable and usually overestimates the width, thus resulting in the large and variable spectral width values observed in the standard width parameter in the cusp. The limitations of the simulations presented by André et al. [1999; 2000a; 2000b] imply that the results obtained should be regarded as minimum values of spectral width.

Regarding the possible sources of electric field variations used in the simulations of André et al. [1999; 2000a; 2000b], there have been many observations of wave activity of the correct frequency and magnitude (section 3.1.1). If the wave signatures observed by the satellites are due to the passage through static field-aligned currents then these would not be related to the high spectral width caused by temporally varying electric fields since they are spatial rather than temporal changes (although there are other mechanisms that could result in high spectral widths from static structures, see section 3.2). However the low frequency activity can also be interpreted in terms of propagating Alfvén waves arising from the magnetopause, distant magnetotail or up going waves from the magnetosphere. Wahlund et al. [1998] found that the low frequency signals (often classed as 'noise') are probably the result of many wave modes superimposed on each other. Where the frequency is below a few tens of Hertz the wave character has been shown to be mostly Alfvénic [e.g. Matsuoka et al., 1993]. Intense, transverse ion
Figure 3.4. Color-coded spectral width as a function of the wave amplitude and wave frequency (from André et al. [2000a]).
Figure 3.5 (left) mean value of the velocity and (right) the spectral width. Both values are shown as a function of the wave amplitude and for wave frequency. The error bars give the standard deviations associated with the mean values (from André et al. [2000a]).
acceleration has also been associated with similar frequency observations within the region of auroral inverted-V electron precipitation [e.g. André et al., 1990].

A broader range of physical causes for high spectral width were considered by André et al. [2000b]. This paper reports simulations of the effect of micro-scale ionospheric turbulence (micro-scale turbulence arises from interactions between irregularities or from micro-scale electric fields), low-frequency wave activity and velocity shears. The authors present a statistical plot (October 1996 to March 1997) of average spectral width over all 24 hours of MLT. This shows the presence of the highest widths in the average cusp location and a general auroral oval like shape of large widths.

Two mechanisms other than low frequency waves were simulated to investigate their effect on the ACF and fitted parameters. These are the presence of a convection reversal or a vortex within a range cell. Across a convection reversal, two opposite velocities should exist within one range cell and the ACF would reflect this with the power spectrum exhibiting two peaks. Barthes et al., [1998] have found (using the MUltiple SIgnal Classification system) that the probability of finding multi-component spectra is strongly enhanced at convection reversals. André et al. [2000b] used a convection model [Rich and Maynard, 1989] to produce vector velocities in a range gate to simulate what will happen to the ACF if a convection reversal is present. This shows a much wider velocity distribution in the convection area as expected. They note the effect of looking at the same region with different radars. The velocity measurements are only line-of-sight, thus one radar may see many components while the other does not. They conclude here that the maximum width due to this kind of process is 150 m s$^{-1}$ and therefore not capable of explaining the spectra from the cusp which tend to be many hundreds of m s$^{-1}$.

Villain et al. [2002] also investigated the effect of flow reversals on the value of the spectral width by performing simulations using a convection pattern model. The radar range cells were divided into subcells of 1 km square and the Heppner and Maynard [1987] model of convection used to generate a velocity distribution within the radar range cell. An example of this simulation is shown as a spatial plot for one full scan of the radar in Figure 3.6a for the Iceland West radar. The two velocity distributions on the right hand side of the figure are taken from the spatial plot where the black rectangles indicate.
Figure 3.6. (a) Simulations of the velocity distribution from a modelled convection pattern and the resulting value of spectral width. (b) The estimated contribution to the spectral width of the effect of convection for the second interval (From Villain et al. [2002])
the regions of flow reversal a clear rise in the spectral width is predicted but this is highly dependent on the beam direction. A larger scale simulation was undertaken to predict the contribution of flow reversal to the average spectral width for six of the northern hemisphere SuperDARN radars (Goose Bay, Kapuskasing, Saskatoon, Iceland West, Iceland East and Finland) from October 1996 to March 1997. The Heppner and Maynard model was used for the appropriate Kp (2⁺) for the data points observed in the second interval of study. Figure 3.6b shows the results of these simulations and Villain et al. [2002] found that the contribution of the flow reversal to the high spectral widths observed was insufficient to produce the observed results.

Vortices with scale sizes of ~10 km were also simulated by André et al. [2000b]. The velocity shear from the vortex introduces non-linearity in the phase and a large spectral width (170 m s⁻¹ even though no turbulent effects were included in the simulation). This agrees with the Barthes et al., [1998] results. The vortex simulation is related to structures that can be created by filamentary FACs. The current closure in the conducting layer will generate a divergent electric field structure and hence a small-scale vortex. The current that sustains the vortex can (depending on its direction) generate irregularities by the current convective instability [Ossakow and Chaturvedi, 1979] and could thus increase the backscattered power in the vortex centre. As with the simulated convection reversal the phase is non-linear and the width high – suggesting a multi-component spectrum. The possibility that plasma vortices may be responsible for the HF spectra with two peaks was put forward by Schiffler et al. [1997] in relation to the preponderance of double-peak spectra observed in the LLBL (see following section). André et al. [2000b] found that the non-linearity in the phase is reduced when decreasing either the maximum velocity in the vortex centre, or the size of the vortex. A 5 km scale vortex does not generate a clear multi-component spectrum, but having many small vortices would increase the non-linearity in the phase and would probably give you more than two peaks. André et al. [2000b] concluded that all mechanisms tested were possible generators of wide, multiple component spectra, but that the low-frequency wave activity is the dominant mechanism in the cusp.

Hosokawa et al. [2002] present a statistical study of the spectral widths on the dayside from the perspective of two conjugate radars, Syowa East and Iceland East,
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Review of the use of HF spectral width between 0900 and 1500 MLT. As expected they find that there is a change from low to high spectral widths with magnetic latitude in the cusp in both hemispheres. Investigating the distribution of spectral width in this sector of MLT reveals three types of distribution, an exponential-like distribution at lower latitudes (below 72°), a Gaussian-like distribution over a few degrees of magnetic latitude around 78° and another type of distribution still further poleward. The authors associate the Gaussian-like distribution to that observed in the cusp by Baker et al. [1995] and the lower latitude exponential-like form to that observed by the same authors in the LLBL. Similar distributions are observed in both hemispheres although the values of spectral width from the Syowa East radar in the southern hemisphere are noticeably larger than those from Iceland East in the northern hemisphere. For the purposes of realistic processing a subset of the data from the radars has been used consisting in each case of 16 summary points arranged approximately meridionally with respect to the magnetic pole. The two radars are approximately magnetically conjugate to each other and the summary points from the two radars were chosen such that there was as much overlap between the two hemispheres as possible. Three years of common mode data were used. Figure 3.7 shows contour plots of the spectral width distributions for the data sets from the two radars used in this study for the interval 0900 to 1500 MLT. The colour scale indicates the percentage occurrence of a spectral width value at a particular summary point, the spectral width distribution at each summary point is normalised to the data from that point. Both panels clearly show an increase in the spectral width value of the peak of the distributions with latitude (the summary point numbers s0, c0 etc. increase poleward). The length of the tails of the distributions also increase to a maximum at around 78° before decreasing again. The spectral width distributions around 78° greatly resemble those seen by Baker et al. [1995] in the cusp and this range of latitudes is typical of the cusp.

3.2 The low-latitude boundary layer

The LLBL is the longitudinally extended region (in comparison to the cusp, see Figure 3.1) just internal to the magnetopause [Smith and Lockwood, 1996]. In the Newell and Meng [1992] description of the dayside magnetospheric regimes the LLBL is defined
Figure 3.7. The distribution of spectral widths observed by (a) Syowa East and (b) CUTLASS Iceland East radars. The vertical axis indicates the summary points from S0 to S15 for Syowa East and C0 to C15 for Iceland East, and the horizontal axis is the spectral width (from Hosokawa et al. [2002]).
by a ten-fold decrease in the maximum flux observed in the energy spectrum, with generally lower bulk flow velocities and larger temperatures compared to the cusp.

As mentioned in the previous section, Schiffler et al. [1997] reported the presence of HF radar spectra with two peaks in the LLBL. Schiffler et al. [1997] used the Saskatoon and Kapuskasing pair of SuperDARN HF radars in Canada to measure F-region dayside scatter. Most of the spectra they observed were single-peaked, but some were double and these occurred poleward of the convection reversal on the 2D convection maps. Comparison with DMSP particle measurements shows that the double-peaked spectra occur equatorward of the magnetopause, in regions where there was structured electron precipitation (~300 eV). The authors explain the double-peaked spectra in terms of small scale vortices, less than the scale of the radar range cell (45 km), using the analogy of weather radar observations of tornadoes. This paper presents the case for 20th February 1995 in the prenoon MLT sector (1630 to 1640 UT) with Bz and By positive. To resolve the double-peaked spectra they have used the maximum entropy method spectral estimator [Schiffler, 1996], specifically the Burg spectral estimator of order 8. They note that the double-peaked spectra appear in spatially organised bands suggesting a physical reason for their appearance. As a mechanism capable of generating small plasma vortices they propose the idea that the filamentary electron currents would have an inner negative core and an outer positive layer due to spreading of the ions [Davidson, 1965]. This in turn leads to a radial electric field and vortical ExB flow around the current. Schiffler et al. [1997] noted that radially divergent electric fields have been observed by S3-2 satellite [Burke et al., 1983], GOES 7 [McDiarmid et al., 1994] and FREJA [Johnson and Chang, 1995] in the appropriate region. Schiffler et al. [1997] indicated that the DMSP electron signature of the 300 eV energy is very spiky [Newell and Meng, 1988] and Schiffler and co-workers link this to filamentary FACs. They conclude that you can map the outer LLBL (as classified by the neural network analysis described by Newell et al. [1991]) using double-peaked spectra.

Huber and Sofko [2000] followed up the analysis of Schiffler et al. [1997] by conducting a statistical study of HF spectra using the Saskatoon radar in high spatial (15 km) and temporal (3 s) scanning modes. They find that the scalesize of the phenomenon is less than ~26 km and the lifetime is less than ~4 s and investigate possible mechanisms
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that could cause the double-peaked spectra. The average separation of the two peaks is 
\( \sim 200 \text{ m s}^{-1} \) and structures of the size mentioned above in the ionosphere map out to scale 
sizes of \( \sim 1000 \text{ km} \) or more in the outer magnetosphere.

Various other explanations for the presence of double-peaked spectra are 
investigated by Huber and Sofko [2000]: i) scattering from plasma waves structures (such 
as those produced by the gradient drift instability), if the waves are travelling towards and 
away from the radar, this is in effect a target for the radar if the wave front separation is of 
the right scale, ii) variation of the ionospheric plasma velocity within the integration 
period, iii) the radar could be accessing two different regions of the ionosphere 
simultaneously (this could be a result of the vertical spread of the radar beam leading to 
different propagation paths [André et al., 1998], which could include low elevations 
scattering from the E region and larger elevations from the F region), iv) simultaneous 
scatter from the main and side lobes of the beam pattern is also a possibility since the side 
lobes are only \( \sim 15 \text{ dB} \) reduced from the main lobe.

A statistical occurrence for double-peaked spectra was found by Huber and Sofko 
[2000] using normal mode operation for November and December 1996, accumulating \( \sim 1 \) 
million daytime echoes. These data are grouped in intervals of \( 1^\circ \) of geomagnetic latitude 
and 10 mins of MLT and is presented in Figure 3.8. The location of the double-peak 
spectra is concentrated around the area of the cusp and LLBL (between \( \sim 0800 \text{ MLT} \) and 
1300 MLT, and 77° to 82° magnetic latitude). There is a distinct absence of double- 
peaked spectra in this plot before \( \sim 0800 \text{ MLT} \).

Two experiments were conducted, one (17th September 1997) had 15 km range 
gates and a first range of 1500 km, 70 range gates, beam 3 (~meridional) is scanned at 7 s 
dwell for 2 mins, then there is a full scan for 2 mins. The second experiment (30th March 
1998) used the same mode as above but at 3 s dwell rather than 7 s. The mean separation 
of the two peaks where a double-peak spectra was found was 200 m s\(^{-1}\) which corresponds 
to an electric field in the F region of \( \sim 10 \text{ mV m}^{-1} \), therefore this could be \( \pm 5 \text{ mV m}^{-1} \) 
either side of the mean DC electric field driving the convection. They note that this is 
larger than the 1 mV m\(^{-1}\) associated with Pc1/Pc2 frequency waves in the cusp that have 
been suggested to cause the multiple-component spectra by André et al. [1999; 2000a; 
2000b].
Figure 3.8. Occurrence frequency of double-peaked spectra (in percent) for ionospheric backscatter, in bins of 1° geomagnetic latitude and 10 min magnetic local time (From Huber and Sofko, [2000]).
In reference to the possibility that the double-peaked spectra could originate from plasma waves, with a mean separation of 200 m s$^{-1}$ the plasma waves would have an average phase velocity of $\sim$100 m s$^{-1}$ over the background convection. This order of phase velocity has no reported mechanisms, this includes the gradient drift waves (which are generally assumed to be responsible for the HF backscatter in the F region) since they have much lower phase velocities [Villain et al., 1985; Ruohoniemi et al., 1987].

To test if the two peaks are a result of the velocity changing within the integration period sequences of three consecutive scans were found where the middle scan was double-peaked and the two either side were single peaked. One would expect that the velocity would change from scans 1 to 3 in a way that is consistent with the peak separation in scan 2. The comparison shows that the difference in velocities between scans 1 and 3 is very small, but the difference between the two peaks of scan two is well over 100 m s$^{-1}$ for nearly all the data. It therefore seems unlikely that temporal variations in velocity are responsible for the two peak spectra.

The proposal that side lobes may be responsible is not accepted on the basis that the radar ray propagation typically remains constant over minutes rather than the few seconds of the lifetime of these structures. The same timing applies to the vertical extent of the beam ($\sim$15° half power width). This is also rejected on the basis that the elevation angle of the double-peaked spectra is typically higher than the single-peaked.

After considering these possibilities Huber and Sofko [2000] conclude that vortices are the number one candidate. They suggest that these vortices could result from the Kelvin-Helmholtz instability driven by the shear between the magnetosheath and magnetospheric plasma. They suggest also that velocity shears are unlikely to be the mechanism because they tend to be spread over several range cells/times whereas the double-peaked spectra generally occur singly and do not persist in space or time. However, the shears would be an excellent source for the Kelvin Helmholtz instability to produce vortices. Modelling of the scattering characteristics of a vortex, both analytically and using the Monte Carlo method by Huber and Sofko resulted in a double-peaked spectrum confirming the possibility that a vortex could create a double-peaked spectrum.
3.3 The nightside HF spectral width boundary

Regions of ionospheric backscatter with similar spectral width features to those seen in the cusp are also found frequently on the nightside [Lewis et al., 1997; Dudeney et al., 1998; Lester et al., 2001; Parkinson et al., 2002]. A sharp gradient between the areas of low (<200 m s\(^{-1}\)) and high (>200 m s\(^{-1}\)) spectral width is frequently observed on the nightside. This sharp gradient is not in general associated with a gradient in the backscatter power (unlike some cusp data [Milan and Lester, 2001]). Since the spectral width boundary is frequently observable by the SuperDARN radars it could make a good ionospheric proxy for a magnetospheric boundary. This well-defined nightside gradient in spectral width has been given different interpretations. Lewis et al. [1997] present observations of a small isolated substorm which occurred on 13\(^{th}\) June 1988 (0000 to 0300 UT). The primary observations are from the Halley HF radar with support from geostationary satellite and ground magnetometer data. The equatorward edge of the radar backscatter is observed to move equatorward as the growth phase of the substorm occurs. Within this region of backscatter a gradient in the Doppler spectral width is observed which they link to latitudinal structure in auroral emissions and magnetospheric precipitation. At substorm onset a reversal in the flow direction seen by the radar is observed within one minute of a dispersionless injection at geostationary orbit and the Pi2 magnetic signature on the ground. They relate this sudden change in flow to the presence of the upward field aligned current of the substorm current wedge.

This paper is aimed at investigating the electric field response to a substorm. The dwell time for Halley was 6 s with range gates of 45 km. The geostationary spacecraft used is LANL. There is no IMF data. An increase in the AU (auroral electrojet upper index) corresponds to an increase in the strength of the eastward electrojet and defines the substorm growth phase. Prior to the growth phase conditions were magnetically quiet for over 12 hours with a Kp of 0+ to 1+ and AE index less than 100 nT.

Two DMSP crossings were used to locate the boundary plasma sheet (BPS) and central plasma sheet (CPS). Two methods were used with the DMSP data, firstly finding the best fit oval for a given Q and secondly assuming a circular oval with an offset using the nearly simultaneous observations in several MLT sectors. Both methods show that the equatorward edge of the discrete aurora expands equatorward during the growth phase
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like the HF scatter does. The plasma sheet as a whole is indicated in Figure 1.4 in Chapter 1, the CPS is the most equatorial region of the sheet and maps to lower latitudes in the ionosphere. The BPS is located poleward of the CPS and is generally defined by the presence of discrete aurora. The equatorward edge of the backscatter seems to be associated with the BPS/CPS boundary. Lewis et al. [1997] link the region of backscatter to the region of magnetospheric precipitation around the BPS/CPS boundary. No specific boundary is attributed to causing the spectral width gradient although they associate it with structure in the magnetosphere.

Dudeney et al. [1998] linked the latitudinal gradient in the Doppler spectral width (which they call sharp) observed by the Halley HF radar to the boundary between the CPS and the boundary layer plasma precipitation observed by the POLAR satellite. The interval in question is 2000 UT (28th May 1996) to 0800 UT (29th May 1996) when B_z was consistently positive. The clock angle exceeded ~40° for all except a few minutes of the interval meaning that sub-solar magnetopause reconnection was unlikely. The solar wind density and velocity increased steadily throughout the interval, from 18 to 28 particles cm\(^{-3}\) and 350 to 380 m s\(^{-1}\) respectively. No substorm signatures were seen with the CANOPUS magnetometers in the night time sector, and conditions seem generally quiet. There was a fortuitous overpass of the POLAR satellite over the Halley field of view during the interval. The spectral width was low (<100 m s\(^{-1}\)) at low latitudes with a sudden increase to high values (> 200 m s\(^{-1}\)) at 71.5° whilst POLAR was passing through. The Earth Camera on the POLAR satellite [Frank et al., 1995] indicated weak diffuse aurora from 65-75° magnetic latitude where the radar field of view was located. POLAR observed no large changes in intensity or structuring of the UV emissions that show this diffuse aurora near the spectral width boundary. The equatorward edge of the scatter did not correspond to the equatorward edge of the aurora, but there was decent agreement (~1°) between the two poleward boundaries. There was also a marked increase in the intensity of electrostatic waves < 100 Hz at the spectral width boundary. Dudeney et al. concluded from the POLAR data that the spectral width gradient straddled the CPS/BPS boundary. They then used this relationship to look at the response of the CPS/BPS at dawn, dusk and midnight to a significant change in B_y whilst magnetic conditions were quiet using the SuperDARN HF radars at Halley, Hanksalsmi (Finland) and Saskatoon (Canada). They found that the motion of the boundary with B_y was consistent with the
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work of Holzworth [1984], and that the response to the change was of the order of minutes near dawn and dusk.

The other interpretation of the spectral width gradient is that it represents the OCFLB [Lester et al., 2001; Parkinson et al., 2002]. Lester et al., [2001] suggested that the gradient is the radar representation of the OCFLB, at least for part of the interval discussed. Lester et al. [2001] presented a comparison of Finland radar data with optical data from the meridian scanning photometer (MSP) instrument at Longyearbyen on Svalbard, IMAGE magnetometers and the DMSP F12 satellite. It was a mainly pre-midnight interval (1850 to 2300 UT, ~2120 to 0130 MLT on 27th November 1997) during which the IMF was weakly northward. The poleward border of the 630.0 nm (red) optical emission was located to within 1° of the boundary between high (> 200 m s\(^{-1}\)) and low (< 200 m s\(^{-1}\)) spectral width for parts of the interval as shown in Figure 3.9 (the top three panels are backscatter power, line of sight velocity and spectral width from the Finland radar respectively and the bottom two panels are the 630.0 nm and 557.7 nm optical observations from the MSP). The significance of this is related to the work of Blanchard et al. [1995; 1997] which identifies the poleward edge of the 630.0 nm emission as being co-located with the OCFLB in the pre-midnight sector. DMSP particle observations in the 20 eV to 30 keV energy range showed that both the poleward edge of the 630.0 nm emission and the spectral width boundary were collocated with the change from auroral precipitation to polar rain energies. Lester and co-workers therefore concluded that the high spectral widths were not caused by auroral oval type particle precipitation.

Two periods were identified when the relationship between the red line and spectral width broke down. The first occurred in a period when the westward electrojet was enhanced as were the red (630.0 nm) and green (557.7 nm) optical emissions. The authors associate this with a substorm occurring at higher latitudes than is usual. The second breakdown contained equatorward moving bands of large spectral width. These narrow bands were associated with thin channels of enhanced westward ion velocities. Lester et al. concluded that these bands may be a result of reconnection processes in the tail.
Figure 3.9. Backscatter power, line of sight velocity and spectral width from beam 9 of CUTLASS Finland, as a function of latitude for the interval 18-23 UT on 27th November 1997. Also plotted are the 630.0nm and 557.7 nm emission intensity as a function of zenith angle. The full line marked on each panel of the radar data represents the poleward 1.5 kR contour of the 630.0 nm emission (from Lester et al. [2001]).
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Distributions of spectral width poleward and equatorward of the 1.5 kR contour for the interval 1845 UT to 2300 UT show a change from a Gaussian-like, to a more exponential shape (see Figure 3.10). The distributions are for 1845 UT to 2300 UT only where the 1.5 kR line was present. Data from all 16 beams was included with the assumption that the red line emission is at constant latitude. Polar rain is characterised by weak electron flux with an average energy of 100 eV [Hardy et al., 1986], whereas the red line emission is generally believed to be from 1 keV electrons and would therefore be attributed to the auroral oval where higher electron energies are observed. The red line emission is therefore expected to be on closed field lines. Comparison with a DMSP pass just prior to the start of the interval found that the high spectral widths were observed in the region of polar rain and the low spectral width in the region with structured precipitation that resulted in the red and green auroral emissions. This disagrees with the observations of Dudeney et al. [1998] which found the high spectral width in the BPS region. This of course does not include the excursions of the spectral width boundary below the poleward edge of the 630.0 nm emission in the Lester et al. study.

The equatorward moving bands in the Lester et al. interval were compared to observations by de la Beaujardière et al. [1994] of intensifications at the poleward edge of the auroral oval in the optical emissions. De la Beaujardière et al. [1994] concluded that the features were related to a local increase in the reconnection rate in the tail. Lester et al. [2001] noticed many similarities between the interval discussed in their paper and the interval studied by de la Beaujardière et al. [1994], the main difference being that the de la Beaujardière et al. [1994] interval was dominated by IMF $B_x$. The overall conclusion of Lester and co-workers was that the spectral width boundary may be used as a proxy for the OCFLB but with 'extreme caution'. In terms of the spectral width parameter there are two interesting features firstly the boundary in the spectral width and secondly there are the equatorward moving bands of high spectral width.

Parkinson et al. [2002] also propose that the spectral width gradient can represent the OCFLB and present an extended interval of a nightside spectral width boundary from the Tasman International Geospace Environment Radar (TIGER) in the southern hemisphere from 1200 UT to 1500 UT on 10th December 1999. A crossing of the DMSP F14 satellite indicated that the high spectral width (>200 m s$^{-1}$) was on open field lines.
Figure 3.10. Occurrence histograms of spectral width poleward of the 1.5 kR contour (thin line) and equatorward of the 1.5 kR contour (thick line), (from Lester et al. [2001]).
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Bursty flows were observed in the region of high spectral width. The geomagnetic conditions were quiet to moderate with a Kp of 2. \( B_y \) was mostly positive and \( B_z \) mostly negative although there were short, weak and separate excursions from this state by each component during the interval. Ground magnetometer and satellite particle measurements indicated a pseudo-breakup just after the interval with a weak growth phase observable during the interval in the magnetometer data from Macquarie Island (65°S geomagnetic). The TIGER backscatter power, line-of-sight velocity and spectral width are shown in Figure 3.11a, b and c respectively. The power shows several patches that move equatorward which the authors associated with irregularity production at the trailing edge of electron density patches. The combination of these enhanced regions of power with the equatorward flow bursts apparent in Figure 3.11b probably resulted in the equatorward motion of the patches of large power. The shape and timing of the flow bursts also seemed to have an effect on the location of the spectral width boundary between low and high values. The spectral width boundary had no large net motion in latitude although there are many small movements toward and away from the equator during the interval.

The authors also note the similarity of the region of low spectral widths to the dusk scatter associated with the main ionospheric trough by Ruohoniemi et al. [1988]. The DMSP boundary identification of Newell et al. [1996] indicated that the low spectral width in this case was associated with the diffuse and discrete auroral ovals and the large spectral width with the polar cap ionosphere (as Lester et al. [2001] also found for part of their interval). Although there was only one crossing of the DMSP during the three hours of this interval, the authors believed that the subsequent behaviour of the spectral width boundary was consistent with the expected behaviour of the OCF LB under the given conditions and compare it to Figure 7 of Cowley and Lockwood [1992]. Parkinson and co-workers believed that the motion of the spectral width gradient, used as a proxy for the OCF LB, showed balanced nightside and dayside reconnection rates keeping the OCF LB at approximately the same location.

3.4 Mechanisms for large spectral width on the nightside

Thus far, work on the mechanisms responsible for this feature of the spectral width has concentrated in and around the cusp area on the dayside. The mechanisms
Figure 3.11. Data from the TIGER HF radar on 10th December 1999 (a) backscatter power, (b) line-of-sight velocity, and (c) spectral width (from Parkinson et al. [2002]).
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proposed for this feature on the dayside could also be responsible for the high and variable spectral width observed on the nightside. Certainly within the auroral oval there are likely to be filamentary field aligned currents that could generate vortical turbulence in the manner described in section 3.2. Also the velocity shear at the flow reversal boundary (FRB) could be a source for the Kelvin-Helmholtz instability that in turn could generate small vortices in the ionospheric plasma. Satellites have also detected the presence of electric field variations of the appropriate frequency in the region of the auroral oval [Gurnett *et al.*, 1984; Gurnett, 1991]. Therefore, all mechanisms proposed for the cusp/LLBL are also possible on the nightside.

Villain *et al.* [2002] use two winter intervals of data from the northern hemisphere SuperDARN radars to demonstrate the average spectral width behaviour over all MLT. Although the two periods include different sets of radars (as more radars became operational) the results are very similar. Figure 3.12 shows the results for the second interval (October 1996 to March 1997) where six radars contributed to the statistics. The average backscatter power (in panel (a)) shows a similar pattern to the overall data occurrence since both these parameters depend upon propagation and absorption effects as well as the presence of irregularities. Panel (b) shows the average spectral width where two features in particular are noticeable. Firstly the peak in spectral width near magnetic noon in the region of the cusp/LLBL/mantle. The black line delineating this is from the Newell and Meng [1992] contour of the cusp/LLBL/mantle region estimated from satellite measurements at low altitude. The second feature in panel (b) is the oval shaped region of high widths which compares favourably with the poleward edge of the Holzworth and Meng [1975] statistical auroral oval which is overlaid in the figure (this is the poleward edge of the statistical oval for the appropriate Kp value). The location where spectral widths in excess of 300 m s$^{-1}$ are found is shown in panel (c) which depicts a very similar pattern to panel (b). Finally in panel (d) examples of the spectral width distributions, which contributed to the figure in panel (b), are shown, the locations in MLT and magnetic latitude from which these distributions are taken are indicated by the white rectangles on panel (b). The cusp distribution (shown in blue on panel (d)) shows a similar pattern to that of Baker *et al.* [1995].
Figure 3.12. The results of the second interval of study from Villain et al. [2002], (a) the average power, (b) the average spectral width with overlaid contours of the cusp/LLBL/mantle and poleward edge of the auroral oval, (c) the locations where spectral widths over 300 m/s were observed and (d) examples of spectral width distributions from the grid cells marked by white rectangles in panel (b).
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André et al. [2002] used a novel approach to the statistical mapping of where spectra with many peaks occur. They utilised the errors on the fitting procedures, specifically the standard deviation on the phase and power fits to the ACFs. As mentioned in various papers [e.g. André et al., 2000a; 2000b] the variability associated with the large spectral widths due to multiple-peaked spectra is a consequence of the non-linearity of the phase and how the ACF decorrelates. A perfect, single frequency ACF has a linear change in the phase and an easily identifiable decorrelation shape (exponential or Gaussian). Thus mapping statistically where the errors in fitting the phase and power curves is a good indication of where multiple peak spectra are being observed. In this paper André et al. have classified the type of spectra using three criteria, the standard deviation for the phase, the standard deviation for the power and the value of the fitted spectral width. They split the data into three classes of spectra, 'S' which are narrow, single component spectra, 'T' which are wide, single component spectra and finally 'm' which are the multiple-component spectra. The statistical study presented in this paper uses common mode data for 6 SuperDARN HF radars in the northern hemisphere (Finland, Iceland East, Iceland West, Goose Bay, Kapuskasing and Saskatoon). The data is restricted to winter (November 1995 to April 1996 and October 1996 to March 1997), and to ranges beyond 900 km from the radar to create a database from a majority of F-region echoes. Figure 3.13 shows the distributions of the three classes of spectra over MLT in bins of 1° of magnetic latitude and 30 minutes of MLT. These three panels show that the different type of spectra are dominant in different sectors of MLT implying that their sources are in different regions of the magnetosphere. Figure 3.14 demonstrates more clearly the dominant type of spectra in each sector of MLT. Panel (a) has an overlay of a representative two cell convection pattern [Heppner and Maynard, 1987, Model A] and panel (b) has isocontours of the average energy of electron precipitation from Hardy et al. [1987]. Under both panels the type of spectra is colour coded, 'S' is grey, 'T' is red and 'm' is yellow. Where two classes have similar relevance the two colours are mixed.

The narrow spectra are most prominent at lower latitudes on the dayside where the field lines are closed and where the precipitating particle flux is low (Figure 3.14b). The radar targets in this region are irregularities which are thought to be related to auroral blobs [Robinson et al., 1985; Ogawa et al., 1998], that is regions of enhanced ionisation larger than 100 km. These blobs convect around to dusk having been created in the cusp
Figure 3.13. Occurrence of ACFs of different types (a) class m, (b) class S and (c) class T (from André et al. [2002])
Figure 3.14. (a) Convection pattern defined by Heppner and Maynard [1987] (Model A), superimposed on the dominant class of ACF over the auroral zone. Orange and pink correspond to the combination of T and m, and S and T classes respectively. (b) Isocontours of the average energy of electron precipitation as defined by the model of Hardy et al. [1987], superimposed on the dominant ACF class (from André et al. [2002]).
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The broad but single component spectra are found in conjunction with electron precipitation in the energy range 0.5 to 1.5 keV (Figure 3.14b). The presence of small field aligned currents is suggested as a probable reason for the increase in the width.

Finally, the multiple-component spectra are found to be dominant at high latitudes, particularly on the dayside where the cusp is located. This type of spectra has been attributed to low frequency electric field variations [André et al., 1999; 2000a; 2000b] as already described in section 3.2. The authors expect that the 'm' class spectra away from the cusp but still at high latitudes is a result of the same mechanism.

Figure 3.15 shows a typical radar scan and how it breaks down into different classes of spectra identified by André et al. The ACFs depicted show how the different kinds of spectra arise, panels (b) and (c) result in a multiple component spectrum with (b) showing the phase and (c) the power of the ACF. Similarly (d) and (e) show the phase and power of a broad single component spectrum and (f) and (g) the same parameters for a narrow single component spectrum. The most obvious feature of the ACF which gives rise to a multiple component spectrum is the non-linearity in the phase, one of the characteristics of this class. The example of a T class ACF exhibits characteristics in the power decorrelation described by various authors in terms of the transport characteristics of irregularities [Hanuise et al., 1993; Villain et al., 1996; André et al., 1998]. The decorrelation of the power at short times is best fitted by a Gaussian function but at latter times is better suited to an exponential shape. The three examples in Figure 3.15 are all taken from ranges at a similar distance to the radar but at different magnetic latitudes, thus the authors propose that the ACF shapes are affected more by magnetic latitude than how far the radar beam has propagated. This implies that the different classes of spectra are related to physical processes rather than instrumental effects.
Figure 3.15. a) ACF classes observed by the Stokkseyri radar on the 18th February 1998 at 2206 UT in geomagnetic (MLT, MLAT) coordinates. Class m, T and S are coded in yellow, red and gray, respectively. b) and c) are the ACF phase and power recorded on beam 7, gate 31 during this scan. In the same way, d), e) and f), g) are the ACF phase and power recorded on beam 4, gate 31 and beam 1, gate 35 respectively (from André et al. [2002]).
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3.5 A brief summary

Most of the investigations of where, when and how the spectral width parameter from HF radars is large have been conducted on the dayside with the cusp as the focus point. The spectral width associated with the cusp region is found to have high values (>150 m s\(^{-1}\)) which vary widely. The velocity in the cusp is also found to have an increased variability around the background plasma flow velocity. The regions of high and variable spectral width in the cusp are often collocated with other ionospheric proxies for the cusp such as the 630.0 nm emission. Two mechanisms are applicable to the high spectral width on the dayside, in the cusp 0.1 to 5 Hz electromagnetic variations are present and have been shown to be capable of generating high and variable spectral width through their effect on the ACF. In the LLBL, double peaked Doppler spectra have been observed which were attributed to the presence of vortices in the plasma on a scale smaller than the radar range cell and integration time. High and variable spectral width on the dayside has been used as a proxy for the cusp on several occasions to estimate the OCFLB location with various further applications such as the study of FTEs and the measurement of reconnection rates. The most pertinent question left regarding the high spectral width in the cusp region seems to be what happens when the IMF \(B_z\) is northwards.

The small body of work considering the raised spectral width values and sharp gradient on the nightside has presented two key ideas for the spectral width gradient. Firstly that the spectral width gradient could be a proxy for the OCFLB on the nightside, as it seems to be on the dayside, and secondly that the spectral width gradient may represent the change from CPS to BPS. Regarding possible mechanisms for the high spectral width on the nightside both the mechanisms suggested for the dayside are feasible but no evidence has yet been shown to prove that they are responsible. There is much to be done on the nightside to identify the mechanism responsible for the high spectral width and to identify what boundary in the magnetosphere the spectral width gradient may represent (if any). The work presented in this thesis aims to address these questions.
CHAPTER 4

Other instrumentation within the CUTLASS field of view

To assess the usefulness of the HF spectral width parameter as an ionospheric proxy it is necessary to combine measurements from other sources with the coherent HF radar data. In the three case studies presented in the chapters 6 and 7, many different ground based instruments have been employed along with spacecraft which monitor the IMF and solar wind plasma parameters. The instruments and spacecraft relevant to the later discussion are described in this chapter.

4.1 EISCAT and ESR

The European Incoherent SCATter radars (EISCAT) and the EISCAT Svalbard Radar (ESR) are excellent sources of measurements of the plasma which is simultaneously observed by the CUTLASS HF coherent radars. The EISCAT facility on the mainland consists of two radars, a tristatic UHF radar and a monostatic VHF system [Rishbeth and Williams, 1985]. The UHF transmitter is situated at Tromsø, Norway (69.6°N, 19.2°E geographic coordinates) with receivers at Tromsø, Kiruna in Sweden (67.9°N, 20.4°E geographic) and Sodankylä in Finland (67.4°N, 26.6°E geographic), see Figure 4.1 for their relative locations. The UHF antennas are parabolic 32m diameter dishes which transmit/receive at ~933MHz. Figure 4.2 shows the UHF dish at Tromsø. Further discussion of the UHF mainland system may be found in Folkestad et al. [1983].

The VHF system at Tromsø (Figure 4.3) has been described by Hagfors et al. [1982] and Folkestad et al. [1983]. The system consists of a transmitter and receiver, both situated at Tromsø, which operate at 224 MHz and has reliable observations since 1985. The radar consists of a parabolic cylinder antenna in two sections and is capable of operating two beams at once, known as 'split beam' mode.

The ESR is the latest addition to the EISCAT facility inaugurated in August 1996. This is a monostatic UHF radar based at Longyearbyen, Svalbard (78.2°N, 16.0°E
Figure 4.1. A map of northern Europe showing the locations of the EISCAT and ESR antennas.
Figure 4.2 (right) shows the UHF antenna at Tromsø.

Figure 4.3 (below) shows the EISCAT site at Tromsø. The cylindrical antennas to the left of the picture are the VHF system. The dish to the right is the UHF antenna.
geographic) which operates at 500 MHz [Wannberg et al., 1997]. There are two dishes located at Longyearbyen, a fixed, field aligned 42 m and a steerable 32 m diameter dual-reflector Cassegrain dish.

The radars employ various pulse schemes and operating modes. In general two types of transmission codes are used – multipulse (similar to the SuperDARN radars) and alternating code. Details of the multipulse method are described in Farley [1969, 1972] and how EISCAT uses multipulse transmissions in la Hoz [1982]. Alternating code also consists of a series of pulses, but each pulse contains a continuous sequence of 8 or 16 phase coded sub-pulses. For details of the alternating codes the reader is referred to Lehtinen and Häggström [1987]. The annual observing time at the EISCAT facility (~1000 hours) is split into two types, 'special' and 'common'. The common programmes are routinely operated and consist of a set of different experiments with the prefix CP-, with the aim of providing a reasonably consistent data set over time. The special programmes are run and designed by scientists from the various countries that contribute to the running of EISCAT. The common programs at ESR are designed along the same lines as the mainland programmes with complementary experiments where appropriate.

The running mode of the EISCAT mainland radar for the data that will be presented in chapters 6 and 7 is essentially CP-4 (although some of it is special programme data) which involves the VHF in low-elevation (~30°), split beam mode, with beam one pointed at ~345° and beam two at ~359° azimuth. Where ESR data was also available the steerable antenna was used and pointed towards the mainland radars at a similar elevation such that a third beam was co-located with the CUTLASS field-of-view.

4.1.1 Incoherent scatter radars

The term 'incoherent' is a historical misnomer from when the technique was first invented. In 1928, Fabry proposed that it might be possible to investigate ionospheric properties using Thomson (or incoherent) scatter. The term Thomson scattering refers to the scattering of electromagnetic radiation from free electrons, with the amount of scatter given by the scattering cross section [Thomson, 1906]. Fabry's theory predicted that the power spectrum would be Gaussian in form with a width related to the thermal motion of
the electrons, and centred on the transmitted frequency. The important factor for obtaining true incoherent scatter is that the electrons are free and this can be quantified using the Debye length. This scale size is a result of the balance between the electrostatic potential energy and the random thermal energy within the plasma. It is a measure of the radial extent of the 'shielding' around an electron. If a radio wave has a wavelength smaller than the Debye length then the electrons can be considered to be free and incoherent scatter will occur. However, on scales longer than this the random thermal motion of the electrons results in ion-acoustic and electron-acoustic waves, which are longitudinal fluctuations in the plasma. These waves can cause quasi-coherent scatter when the radio wavelength is much greater than the Debye length. The mechanism is very similar to that of the 'coherent' radars, the only difference is that the periodic structure generating the scatter received by the incoherent radars are the troughs and crests of the ion- and electron-acoustic waves. The spectrum which arises from what is termed incoherent (which should really be quasi-coherent) radars has four peaks instead of the originally predicted Gaussian spectrum. These peaks result from the ion- and electron-acoustic waves propagating both towards and away from the radar. A typical quasi-incoherent spectrum is shown in Figure 4.4.

Several ionospheric parameters can be determined from the quasi-incoherent spectrum: electron density, electron temperature, ion temperature, ion composition, ion velocity, electron velocity, ion-neutral collision frequency, photoelectron flux and electric current density. Further parameters can be derived from these measurements: electric field, Hall conductivity, Pedersen conductivity, exospheric heat flux, neutral density, neutral temperature and neutral velocity.

The electron density may be determined from the total power received, $P_s$, provided the transmitted wavelength is much larger than the Debye length:

$$P_s(h) = \frac{K \sigma_e N_e(h)}{[1 + (T_e/T_i)]h^2}$$

(4.1)

where $h$ is the altitude, $K$ is a system constant proportional to the transmitted power and effective collecting area of the receiver, $\sigma_e$ is the scattering cross section of an electron, $N_e$ is the electron number density, $T_e$ and $T_i$ are the electron and ion temperatures respectively. The ratio of $T_e$ to $T_i$ can be determined from the shape of the spectrum.
Interactions between charged particles and the ion-acoustic waves may lead to attenuation of the wave. If the particles are moving in the direction of an ion-acoustic wave (such as the acoustic waves), but at a speed lower than the phase velocity, then the particles can be accelerated by gaining energy from the wave. This process, called Landau damping, attenuates the wave and will lead to broadening of the ion-acoustic spectra. The resulting plasma line will be transformed to a broadened line. The speed of these waves is far greater than the speed of the majority of the thermal electrons and ions with the ion-acoustic spectrum, and the ions are broaden so that they merge with the peaks of the broadened plasma line, but with many less movement in the lower frequency region.

The relative temperature of plasma is important in the ion-$\alpha$ scattering region. If for example the relative temperature is provided with respect to the laser, the relative temperature increases over the level of the observed ion line. This is shown by the two lines in the figure.

Figure 4.4. Cartoon illustration of a quasi-incoherent scatter spectrum.
Interactions between charged particles and the ion- and electron-acoustic waves may lead to attenuation of the wave. If the particles are moving in the direction of an electrostatic wave (such as the acoustic waves), but at a speed lower than the phase velocity, then the particles can be accelerated by gaining energy from the wave. This process, called Landau damping, attenuates the wave and will lead to broadening of the ion-acoustic spectral peaks. The electron-acoustic peaks in the quasi-incoherent spectrum (the so called 'plasma lines') are not broadened by this process since the phase speed of these waves is far greater than the speed of the majority of thermal electrons [Beynon and Williams, 1978]. Figure 4.5 shows typical distributions of thermal electrons and ions with the ion- and electron-acoustic velocities overlaid. The ion lines are broadened so that they merge since the speeds of the ions surround the ion-acoustic phase velocity, but with more ions moving slightly slower than the phase velocity.

The relative temperature of the electrons to the ions is important factor in the amount of Landau damping the ion-acoustic wave undergoes. If for example the electron temperature is elevated with respect to the ion temperature then the ion-acoustic velocity increases such that fewer and fewer ions are moving faster than the phase velocity, approaching a similar condition to the electrons. Thus if $T_e/T_i$ increases the ion lines become narrower as shown in Figure 4.6 [Evans, 1969]. The ratio of the two temperatures can be calculated from the ratio of the peak spectral power in the ion line to the central minimum power.

In order to obtain absolute values of the ion and electron temperature it is necessary to assume a model for the ion composition. If $T_e/T_i$ is already known, then from the Doppler shift arising from the ion-acoustic wave mode:

$$F_i(\lambda) = \pm \frac{2}{\lambda} \left[ \left( \frac{k_BT_i}{m_i} \right) \left( 1 + \frac{T_e}{T_i} \right) \right]^{1/2}$$

the ratio of the ion temperature to ion mass can be found. Thus if a value for the ion mass is assumed, both $T_e$ and $T_i$ can be calculated from the shift of the ion line. This procedure works well in general although problems can be encountered in regions where the ion composition is not sufficiently well modelled, or when the ion composition may be appreciably modified, such as during disturbed conditions. The dependence on ion mass is a result of the superposition of spectra from different ion species. Moorcroft [1964]
Figure 4.5. Typical normalised velocity distribution of thermal electrons with the phase velocities of the electron- and ion-acoustic wave modes superimposed (after Beynon and Williams, 1978)
Figure 4.6. The changing shape of the spectrum as the electron to ion temperature ratio changes (adapted from Evans [1969]).

Figure 4.7. Ion spectrum changes as the mixture of $O^+$ changes (after Moorcroft [1964]).
and Lathuillière et al. [1983] demonstrated the changes to the ion lines for various mixtures of species. Figure 4.7 shows an example of how the composition can affect the ion spectrum.

Bulk motion of the ions results in a Doppler shift of the ion spectrum and this is used to estimate the ion velocity. The velocity measured in this way is the component of the mirror velocity in the line-of-sight of the radar. The mirror velocity is depicted in Figure 4.8 for a bistatic system (transmitter and receiver not co-located). In a monostatic system (one receiver and one transmitter co-located) the mirror velocity is along the direction of the radar beam. The Doppler shift $\Delta F_d$ is given by

$$\Delta F_d = \frac{2v_m}{\lambda} \cos \left( \frac{\gamma}{2} \right)$$

(4.3)

where $v_m$ is the ion velocity, $\gamma$ is the angle between the incident and scattered radar beam, and $\lambda$ is the radar wavelength.

In the lower E-region (<120 km) the ion-neutral collision frequency can be estimated. Below this altitude the ion-neutral collision frequency is greater than the ion-acoustic frequency and therefore ion-acoustic waves cannot propagate. This reduces the ion spectra to only one hump as in Figure 4.9. The spectral shape in this case is dependent on $\psi_i$:

$$\psi_i = \frac{\lambda v_{in}}{4\pi} \left( \frac{m_i}{2k_B T_i} \right)^{1/2}$$

(4.4)

where $v_{in}$ is the ion-neutral collision frequency. If the ratio of the electron to ion temperatures is assumed to be one, then $v_{in}$ can be estimated from the spectrum (provided the electric fields are less than 25 mV m$^{-1}$ [e.g. Wickwar et al., 1981; Huuskonen et al., 1986]).

For further detail on how quasi-incoherent scatter occurs and the parameters obtainable from the scattered spectra, the reader is referred to Beynon and Williams [1978] and Evans [1969].
Figure 4.8. Mirror geometry for a bistatic radar system (after Rishbeth and Williams [1985]).

Figure 4.9. The effect of collisions on the ionic component of the spectrum (after Evans [1969]).
4.1.2 Sources of errors in the measurements

As one would expect there is some element of random error in the incoherent scatter measurements. This has been quantified by du Castel and Vasseur [1972] in terms of the received power ($P_s$), electron density ($N_e$), electron and ion temperatures:

$$\frac{\Delta P_s}{P_s} = \frac{\Delta N_e}{N_e} = \frac{\Delta T_e}{2T_e} = \frac{\Delta T_i}{2T_i}$$

(4.5)

with a less simple formula for the error in the line-of-sight velocity.

The data undergoes a fitting process by which the parameters are automatically estimated which involves minimising the variance between the measured autocorrelation returned by the pulse scheme and a theoretical one. The sum of the residuals between the two is then used to give an estimate of the error in each parameter.

A difficulty would arise if the procedure attempted to fit for the ion temperature and the ion velocity simultaneously. This is avoided by assuming a Maxwellian distribution for the ion and electron thermal velocity distributions in the direction of the measurement. However there are conditions under which this assumption may cause inaccuracies. If the ion and neutral velocities are large relative to each other the ion line-of-sight thermal velocity distribution can depart appreciably from the Maxwellian form, particularly if the aspect angle is large [e.g. Hubert and Kinzelin, 1992]. It has also been proposed that field-aligned currents may also produce non-Maxwellian distributions in the F-region. This effect is dependent on the type of collisions present, but tends to be less significant for molecular ions than for atomic $O^+$. The observed effect of this in the F-region is to produce an ion spectrum where the central minimum is increased in power, even to the point of becoming a maximum. This can lead to overestimation of the ion temperature and underestimation of the electron temperature [e.g. Lockwood et al., 1993].

The assumption of a static model for the ion composition can have a constraining effect on the precision of the results obtained [e.g. McCrea et al., 1995]. During undisturbed conditions the adopted model is reasonably realistic, but under conditions such as ion frictional heating when the ion composition can be modified by the increase in the production of molecular ions, the model will be less accurate. An underestimate in the
fraction of molecular ions present will result in an underestimation of the ion and electron temperatures.

Another problem can occur with the estimated ion temperatures where the ion to neutral relative velocity is large. This is a result of the presence of different ions in the plasma. Each ion species can have its own line-of-sight temperature which cannot be simply accounted for by using a weighted mean of the temperature of each species to give an overall temperature for the ions. Since the properties of each ion species include how it collides with other ions, the temperature of each species will react differently to collisional heating such as that which occurs with a large ion-neutral relative velocity. McCrea et al. [1995] discuss in detail the limitations of the standard EISCAT analysis under conditions such as these.

4.2 Ground Magnetometers

Magnetometers are sensitive to the currents flowing in the ionosphere and magnetosphere and are useful for observing many different waves and substorm currents etc. Networks of magnetometers, such as the IMAGE chain in Scandinavia [Viljanen and Hakkinen, 1997] Figure 4.10, can isolate the location of field line resonances (FLRs) and enhanced electrojets such as they have been used for in Chapters 6 and 7. Magnetometers have quite a low spatial resolution since they do not look in any particular direction and sense all currents within their sensitivity range. The temporal resolution is ~1 s for fluxgate magnetometers, or up to 0.1 s for pulsation magnetometers. The currents that generate the magnetic perturbations cannot be found directly from the magnetometer measurements, but 'equivalent' currents can be determined, that is currents that could produce the signatures seen at the ground.

FLRs are of particular interest for the case studies presented in the following chapters. Sometimes a closed field line given a sufficient impulse will start to ring at a frequency which is dependent upon its length and the electron density along it. The resonance is a consequence of the coupling of fast and Alfvén waves [Southwood, 1974; Chen and Hasegawa, 1974]. Two coincident signatures of such a phenomenon are observed in the amplitude and phase of oscillations observed by the magnetometers in the
Figure 4.10. The IMAGE network of magnetometers in geographic coordinates (courtesy of Lasse Håkkinen).

Figure 4.11. A schematic of the amplitude and phase response of a field line resonance oscillation.
area of the principle field line. This is where having a meridional chain of magnetometers is useful since this allows you to identify (to a degree or two depending on the latitudinal spread of the magnetometers) the L-shell at which the resonance peaks. The phase of a FLR changes by 180° across the latitude of the peak amplitude as in Figure 4.11.

4.3 WIND

The WIND spacecraft is a solar wind and IMF monitoring spacecraft. Launched in November 1994 (Figure 4.12), WIND was destined for a sunward, multiple double-lunar swing-by orbit with a maximum apogee of 250 R_E for its first two years, followed by a halo orbit at the Earth-Sun L1 point (where the gravitational and centrifugal pull of the Sun and the Earth cancel each other out). Since October 1998, WIND has been performing 'petal' orbits reaching as close as 10 R_E to the Earth and out to 80 R_E. From September 2001 to December 2003 the orbit will be a distant prograde type followed by a return to Earth orbit until September 2006.

Two of the seven instruments on board WIND (Figure 4.13) are of particular interest for the data which follows, namely the Magnetic Fields Investigation (MFI) [Lepping et al., 1995] and the Solar Wind Experiment (SWE) [Ogilvie et al., 1995]. The MFI instruments are supported on the booms of the spacecraft and consist of dual, triaxial fluxgate magnetometers. The dual nature of the system provides a redundancy safeguard but also allows the accurate removal of the dipolar portion of the spacecraft magnetic field. The SWE instruments consist of 2 Faraday cup ion detectors which provide measurements of the solar wind protons and alpha particles at energy/charge up to 8 keV, and also an array of detectors for characterizing solar wind electrons.

4.4 Meridian Scanning Photometers

A meridian scanning photometer (MSP) run by the Geophysical Institute at the University of Alaska at Fairbanks is situated near Longyearbyen on Svalbard. The MSP has filters that isolate the wavelengths given in table 4.1. The MSP consists of five independent phototube and counting systems. The phototubes are cooled to approximately
Figure 4.12 (left) shows the launch of the WIND spacecraft (picture courtesy of NASA GSFC).

Figure 4.13 (right) shows the layout of the instruments aboard the WIND spacecraft (picture courtesy of NASA GSFC).

SMS, not shown, is on the far side of the spacecraft. Second sensor for KONUS is obscured on the bottom of the spacecraft.
<table>
<thead>
<tr>
<th>Wavelength, nm</th>
<th>Colour</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>557.7</td>
<td>green</td>
<td>neutral atomic oxygen</td>
</tr>
<tr>
<td>630.0</td>
<td>red</td>
<td>neutral atomic oxygen</td>
</tr>
<tr>
<td>427.8</td>
<td>blue</td>
<td>ionised diatomic nitrogen</td>
</tr>
<tr>
<td>486.1</td>
<td>blue</td>
<td>neutral hydrogen (Balmer-beta)</td>
</tr>
<tr>
<td>732.0</td>
<td>red</td>
<td>ionised atomic oxygen</td>
</tr>
<tr>
<td>656.3</td>
<td></td>
<td>neutral hydrogen (Balmer-alpha)</td>
</tr>
<tr>
<td>520.0</td>
<td></td>
<td>neutral atomic nitrogen</td>
</tr>
<tr>
<td>844.6</td>
<td></td>
<td>neutral atomic oxygen</td>
</tr>
<tr>
<td>846.5</td>
<td></td>
<td>OH</td>
</tr>
</tbody>
</table>

Table 4.1 available filters at the Longyearbyen MSP (source Geophysical Institute, University of Alaska, Fairbanks)
-30°C to reduce thermal noise. The full width at half maximum of the filter bandpass transmission for the various filters are of the order of 0.4 nm to 0.7 nm.

A mirror that rotates continuously about an axis perpendicular to the meridian plane collects a field of view approximately 1° wide along the magnetic meridian (~45° west of geographic north). Each rotation of the mirror takes 4 s with 2 s needed to sample the sky from the north to the south horizon. The final time resolution of the data is 16 s after all the necessary data has been taken.

The background optical emission is eliminated by tilting the filter. The angle of the filter is alternated between two positions: a 'peak' position that gives maximum transmission for the wavelength of interest and a 'background' position that samples the continuum near the peak. One complete observation is obtained by subtracting the average signals of two 'background' scans from the average of two 'peak' scans.
CHAPTER 5

An inter-hemispheric, statistical study of nightside spectral widths

5.1 Introduction

This chapter investigates the statistical behaviour of the spectral width parameter measured by magnetically conjugate coherent HF radars on the nightside, complementing work by Hosokawa et al. [2002] regarding the dayside. The differences between radars of the same hemisphere, but with different pointing directions are also explored. The approximately meridional arrangement of the summary range gates employed in the statistics database (described below) is used to determine the statistical location of the spectral width gradient, i.e. the transition from high to low spectral width, over time. This in turn may reveal information on the nature and origin of the spectral width gradient which is one of the main aims of this thesis.

Data from the SuperDARN radars Iceland East, Finland and Syowa East have been employed for this purpose. Three years of data from both radars have been analysed both for the spectral width and line-of-sight velocity. The pointing direction of the two conjugate radars, Iceland East and Syowa East, is such that the flow reversal boundary, which can be used as a proxy for the open/closed field line boundary, may be estimated from the line-of-sight velocity data alone.

5.2 Data processing

The Iceland East and Syowa East radars form a conjugate pair as shown in Figure 5.1 (the Syowa East field-of-view has been mapped into the northern hemisphere using the IGRF95 model [Barton, 1997]). Altitude Adjusted Corrected Geomagnetic coordinates, AACGM, are used throughout this chapter and are adapted from Baker and Wing. [1989].
Figure 5.1. The locations of the statistics summary points for the two CUTLASS radars (C0 etc) and from Syowa East (S0 etc, mapped into the northern hemisphere). The locations are shown here in magnetic latitude and magnetic local time.
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Each SuperDARN radar produces a large amount of data making study of long-term variations in the observations problematic in terms of data storage requirements and processing time. To overcome this a representative subset of the observations from the CUTLASS Finland and Iceland East radars are routinely stored in a "statistics database" which is kept on hard disk allowing easy analysis of the ~6 years of radar measurements made to date (August 2002) in the common mode operations of the radars. The database resulting from this extra processing contains all the normal radar parameters but for only 16 summary radar cells. Such a database was originally introduced by Milan et al. [1997a]. In that study the 16 summary radar cells for Iceland East were taken from beam 7 of that radar whereas the present study makes use of the summary points originally identified in the Finland radar field of view. Thus the summary points for Iceland East in this study are located approximately along a geomagnetic meridian and the gates used are chosen for the large range of magnetic latitudes they encompass, 65°N to 81°N. The location of the summary points are given as C0 to C15 in Figure 5.1. A similar set of summary range gates (S0 to S15 in Figure 5.1), spanning the latitude range 70°S to 86°S, has been determined for the Syowa East radar data using the IGRF95 model [Barton, 1997] to find magnetically conjugate positions. In order to produce a more accurate comparison between the radar data sets only mutual common time data (where the radars are run in the same mode) have been used for the interval 1st January 1998 to 31st December 2000. For the majority of the data the frequencies used in the common mode were consistent with Iceland East running in the frequency band from 10.2 MHz to 10.7 MHz twenty-four hours a day from January 1998 until October 2000. During November and December 2000 the daytime frequency (0800 to 1800 UT) for Iceland East was changed to the band from 12.1 MHz to 12.2 MHz. Comparisons of the results using just 1998 and 1999 with those presented here, show that this change in the frequency has no noticeable effect on the results. The Syowa East radar was run in the band 10.2 MHz to 10.5 MHz twenty-four hours a day for all the days except the period from 6th to 10th February 1998 where the daytime frequency (0600 to 1800 UT) was from the 11.1 MHz band. This also has very little appreciable effect on the results and conclusions reached.

Figure 5.2 presents an example of how the spectral width varies with the power. The width and power have been estimated using the exponential decorrelation fitting described in Chapter 2, Section 2.3.3. Typically ~80% of spectra are Lorentzian in form.
Figure 5.2. An example of power against spectral width values. This example includes all data from 2200 to 0200 MLT from all the Iceland East summary points for January 1999.
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[Villain et al., 1987; Hanuise et al., 1993]. This example includes all the available data for all the Iceland East summary points for the interval 2200 to 0200 MLT during January 1999. There are two separate domains, low width ($<500 \text{ m s}^{-1}$) with all powers, and higher width ($>500 \text{ m s}^{-1}$) and low power ($>3 \text{ dB}$). The region of the plot $>500 \text{ m s}^{-1}$ and $<3 \text{ dB}$ has been marked off and shaded in grey. The first of the two domains is where most of the usable data occur. The second domain of high width and low power is indicative of power spectra where no clear peak is apparent and the scatter is attributed to noise, i.e. uncorrelated scattering. Data with a received power below 3 dB or spectral width greater than 500 m s$^{-1}$ are therefore not used in the analysis. Data identified as ground scatter by the FITACF software have also been removed.

The analysis presented here takes the form of occurrence distributions of spectral width. The data have been sorted into 15 minute intervals of MLT and bins which are 20 m s$^{-1}$ wide for both spectral width and line-of-sight velocity. Since the fields of view of the conjugate radars do not overlap completely there are some summary range gates that do not have a close conjugate partner. For Iceland East points C0 to C3 fall into this category, while for Syowa East points S12 to S15 have no conjugate partner. The summary points are located along beam 9 of the CUTLASS Finland radar, which is almost meridional to the magnetic pole. The Finland and Iceland East summary points overlap almost precisely although the different radar pointing directions mean that the length and width of the range cells are almost reversed between the two radars. The aim of having the points aligned with a large variation in magnetic latitude and a small variation in longitude ($\sim15^\circ$ for the points with conjugate partners) is that a long term analysis of the latitudinal location of the spectral width gradient can be achieved.

5.3 Statistical observations

5.3.1 Data occurrence

Figure 5.3a shows the occurrence of ionospheric backscatter echoes for Iceland East over the three years of data used, split into seasons (winter consisting of November, December and January, spring taken as February, March and April etc, for the northern hemisphere). Each colour coded square represents a 15 minute interval of MLT for each
Figure 5.3. Data occurrence for (a) Iceland East, (b) Syowa East and (c) Finland over the time interval of the study. The colour scales represent the number of occurrences of data within a 15 min MLT window for each summary point as a percentage of the total possible observations at that local time. A statistical auroral oval for a Kp of 2 has been overlaid on each plot.
statistics point. The colour scale indicates the occurrence of scatter as a percentage of possible observations in that region and season over the three years of data presented. The Iceland East range gates coincident with the summary points vary between 39 and 48, equivalent to ranges 1935 km to 2340 km. Thus, one expects mainly F-region scatter, with mostly 1 ½ hop propagation to have originated from these locations. However, there may be some E-region contamination at these ranges resulting from 1 ½ hop propagation. An analysis of Iceland East backscatter similar to that conducted by Milan et al. [1997a], shows a small population of Type 1 E-region scatter, identified by a low spectral width and a velocity which is close to the local ion acoustic speed, observed in all of the Iceland East summary points. An investigation of this Type 1 scatter for the data used indicates that the contamination of the F-region scatter is small, at most 12% of the observations (based on the percentage of observations in the range ±(320 to 420 m s⁻¹)). A similar analysis of the Syowa East data also indicates only small amounts of Type 1 E-region scatter on the nightside.

The largest number of observations tends to occur in winter, and the least in summer, agreeing with work by Milan et al. [1997a]. These authors found that in summer most of the observations by the Iceland East radar involve ½ hop propagation and as such are in the range gates close to the radar. As the summary points employed in the current study are all in the 1 ½ hop range, the amount of data observed in the summer is reduced. The peak occurrence in winter is over 27% of possible observations in the 15 minute interval and occurs between 75°N and 80°N from 1800 MLT to 2000 MLT followed by a brief lull between 2000 and 2200 MLT. The number of observations then rises again, but at a lower latitude, with the maximum between 70°N and 75°N until the occurrence begins to fall off again from 04 MLT. The situation in spring is similar, although the maximum is smaller (approximately 24% of possible observations) and the change in latitude is more gradual. Autumn is very similar to spring in the distribution of data observations. The maximum number of observations in the summer months is only 9% to 12%, and this occurs mainly below 70°N and between 2200 and 0400 MLT.

The same analysis (except with southern hemisphere seasons) for the data from the Syowa East radar is presented in Figure 5.3b. The data distribution in the southern hemisphere winter includes a peak at dawn similar to that of the northern hemisphere
winter occurrence at dusk shown in Figure 5.3a. The main difference between the Iceland East and Syowa East radar scatter occurrence is due to the reflective properties of the ice sheet which beams 0 to 8 of Syowa East are incident on. The ice is transparent to the radio waves for all but the last ~200 m of the 3 km depth. In this thin layer the attenuation of the radio waves is ~75 dB and consequently the radio waves do not scatter off the bedrock at a level the radar could detect. This restricts the beams in which the 1 ½ hop mode can propagate to beam 9 to 15, hence the small quantities of data poleward in the plots of Figure 5.3b compared to the Iceland East results (which achieve 1 ½ hop propagation through sea or ground scatter). The amount of winter data is low (<4% of possible observations) from 1800 to 2000 MLT in Figure 5.3b, when a region of maximum occurrence begins to become clear at around 75°S. This continues until 0300 MLT when the occurrence increases to >10% at the peak. The situation in spring is very different, the peak occurrence from 1800 through to 0600 MLT is over 10%. The width of the maximum occurrence is approximately 7°, centred on ~76°S from 1800 to 2100 MLT. After this there is a smooth, but rapid motion of the region of maximum occurrence equatorward with MLT, so that the region is centred nearer to 73°S, and this remains until 0600 MLT. The pattern in the summer months is relatively uniform, very few data points poleward of 78°S. Equatorward of this there is a band of larger occurrence varying between 6% to 12%. The autumn picture is similar to that in the spring, although the overall level of occurrence is lower.

The data occurrence for the Finland summary points is presented in Figure 5.3c. For winter, spring and autumn the distribution of data occurrence is similar with the most data found between ~68°N to 75°N. The range of the highest data occurrence in MLT (>27%) is larger in winter where it spreads from 2000 to 0600 MLT. In summer the amount of data is once again reduced although a small region of large occurrence is still apparent between 2400 and 02 MLT. The modes of propagation for the Finland summary points will likely change from ½ to 1 ½ hop somewhere between C0 and C15 since the range varies from ~760 to 2520 km. Where exactly the change will occur will vary on the ionospheric conditions at the time.

Figure 5.3 shows that the distribution of available data can be quite variable, although as will become apparent in the following sections, the spectral width distribution
results are not biased by this fact. Only in the southern hemisphere summer, at the 4 summary points closest to the geomagnetic pole does an absence of a reasonable amount of data cause significant problems in interpreting the spectral width results.

5.3.2 Spectral width distributions

Typical examples of histograms of spectral width occurrence produced from the statistics databases are presented in Figure 5.4. The spectral widths are separated into two hour intervals of MLT and the data are put into bins 20 m s\(^{-1}\) wide. The distribution for each summary point is normalised using the total number of points observed at that summary point. Figure 5.4a shows the distributions of spectral width for the Iceland East radar from summary points C4 (69.7°N) and C12 (77.8°N), for the northern hemisphere winter 0400 MLT to 0600 MLT. The red and blue lines represent the smoothed distribution for the shaded and unshaded histograms respectively. The shaded histogram, depicting the spectral width distribution for point C4, is narrower than the unshaded histogram showing the distribution for point C12. The standard deviations are 95 m s\(^{-1}\) and 106 m s\(^{-1}\), respectively, reflecting the narrower nature of the distribution at point C4. The means of the two distributions are also very different, 145 m s\(^{-1}\) and 182 m s\(^{-1}\) for points C4 and C12 respectively. The median values in general are similar to the means e.g. they are 128 m s\(^{-1}\) and 161 m s\(^{-1}\) for points C4 and C12. The mean and median values are similar in the analysis because the spectral width data is restricted to <500 m s\(^{-1}\). Hence there is no long tail to the distributions which would cause the mean to greatly exceed the median. The results presented throughout this chapter were investigated using the mean, mode, median, standard deviation, and Pearson's skewness coefficients. The mean and median proved the most meaningful and due to their similarity the mean was picked as a representative quantity. The skewness coefficients showed up no more information than the means, particularly for the zonally pointing radars (examples of this will be discussed in section 5.3.4).

The distributions have a sufficient number of points to be considered in a statistical manner. Both the distributions here resemble that found to be co-located with the low-altitude, low-latitude boundary layer (LLBL) [Baker et al., 1995, Figure 5.9]. The mode of all these distributions is below 150 m s\(^{-1}\) whereas the cusp distribution from
Figure 5.4. Spectral width distributions for (a) Iceland East, points 4 and 12, (b) Syowa East, points 0 and 9, and (c) Finland, Points 4 and 12.
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Baker et al., [1995] has a mode of ~200 m s\(^{-1}\). However the tail of more equatorward distribution from point C4 is more exponential in shape than that from point C12 (although the distribution is not strictly exponential). The broader distribution also resembles the spectral width distribution found in the Finland radar data (mode 230 m s\(^{-1}\)) above the poleward edge of the 630.0nm optical emission by Lester et al., [2001]. However, the distributions in this case study were more distinct than those of Figure 5.4a, which may be a result of the averaging with the statistical database, or a result of the more zonal pointing direction of the Iceland East radar compared to the Finland radar.

The distributions in Figure 5.4b are from statistics points S0 and S9 of the Syowa East radar, for southern hemisphere winter, 0400 to 0600 MLT. These points are approximately conjugate to the summary points C4 and C12 from the Iceland East summary range gates (Figure 5.1). The unshaded distribution from point S9 is more Gaussian shaped than that of C12 in Figure 5.4a, with a standard deviation of 117 m s\(^{-1}\) and a mean of 221 m s\(^{-1}\). This distribution resembles a cusp-type distribution following Baker et al. [1995]. The distribution at point S0 is very similar to the conjugate distribution observed at point C4, though the mean and standard deviation for point S0 are much larger, 160 m s\(^{-1}\) and 109 m s\(^{-1}\) respectively, than the values at the conjugate point. There is also a noticeable peak in the range 0 to 20 m s\(^{-1}\) in both of the Syowa East distributions. This is a common feature in the Syowa East data and is most likely caused by the inclusion of ground scatter that has been misidentified as ionospheric scatter. The broader distribution, with a larger mean at point S0 than that seen from the conjugate summary point C4 is also a regular feature. In general it is found that the spectral width distributions from Syowa East are broader, with larger standard deviations and higher means than for Iceland East. This is perhaps a common feature of spectral widths in the northern and southern hemispheres as Milan and Lester [2001] suggested a similar asymmetry in the spectral width observations of the SuperDARN Goose Bay and Halley radars when observing the cusp region.

The spectral width distributions for summary points C4 and C12 of Finland are presented in Figure 5.4c. The format of the plots is as in the previous two panels. The difference in the spectral width distributions with latitude is more marked in the Finland results and resembles those presented in Lester et al. [2001]. This implies that the Iceland East and Syowa East spectral width distributions are more generally different to those
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from Finland, not simply a result of the averaging process. The lower latitude distribution has a mean much less than either of the equivalent points in Figures 5.4a and b. The standard deviations of the two distributions in Figure 5.4c are not dissimilar, 89 and 113 m s⁻¹ for C4 and C12 respectively.

It is important to realise that the data from the three radars are not necessarily coincident in time since the radars will not necessarily be observing scatter in the same place at the same time. This factor aside, the similarities between the two zonally pointing radars and the difference between these and the more meridional Finland data implies that there is a statistical tendency for the Finland lower latitude spectral width distributions to have a smaller mean.

5.3.3 Variation with latitude and magnetic local time

The variation of the spectral width at the Iceland East summary points as a function of latitude and magnetic local time is illustrated in Figure 5.5. Here the distributions of spectral width for the northern hemisphere winter months between 1800 to 0600 MLT on the nightside are presented in bins of two hour duration. The distributions are shown in the form of contour plots with the colour scale representing the occurrence frequency of the spectral width values. The distribution for each summary point is self-normalised to the total for that point. The dashed black line indicates the lower limit of the overlap with the Syowa East field of view. The thin, solid black lines indicate 70°N and 80°N as labelled. The white on black line shows the mean value for the spectral width distribution from each summary point with values on the lower axis. The minimum number of points contributing to the spectral width distribution of a given summary point is ~500 and the maximum is ~4000. The 500 m s⁻¹ limit set on the spectral width does not affect the contours since there are so few points at or above this level. A comparison of Figure 5.3a showing the occurrence of data points and Figure 5.5 shows that although the broadest spectral width distributions at first glance appear to follow the location of the most observations, the spectral width distributions in the 0400 to 0600 MLT bin of Figure 5.5 are the most broad, but the maximum number of observations is in the 1800 to 2000 MLT region. Thus the form of the spectral width distributions is not biased by the data occurrence. Also the smooth variation across the
Figure 5.5. Contour plots showing the northern hemisphere winter variation of spectral width distributions with MLT from Iceland East. The points below the black dashed line do not overlap with the conjugately mapped Syowa East summary points. The 70°N and 80°N positions are indicated by the thin black lines. The white on black lines show the mean spectral width value for each point on the lower axis scale. The colour scale indicates the occurrence at each width normalised to the total occurrence for each summary point.
1800-2400 sector in figure 5.5 when compared to the data occurrence in Figure 5.3 indicates a lack of bias in the results.

The shape described by the means of the distributions for each point varies as the MLT changes (the white on black line in Figure 5.5). In the pre-midnight sector the mean value of the spectral width varies slowly between ~90 and 150 m s\(^{-1}\) across the 16 summary points. The distributions here are also in general quite narrow even where the occurrence is large. The observations from 0000 MLT onwards are somewhat different. The distributions become broader and the values of the means over the summary points have larger ranges, from 90 to 220 m s\(^{-1}\) with the spread greatest in the final nightside bin (0400 to 0600 MLT). In addition the location of the largest value of the mean progresses northwards as the MLT increases in the post-midnight sector. Two distinct types of distribution emerge in the post-midnight sector, one narrow with a low mean, typically seen at low latitudes (e.g. summary point C0 in the 0200 to 0400 MLT bin), and the other broad with a higher mean typically seen at higher latitudes (e.g. summary point C9 in the 0200 to 0400 MLT bin). These two types of distribution are shown in histogram form in Figure 5.4a. The changeover point between these two forms of distribution in Figure 5.5 represents the average position of the spectral width gradient for the northern hemisphere winter. The distributions and mean values suggest that the regions of high spectral width in the pre-midnight sector are comparatively less common events for the Iceland East radar.

The general trend appears to be that the separatrix between narrow, low valued mean distributions and broader distributions with higher means (>~150 m s\(^{-1}\)) appears after 22 MLT at which time it appears to be equatorward of point C5 becoming clearer towards dawn. A similar picture is true for the other three seasons, although in summer the distributions are much narrower overall, an observation that will be explored further in the following section.

The same analysis has been applied to the Finland summary points, the results of which are presented in Figure 5.6. The 1800 to 2000 MLT data is very similar to that from Iceland East poleward of point C2. Summary points C0 and C1 show unusually large widths for these latitudes (in comparison with the Iceland East, and also the Finland data from point C2) with a mean of nearly 200 m s\(^{-1}\), sharply reducing at point C2. This
Figure 5.6. Contour plots showing the northern hemisphere winter variation of spectral width distributions with MLT from Finland. The points below the black dashed line do not overlap with the conjugately mapped Syowa East summary points. The 70°N and 80°N positions are indicated by the thin black lines. The white on black lines show the mean spectral width value for each point on the lower axis scale. The colour scale indicates the occurrence at each width normalised to the total occurrence for each summary point.
feature is only clear in this time interval although it seems to appear at a much reduced value in the 2000 to 2200 MLT as well. The sharpness of the change between summary point C1 and C2 implies that the low latitude, high widths could originate from the E-region rather than the F-region, particularly given the small range from the radar at these two points.

From 2000 to 0600 UT the Finland spectral width distributions diverge from the behaviour demonstrated in the Iceland East data. There is a distinct region of low widths (mean $< 100$ m s$^{-1}$) from C0 through to C5 and poleward of this the mean spectral width rapidly increases reaching a peak value around 200 m s$^{-1}$ the location of which varies with MLT. Poleward of the peak the mean spectral width tends to decrease again with latitude, less sharply than the increase equatorward of the peak. This kind of pattern is also observed in the Iceland East spectral width distributions but it is not so pronounced.

Figure 5.7 shows a similar analysis for the Syowa East summary range gates for southern hemisphere winter (May, June, July). The dashed line shows the upper limit of the overlap with the Iceland East summary points. The thin, solid black lines indicate 70°S and 80°S as labelled, and the white on black line shows the mean spectral width. The field-of-view from point S12 (82.1°S) and poleward shows significantly less observed ionospheric scatter compared with points S11 and below (see Figure 5.3a). However, summary points S12 to S15 are poleward of the conjugate points of Iceland East and therefore this lack of data is not overly detrimental to this study. The distributions of spectral width observed by Syowa East are much broader, with higher means, than those presented in Figure 5.5 from Iceland East. The peaks of the distributions are also less well defined than either those of Iceland East or Finland. The latitudinal variation in the mean for each MLT bin is for the most part small, but the means do vary noticeably with MLT. In the 1800 to 2000 MLT bin the mean spectral width decreases by approximately 40 m s$^{-1}$ between S0 and S11 as the latitudes become closer to the pole. The situation is the same from 2000 to 2400 MLT. After midnight MLT the mean width shows no overall trend from S0 to S11, then from 0200 to 0600 MLT the mean increases slightly from S0 to S11, particularly in the 0400 to 0600 MLT interval. The similarity to the Iceland East and Finland data is most noticeable in the change of the overall broadness of the spectral width distributions, with narrower
Figure 5.7. Contour plots showing the southern hemisphere winter variation of spectral width distributions with MLT from Syowa East. The points above the black dashed line do not overlap with the Iceland East points. The 70°S and 80°S positions are indicated by the thin black lines. The white on black lines show the mean spectral width value for each point on the lower axis scale. The colour scale indicates the occurrence at each width normalised to the total occurrence for each summary point.
distributions before midnight MLT and much broader ones as the morning sector is approached. A very similar set of contours is produced from the spring data, despite the different data occurrence between the two seasons (Figure 5.3b). This implies that the database is not biased (except at the latitudes closest to the pole where there is very little data from the Syowa East radar).

Figure 5.8 presents two scatter plots of the simultaneous and co-located mean spectral width values for all points and all nightside intervals. Figure 5.8a is from the Syowa East and Iceland East and Figure 5.8b is from the Finland and Iceland East statistics databases. The diagonal line on each plot represents the centre line for a one to one relationship. In the Iceland East/Syowa East comparison the main cluster of points is below this line indicating that on average the Syowa East radar does have larger spectral widths, although not necessarily all the time. Bearing these differences in mind, the spectral width distributions in the region of overlap (Figures 5.5 and 5.7) between the two sets of summary points show the same trend from narrower to broader distributions as 0000 MLT is passed. The mean values increase overall from 2200 MLT to 0600 MLT and the change in the shape of the distributions (as seen by looking at the modal values) is similar to that in Figure 5.4. The Iceland East to Finland comparison shows that overall the mean spectral width values tend to be slightly larger from the Finland radar with 65% of points below the one to one line, but the highest widths observed by the Finland radar tend not to be observed in the Iceland East data. This agrees with the differences between the spectral width distributions in Figures 5.5 and 5.6 where the Finland mean spectral widths at the more poleward points were larger than those for Iceland. Overall there is a reasonable correlation between the Iceland East and Finland mean spectral widths indicating that where one sees higher widths so does the other which again is borne out by Figures 5.5 and 5.6.

In general the separatrix between narrow and broad distributions is best defined in the Finland data and hardest to locate in the Syowa East spectral width distributions. Whether this is because the separatrix is simply equatorward of the field of view in the Syowa East data or that it is not observable is unknown. Given the similarity of the trends between Syowa East and Iceland East however, it is most likely to be the former explanation.
Figure 5.8. Scatter plots of simultaneous and co-located mean spectral widths from the statistics databases for (a) the Syowa East and Iceland East radars and (b) the Iceland East and Finland radars. The diagonal lines represent a one to one relationship for comparison.
5.3.4 Comparison of spectral width values to the estimated flow reversal boundary

It has been suggested that the spectral width boundary is a proxy for the OCFLB. To test this proposal the flow reversal boundary (FRB) is employed as another proxy of the OCFLB assuming purely reconnection-driven convection [Lockwood et al., 1988] and compare its location with the spectral width distributions. The beams of the Iceland East radar point in a generally azimuthal direction and therefore the line-of-sight velocity measurements are ideally placed to locate the FRB of twin cell convection of plasma around the polar cap over a large range of MLT. The measurements of line-of-sight velocity corresponding to the spectral widths already presented have also been collected into 15 minute intervals of MLT. The mean velocity has then been calculated and the results are presented in the top four panels of Figure 5.9 with the colour scale indicating the magnitude and direction of the line-of-sight velocity. In all but the northern hemisphere summer there is a clearly defined change in the direction of plasma flow with latitude. Statistical auroral ovals [Feldstein, 1963; Holzworth and Meng, 1975] for a Kp value of 2 are overlaid for comparison (the average Kp value over the three years was approximately 2). In winter the poleward edge of the auroral oval matches the FRB very closely and the changeover between convection cells at the Harang discontinuity is over a small range of MLT, ~30 minutes. The magnitude of the line-of-sight velocity in the changeover region is small since the plasma motion here is mainly out of the polar cap and directly across the radar beams. The spring and autumn FRBs are also clear. The spring FRB from 1800 MLT to the changeover region start at ~2200 MLT is ~4° poleward of the inner boundary of the statistical auroral oval. However, the FRB from ~2400 MLT once again lines up with the poleward edge of the oval. A similar situation occurs in the autumn. In the summer, the results of the analysis are unclear, probably due to the much smaller number of observations available.

A comparison has been made with the statistical merged vectors available for the Iceland East, Finland pair of overlapping SuperDARN radars. The line-of-sight velocities for the overlapping summary points are combined to give two dimensional vectors averaged over two hours of MLT at each summary point. Both Iceland East and Finland must have data at the relevant summary points for a two dimensional vector making the amount of observed data more critical. This analysis is shown in Figure 5.10 as the black
Figure 5.9. The top four panels depict the mean plasma flow line-of-sight velocity observed by the near azimuthal beams of the Iceland East radar. The data are separated into northern hemisphere seasons, 15 minute MLT intervals and one square for each summary point. A statistical Feldstein auroral oval is overlaid for comparison. The middle four panels show the similarly separated results for the mean spectral width. The bottom four panels show Pearson's 2nd coefficient of skewness for the spectral width distributions.
Figure 5.10. The nightside merged Iceland East and Finland line-of-sight velocity vectors (black arrows) averaged in two hour bins of MLT. Underneath is the Iceland East line-of-sight average velocity direction. The Kp=2 statistical auroral oval is overlaid in yellow.
arrows superimposed on the mean Iceland East line-of-sight velocity direction (pink is westward, blue is eastward). The size of the arrow tail gives an indication of the magnitude of the velocity on a linear scale. This shows that the one dimensional depiction of the FRB in Figure 5.9 is generally realistic for the two dimensional vectors found using the overlapping radars. It would appear however, that the seasonal variation in the location of the one dimensional FRB in the pre-midnight sector is not valid in the two dimensional picture, and is therefore likely to be a product of using just one radar.

The middle four panels of Figure 5.9 represent the mean spectral width in each season, again in 15 minute intervals of MLT. The same statistical auroral ovals are overlaid on each of these panels. Examining the winter results first note that the highest mean values of spectral width, 160+ m s\(^{-1}\), occur from -2300 MLT through to 0600 MLT with a gradual rise in latitude from -70 °N to 76 °N. It would seem at first glance that the high widths are centred on the FRB as identified from the Iceland East line-of-sight velocities. It is entirely possible that the flow reversal is contributing to the high widths at this point as described by Villain et al. [2002]. However, the high widths significantly poleward of where the statistical FRB is located would require another explanation. So again we are left with the conclusion that there is more than one mechanism capable of producing large spectral widths.

Approximately half of the highest mean spectral widths occur within the auroral oval represented here, and since the FRB matches closely to the poleward edge of the oval, this means that half of the large spectral widths observed occurred on closed field lines, and half on open field lines. The gradual increase in latitude of the maximum in the mean spectral width appears to follow the motion of the auroral oval, so although it appears the two are somehow linked, it would seem that (at least from ~2200 MLT) the frequently observed spectral width gradient does not represent the OCFLB. A similar situation occurs in spring and autumn, although the start of the high spectral width region is further around in MLT at ~0100 MLT. The MLT sector between 1800 and 2100 MLT shows different behaviour in winter, spring and autumn to the post-midnight sector. Pre-2100 MLT the highest mean spectral widths seem to be mostly above the poleward edge of the auroral oval, with the maximum being lower than that in the post-midnight sector.
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The summer results show much lower widths throughout the nightside even where the velocity results are clearest and the data occurrence largest.

Pearson's second coefficients of skewness for the spectral width distributions from Iceland East are shown in the bottom four panels of Figure 5.9. The second coefficient is calculated using the formula in Equation 5.1.

\[
\text{coeff}^2 = \frac{3(\text{mean} - \text{median})}{\text{standard deviation}} \tag{5.1}
\]

The value of the second coefficient may vary between +/- 3 although values outside the range -1 to +1 are extremely skewed distributions. In the winter, spring and autumn data the skewness is mostly positive at all latitudes and MLT with no discernable pattern in magnitude. Thus no extra information beyond what the mean values tell us is available from the skewness of the distributions.

The mean line-of-sight velocities for the Finland radar are presented in the top four panels of Figure 5.11. As expected from the pointing direction of the radar beam from which these data come there is no clear indication of the FRB location. Instead the highest velocities indicate the average location of the Harang Discontinuity which for this data is pre-midnight. In the middle four panels the average spectral width values are shown. The same region of low mean spectral widths post dusk is observed although its extent is reduced to between 2000 and 2200 MLT depending on the season. Perhaps most importantly the highest spectral widths (180+ m s\(^{-1}\)) are all at or poleward of the average FRB location (± 2 summary points) found from the Iceland East data in Figure 5.9 (top four panels). This contrasts strongly to the Iceland East data in the post-midnight sector where approximately half the highest widths were distinctly equatorward of the average FRB (cf. Figure 5.9, bottom four panels). Another feature which differs from the Iceland East data is the presence of high widths (160+ m s\(^{-1}\)) at the two most equatorward summary points in the 1800 to 2000 MLT interval, as noted in the discussion of Figure 5.6. This feature is most apparent in the winter months although it also appears in spring and autumn but at a reduced value. The larger quantity of data in the summer months for Finland maintains the location of the highest widths, but again the actual values are much reduced in comparison with the other seasons (<180 m s\(^{-1}\)).
Figure 5.11. The top four panels depict the mean plasma flow line-of-sight velocity observed by the near azimuthal beams of the Finland radar. The data are separated into northern hemisphere seasons, 15 minute MLT intervals and one square for each summary point. A statistical Feldstein auroral oval is overlaid for comparison. The middle four panels show the similarly separated results for the mean spectral width. The bottom four panels show Pearson’s 2nd coefficient of skewness for the distributions.
Pearson's second skewness coefficient for the distributions, shown in the bottom four panels of Figure 5.11, are more revealing than in the Iceland East case. There is a region of negative skewness apparent poleward of the statistical auroral oval for winter, spring and autumn. The more marked change in the Finland skewness compared to that from Iceland East agrees with the more significant change observed in the distributions as in Figure 5.4. The regions of negative skewness in the Finland data correspond to the regions with high mean spectral width as expected from the form of the distributions in Figure 5.4.

Figure 5.12 presents a similar analysis for the southern hemisphere seasons. The Syowa East radar beams are also azimuthal in general and hence again a clear indication of the location of the FRB is seen in the top four panels of Figure 5.12. The correspondence of the FRB location to the statistical auroral oval in this case is close throughout the southern hemisphere winter, spring and autumn. The observations in the post-midnight sector of the summer data also line up closely to the auroral oval (there is more data here than for Iceland East, see Figure 5.3b). Unfortunately for the time period used in the database no overlapping radar field-of-view was available for the Syowa East radar therefore no two dimensional flow vectors are available for Syowa East during this time. Given the good relationship between the one and two dimensional flows for the Iceland East radar and the lack of a seasonal variation in the one dimensional Syowa East observed flows it seems reasonable to assume that the Syowa East one dimensional data is a good substitute for two dimensional vectors. The mean spectral widths shown in the bottom four panels are in general higher than those from Iceland East as mentioned previously. The skewness coefficients for Syowa East distributions are very similar to those from Iceland East with no significant pattern in the data. Similarly to the Iceland East analysis, the highest spectral widths tend to occur from a little before midnight to 0600 MLT although over a wider range of latitudes. Again, the summer widths are much lower bearing in mind that the data poleward of 76°S is in very low abundance. Although the equatorward limit of the Syowa East data is somewhat reduced compared to the Iceland East and Finland data it would appear that the high widths continue somewhat equatorward of the average FRB as in the Iceland East case. It would seem therefore that
Figure 5.12. The top four panels depict the mean plasma flow line-of-sight velocity observed by the near azimuthal beams of the Syowa East radar. The data are separated into northern hemisphere seasons, 15 minute MLT intervals and one square for each summary point. A statistical Feldstein auroral oval is overlaid for comparison. The bottom four panels show the similarly separated results for the mean spectral width, again with a statistical oval overlaid.
the presence of high widths on closed field lines in the post-midnight sector on a statistical basis is limited to azimuthally pointing radars.

5.4 Discussion

The results presented in the previous section reveal four key points that require further comment.

1) The spectral width gradient previously observed in case studies is seen to persist in statistical studies of the spectral width, most notably in the Finland data.

2) There is a variation in the latitude of the statistical gradient in the spectral width as MLT changes on the nightside. The highest widths seem to occur on both open and closed field lines for the azimuthally pointing radars but not for meridionally pointing beams. This was found using the FRB obtained from the azimuthal velocity measurements as a guide.

3) There is a seasonal effect seen in the data, where the broader spectral width distributions do not appear to be present in the summer months.

4) The southern hemisphere spectral width values are typically larger than those from the northern hemisphere.

The change from low (<200 m s\(^{-1}\)) to high (>200 m s\(^{-1}\)) spectral width is a feature that occurs both on a case by case [Lewis et al., 1997; Dudeney et al., 1998; Lester et al., 2001; Parkinson et al., 2002] and a statistical basis in the nightside ionosphere. The output of the FITACF software has two distinct forms of spectral width, high and variable, and low, which can be identified using the distribution of spectral width over time. The low spectral width regions are characterised by narrow distributions dominated by a large peak close to 0 m s\(^{-1}\) and the distributions tail away from this peak. The Finland data shows the mode closest to 0 m s\(^{-1}\), with the other two radars investigated showing peaks slightly further away. The high and variable spectral width regions are characterised by a broader distribution with a less prominent peak distinctly removed from 0 m s\(^{-1}\), and a larger mean (well above 100 m s\(^{-1}\)). There is nearly always a distinct latitudinal gradient in the value of spectral width between the two regions in individual
cases and this often moves with time, thus averaging over time the sharp gradient becomes a smoother change between the two types of distribution. This effect is prominent in the statistical distributions presented in this chapter, particularly those from the meridionally pointing Finland radar.

The sharp gradient in the width seen in individual cases is not in general collocated with a sharp change in either backscatter power, line-of-sight velocity or elevation angle. Likewise in the statistics presented here the gradient, although slightly smoother than in an individual case due to the averaging process, is not collocated with sudden changes in occurrence (the occurrence pattern is similar to that of the backscatter power, Villain et al. [2002]) or line-of-sight velocity. The broader spectral width distributions resemble those observed in the cusp, whereas the narrower distributions are more like those observed in the low-latitude boundary layer [Baker et al., 1995]. This implies that a similar mechanism to that causing high and variable spectral width in the cusp may also be manifest on the nightside.

Intense electric and magnetic field fluctuations of the order of 1 Hz have been observed over the auroral zone by low-altitude, polar-orbiting satellites [Gurnett et al., 1984; Gurnett, 1991; Dudeney et al., 1998]. As described in Chapter 3 two models for the generation of these 0.1 to 5 Hz fluctuations measured by low-altitude satellites have been put forward. The first model assumes that the fluctuations are observed due to the motion of the satellite through a system of static field-aligned current structures (FACs) embedded in the ionosphere [Smiddy et al., 1980]. This is a space/time ambiguity problem in the spacecraft data, not a wave in the ionosphere, and the scale size of these features would be small, approximately 200 m which is well below the size of a radar range cell. These FACs are capable of producing vortex patterns in the plasma flow around them [Lanzerotti et al., 1990 and references therein]. The work of Schiffler et al. [1997] and Huber and Sofko [2000] with HF coherent radar spectra has attributed double-peaked spectra to vortices less than the scale size of the radar range cells (~45 km) such as these static FACs could produce. It is possible that double-peaked spectra may be observed with over estimated spectral widths, although simulations by André et al., [2000b] suggest that there would need to be several vortices smaller than the size of the radar range cell to in order cause high spectral widths. If the dominant mechanism for the
high spectral width on the nightside is precipitation/FAC produced vortices then a correlation is to be expected between regions of high precipitation and FAC structures. However, the fact that high spectral widths occur on open field lines as well means that precipitation could not be the sole mechanism responsible for the high widths.

The second model suggests that disturbances in the distant magnetosphere are transmitted to the ionosphere as Alfvén waves and such waves in the Pc1 and Pc2 frequency range fluctuations are observed by the low-altitude satellites [e.g. Goertz and Boswell, 1979; Lysak and Dum, 1983]. This would produce the kind of temporal electric field variation required for the proposed cusp mechanism of André and co-workers [1999; 2000a; 2000b].

The variation of the spectral width distributions observed with MLT indicates that the root cause of the high spectral width does not map to a constant magnetic latitude as MLT varies. This is encouraging for the idea of using the spectral width boundary as an ionospheric proxy since both the OCFLB and CPS/BPS boundary move in latitude with MLT. The FRB identified using the azimuthal pointing directions of the two radars in Figures 5.9 and 5.12 shows that approximately half the highest spectral widths are likely to be on closed field lines in the MLT sector from 2300 to 0600 MLT for the Iceland East and Syowa East radars. This implies that, in this sector at least, the spectral width gradient is unlikely to represent the OCFLB since this would require all the highest values to be above the poleward edge of the auroral oval and the FRB. However, the more meridionally pointing Finland radar does not observe this feature with nearly all the highest widths appearing very close to and poleward of the average FRB implying that the very large widths occur almost exclusively on open field lines. This contradiction is very probably related to the different pointing directions of the radars. Perhaps the Iceland East and Syowa East radars are more susceptible to increases in spectral width due to flow reversals as suggested by Villain et al. [2002] where this would not impact so greatly on the Finland data. Upon adding the Finland and Iceland East spectral width distributions together for the data presented here, the mean spectral width pattern in MLT strongly resembles that of Villain et al. [2002] (shown in Chapter 3, Figure 3.12). This indicates that the high widths at lower latitudes observed by the Iceland East radar in the post-midnight sector are overcome by the presence of many low widths in this region observed.
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by the Finland radar and will not be apparent in more general databases such as that of Villain et al. [2002].

The spectral widths prior to 2300 MLT are lower in magnitude for all three radars and the distribution is such that the spectral width boundary observed between 1800 and 2300 MLT could reasonably represent the OCFLB agreeing with the observations of Lester et al. [2001] made with the Finland radar. This asymmetry of the spectral width magnitudes in the pre- and post-midnight sectors of MLT indicates that the source region for generating high and variable spectral widths on the nightside is more prominent in the post-midnight sector. In terms of the FAC system, the OCFLB on the dawnside is coincident with the region 1 downward FAC [Cowley, 2000]. The estimation of the OCFLB location using the FRB presented in this Chapter would suggest that the majority of high spectral widths (certainly in the Finland data) are on open field lines and therefore poleward of the region 1 downward current. The observation that in general the high spectral widths are poleward of the auroral oval also indicates that the large values are not related to the type of particle precipitation observed within the auroral oval. This implies that the precipitation mechanism for forming plasma vortices which could increase the spectral width suggested by Schiﬀler et al. [1997] and Huber and Soiko [2000] has little effect on the nightside spectral width. To counteract the generalisation present in this chapter due to the averaging process, Chapters 6 and 7 present case studies to further investigate these ideas.

A seasonal variation is observed in the magnitude of the mean spectral widths and an attempt is made here to try to identify here what seasonal influences might control this variation. One obvious seasonal factor to consider is the level of solar illumination. During the summer in the respective hemispheres all the summary points are fully illuminated by the sun at 300 km altitude for all of the nightside. The plasma density and therefore plasma frequency is different in the summer. It is unlikely that changes in the propagation of the HF radar signals in summer are the cause of the decrease in the mean spectral widths. The decrease in the number of observations available during the summer is due to this reason, but the propagation itself would be unlikely to decrease the mean width unless the spectral width is height dependent. Over the three years of data studied
here there are enough data points available to assume an accurate description of the summer spectral widths is depicted.

It seems most likely that there is a seasonal variation in either the source of the high spectral widths, or how the different plasma conditions affect the propagation from the source. For example, if the high spectral widths are a result of a time-varying electric field [André et al., 1999; 2000a; 2000b] which originates from a down-tail disturbance in the magnetosphere and travels by Alfvén waves along magnetic field lines to the F-region ionosphere, then changes in the plasma properties along the path in the ionosphere will change from season to season. If vortices are the mechanism then the seasonal variation in the strength of FACs [e.g. Shue et al., 2001] is important. It is also possible however, that the source region for this mechanism does not exist, or does not map to the same place, in the summer months.

The work of Weimer et al. [1985] provides a possible explanation for the decrease in the spectral widths during the summer. These authors analysed 18 conjugate cases from the DE 1 and DE 2 spacecraft when DE 2 was at an average altitude of 800 km and DE 1 at 12400 km. The electric field measurements from the two spacecraft were mapped to a common altitude of 1 Re to account for the convergence of the magnetic field lines. The principle result relevant to the current investigation is that in the auroral zone, the small wavelength (10 to 100 km) electric field variations are much stronger in the higher altitude observations, particularly when the height integrated Pedersen conductivity is large. The impact of this result is to suggest that when the ionosphere is highly conductive (as in the summer) that small wavelength/high frequency variations in the electric field are attenuated in the auroral zone. This could potentially explain the decrease in the spectral width values during the summer on closed field lines. However, the Weimer et al. [1985] results found that the electric fields outside the auroral zone measured at the two spacecraft showed no attenuation of the smaller wavelength observations at lower altitudes. Thus this explanation would not extend to the open field line spectral widths.

The small region of high widths observed by the Finland radar at the two most equatorward summary points also shows a seasonal dependence, being most prominent in the winter. This region has a very sharp cut-off between points C1 and C2 and is located
less than 1000 km from the radar. It seems highly likely that this is a small region of E-region scatter possibly related to the Slow Long-lived E-Region Plasma Structures (SLERPS) observed by Jayachandran et al. [2000]. SLERPS were observed Doppler echoes within this range and sector of MLT but using the Saskatoon radar (see Chapter 2) although the widths observed in these features were not as high (~ 125 to 150 m s\(^{-1}\)) as those found here in the Finland data (mean ~200 m s\(^{-1}\)). The SLERPS were attributed to the presence of a thick sporadic E layer and the gradient-drift mechanism. The region of high widths observed at low latitude in the present study were co-located with fairly low average velocities, lower than one would expect the typical ion-acoustic speed to be. It therefore seems unlikely that the scatter is from irregularities generated with the two-stream mechanism.

On a statistical basis the nightside spectral widths observed by the Syowa East radar are larger and more varied than those observed by its conjugate counterpart Iceland East. A similar situation exists on the dayside [Hosokawa et al., 2002]. There are several possible explanations for this: a) the difference in ionospheric conditions in the two hemispheres, both in terms of the propagation of the radar beams and the local conditions affecting any generating mechanisms, b) an inter-hemispheric/seasonal difference in wave activity, c) a variation in field-aligned current activity, d) the difference in the dip-angle of the magnetic field lines for the two sets of summary range gates, or e) instrumental noise levels. The fields-of-view of the two radars, although in conjugate geomagnetic positions, are not geographic mirror images of each other. The geographic latitude ranges for Syowa East and Iceland East are 63°S to 72°S and 73°N to 84°N respectively. As such, the level of solar illumination at the summary points for each radar will be different in their respective seasons. This will likely cause a small difference in the propagation of the respective radar beams to the summary point locations, leading to a small difference in the height of the observations. However, even in the respective summers of each hemisphere the Syowa East spectral width distributions are still broader, despite there being full (all be it at a slightly different zenith angle) illumination.

Points b) and c) amount to the same problem, the mechanism for creating the high spectral width may itself vary between the hemispheres and also with season. Point d) relates to the difference in magnetic field line dip-angle, which is ~10°, where the Iceland
East summary points are subject to more vertical field lines. The dip-angle is important since this determines where and at what height the radar beam will be orthogonal to the magnetic field lines and hence able to be backscattered by field-aligned irregularities. However the range change introduced by the dip angle difference is outweighed by the typical error in the range estimation of a radar range cell at $1 \frac{1}{2}$ hops, which is 60km [Yeoman et al., 2001].

Instrumental effects, point e), are an important consideration. Although the processing software used by both radars is identical throughout the dataset, the noise level in the readings could affect the overall output. A power level of 3dB and spectral width limit of 500 m s$^{-1}$ was set in the analysis of the data conducted to eliminate approximately 95% of the data affected by low signal to noise ratios. A check was also performed on the comparative noise levels of the two radars and found that the amount of noise observed by the Syowa East radar was significantly lower than at Iceland East, likely due to the lack of local radio interference on Antarctica. If extra noise in the signals were the cause of the broader widths (by the introduction of powerful multiple peaks into the spectra) then one would expect to see higher values in the Iceland East data not, as was have found, in the Syowa East data. Another instrumental point worth noting is that the antennas at Iceland East and Syowa East were made by different manufacturers. It is possible that the beam widths of the two radars are not the same which could lead to different typical values of spectral width, although this would depend on the mechanism generating the high spectral widths. The influence of this factor is difficult to quantify, but given that comparisons between other southern and northern hemisphere radars have also shown the larger widths in the southern hemisphere it would seem to be unimportant. It would therefore appear that the broader spectral widths in the Syowa East data are caused by a geophysical effect, not one of radar propagation or processing of instrumental origin.

5.5 Summary

A statistical study of SuperDARN radar spectral width data from the nightside in both hemispheres has been carried out using data from the Syowa East, Finland and Iceland East radars. These three radars often observe similar features in their spectral width data. This implies that the generating mechanism of high spectral width values is
capable of travelling into both the southern and northern hemispheres from a magnetospheric source region. The data from the two azimuthal radars conflicts with that from the meridional Finland radar in the post-midnight sector where Finland observed high widths mainly on open field lines but the other two radars observe almost half of the highest widths on closed field lines. Nevertheless it appears that the mechanism responsible for the high widths must be present and operative on closed and/or open magnetic field lines. There is a definite latitudinal dependence of the spectral width distribution seen in both hemispheres that shows a statistical location of the spectral width gradient. The magnetic local time affects the spectral width distributions, notably in the location of the spectral width gradient which reaches minimum latitude around magnetic midnight. Season also plays a part in the magnitude of the spectral width, in summer the spectral widths are decreased. The most marked difference between the Syowa East and Iceland East data is that the Syowa East spectral width distributions are in general broader and peaked at values greater than those of Iceland East. This increase is thought to be due to a geophysical rather than instrumental difference.
CHAPTER 6

A multi-instrument case study of high spectral widths on the nightside

6.1 Introduction

This chapter describes a case study from 20th December 1998 which shows that a gradient between low (<200 m s\(^{-1}\)) and high (>200 m s\(^{-1}\)) spectral width is not always a good proxy for the open/closed field line boundary on the nightside. Several complimentary instruments are utilised to this end. It is found that during the interval in question the spectral width gradient is within the region of the 630.0 nm optical emission.

The presence of the EISCAT and ESR radars (see Chapter 4) within the field-of-view of the CUTLASS radars (Co-operative UK Twin Located Auroral Sounding System) provides an ideal opportunity for more detailed observations of the plasma conditions where large spectral widths are found. A comparison of coherent and incoherent scatter radar data was conducted using the EISCAT, ESR and CUTLASS Finland radars. This analysis indicated that high spectral widths were co-located with elevated F-region electron temperatures. Elevated electron temperature can be an indicator of precipitation [e.g. Kofman and Wickwar, 1984] and could therefore be linked to small plasma vortices.

6.2 Data sources for 20th December 1998

The CUTLASS Finland HF radar, as described in Chapter 2, is the primary instrument in this study, the field-of-view is shown in Figure 6.1. As mentioned previously, the whole field-of-view of the radar is not expected to produce ionospheric scatter simultaneously and care is required in assigning boundaries in the scatter to magnetospheric boundaries. However, in this interval, the boundary between low (<200 m s\(^{-1}\)) and high (>200 m s\(^{-1}\)) spectral width is in the middle of a region of powerful backscatter from similar elevation angles and can therefore be assumed to be due to a change in the physical characteristics of the irregularities being observed.
Figure 6.1. Map indicating the location of the fields of view of the instruments used in this study. Only the IMAGE magnetometer stations referred to in the text are plotted, for a complete map of IMAGE stations see Chapter 4.
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The Finland radar was performing 7s dwell time scans on each beam with standard common mode range gates, although the beam direction reverted to beam 5 after each other beam to give a higher time resolution for this beam until 0500 UT when the scan resumed its normal consecutive order. The time resolution for beam 9 from 0100 UT to 0500 UT was 224s and from 0500 UT to 0600 UT it was 120s.

Observations from two of the EISCAT radars have also been included in this work. The VHF radar at Tromso and the UHF ESR are used to provide estimates of a variety of plasma parameters including electron temperature and line-of-sight ion velocity. The VHF radar at Tromso was operating in split beam mode for the majority of the interval 0100 to 0600 UT on 20th December 1998, the two poleward pointing beams are shown in Figure 6.1. Beam one has an azimuth of 345.0° clockwise to geographic north and beam two has an azimuth of 359.5°. Also shown is the equatorward pointing ESR beam which has an azimuth of 161.6°. All three beams were at an elevation of 30.0°. Only data from the modes of operation described above are included in this investigation.

Optical observations from the meridian scanning photometer (MSP) at Longyearbyen on Svalbard are employed (see Chapter 4). Observations from the IMAGE network of magnetometers [Viljanen and Hakkinen, 1997] supply information about ionospheric currents during the interval. The locations of the IMAGE stations and MSP employed in this paper are also plotted in Figure 6.1.

6.3 Observations

6.3.1 Interplanetary conditions

The interval under investigation takes place on 20th December 1998, from 0100 UT to 0600 UT. The IMF and solar wind data taken by the MFI and SWE instruments on the WIND spacecraft (see Chapter 4) are shown in Figure 6.2. The spacecraft was located at (40Re, 60Re, 10Re), (X, Y, Z) in GSM co-ordinates from which point a time delay of ~10 minutes from the satellite to the magnetopause has been estimated. This time delay has not been added to any of the times referred to below for the spacecraft. The z component of the interplanetary magnetic field (Bz) was northward at the spacecraft from 0030 UT until 0225 UT, when it became weakly southward at first and then more strongly
Figure 6.2. Solar wind and IMF data from the WIND SWE and MFI instruments on 20th December 1998. The times shown are at the spacecraft, a time delay of ~10 minutes to the ionosphere has been estimated but not added to the figure. The top three panels display components of the interplanetary magnetic field in GSM co-ordinates. The bottom three panels indicate solar wind bulk velocity, density and pressure respectively. WIND was located at approximately (40RE, 60RE, 10RE), (X, Y, Z) in GSM co-ordinates during this interval.
southward after 0250 UT. At 0300 UT $B_z$ returned northward until 0340 UT when it became variable until 0535 UT, after which it became increasingly southward. The $y$ component ($B_y$) was positive until a sudden, large jump from +6 nT to −6 nT at 0220 UT. It was variable after this until another extended period of positive values began at 0435 UT. The $x$ component ($B_x$) was approximately in antiphase with $B_y$ throughout the interval.

The solar wind velocity at the spacecraft increased from ~350 km s$^{-1}$ at 0000 UT to ~420 km s$^{-1}$ at 0330 UT after which it decreased to ~400 km s$^{-1}$. The density and pressure values indicated a trough between 0120 UT and 0220 UT with the density decreasing sharply from 12 cm$^{-3}$ to 7 cm$^{-3}$. At 0220 UT the density and pressure recovered quickly to their previous levels where they remained until 0520 UT when another sharp decrease was observed.

### 6.3.2 CUTLASS Finland data

The Doppler spectral width, line-of-sight irregularity drift velocity and backscatter power from beam 9 of the Finland radar from 0100 UT to 0600 UT on 20th December 1998, are shown in panels (a) through (c) of Figure 6.3 (positive velocities are directed toward the radar). To convert UT to magnetic local time (MLT) in the region of magnetic latitude covered by the CUTLASS Finland field of view, add approximately 2.5 hours to the UT. F-region backscatter was observed from 0200 to 0500 UT northward of 65°N during this time. The scatter shown between 0100 UT and 0130 UT, and also from 0545 UT to 0600 UT, has been identified as ground scatter using elevation angle data. The SuperDARN radars ground scatter as described in Chapter 2. In general this approach is highly effective. However, for the particular F-region scatter interval between 0130 UT and 0530 UT of interest here, the standard method lead to the misidentification of some of the ionospheric scatter between 68°N and 75°N as ground scatter. Consequentially all ground scatter was identified by studying the elevation angle data. The F-region backscatter power, panel (c) of Figure 6.3, was consistently high throughout the interval 0200 UT to 0500 UT. The position of the poleward edge of the F-region backscatter
Figure 6.3. HF radar data from CUTLASS Finland beam 9, 20th December 1998, a) Doppler spectral width, b) line-of-sight velocity (blue is towards the radar), c) backscatter power. MSP data from Longyearbyen, d) 630.0 nm, red emission, from an assumed altitude of 250 km, e) 557.7 nm, green emission, from an assumed altitude of 110km. All 5 panels have the spectral width gradient at 200 ms$^{-1}$ overlaid on them in white for comparison. The intervals marked 'G.S' have been identified as groundscatter.
varied between 73°N and 84°N whilst the equatorward edge remained fairly static between 67°N and 69°N.

In the Doppler spectral width data, Figure 6.3a, there was an area of low spectral width (<200 m s\(^{-1}\)) equatorward of a large area of high (>200 m s\(^{-1}\)) and variable spectral width. A typically sharp nightside gradient in width, \(\sim 60 \pm 30\) m s\(^{-1}\) degree\(^{-1}\), existed between these two regions and is shown by the white line in Figure 6.3a. This boundary has been overlaid on all the other panels of Figure 6.3 for comparison. A plot of the spectral width distributions for each range gate from 20 to 60, covering a latitude range from 67.5°N to 83.0°N, is shown in Figure 6.4. A bin width of 20 m s\(^{-1}\) has been used. The data are taken from the interval of F-region scatter from 0130 UT to 0530 UT and have been normalised to the total number of observations in each range gate. The very low spectral widths are not a result of ground scatter since the time interval and range gates chosen contain only F-region scatter. There is an obvious change from distributions peaked between 0 to 20 m s\(^{-1}\) up to range gate 30 (~71°N), to those distributions where the peak is around 250 m s\(^{-1}\) above range gate 40 (~75°N). In between 71°N and 76°N a transition between these two extremes is observed, this corresponds to the latitude region within which the spectral width gradient moves during this interval.

Figure 6.5 presents the distributions of the spectral width for range gates 25 (~69.9°N) and 39 (~75.3°N) of Finland beam 9 for the interval 0130 UT to 0530 UT, the black lines on Figure 6.4 show their location. The more northerly range gate (39) shows a much more rounded distribution, with a significant percentage (~66%) of spectral width values larger than 200 m s\(^{-1}\), while range gate 25 has virtually no data points >100 m s\(^{-1}\). The distributions in Figure 6.5 are very similar to the statistical distributions for Finland found in the previous Chapter, specifically in Figure 5.4c, and also those in Lester et al. [2001]. The form of the rounded distribution for gate 39 also resembles closely that of the spectral width distribution identified by Baker et al., [1995] as a proxy for the location of the cusp on the dayside. Since the majority of observations in the more rounded distribution are above 200 m s\(^{-1}\) and vice versa for the more exponential distribution this value has been used to identify the spectral width gradient in the time series plots of Figure 6.3.
Figure 6.4. A contour plot of spectral width distributions for beam 9, range gates 20 (~67.5°N) through 60 (~83.0°N) for the interval 0130 UT to 0530 UT. The colour scale indicates percentage occurrence with the distributions normalised to the total number of observations from each range gate. The very low spectral width values are not due to ground scatter.
Figure 6.5. Two histograms displaying spectral width distributions for a) beam 9, range gate 25 (~69.6°N), and b) beam 9, range gate 39 (~75.3°N). Each histogram is normalised to the total number of observations from that gate.
The line-of-sight velocity data (Figure 6.3b) indicates that the highest velocities were at the poleward edge of the F-region backscatter, and that these velocities had a component that was directed toward the radar (in blue). The strong bursts of flow with components towards the radar that occurred at 0310 UT and 0350 UT were associated with pronounced velocity enhancements in anti-sunward flow. There was evidence for long period, ULF, wave activity in the line-of-sight velocity data, from 0210 UT to 0400 UT between 69° and 74°. The period of the wave was approximately 10 minutes and this will be investigated further in Section 6.3.4 with magnetometer data.

The work of André et al. [1999; 2000a; 2000b] on the high spectral width in the cusp stated that the effect of electric field variations in the 0.1 – 5 Hz frequency range on the HF power spectra would be to produce multiple component spectra due to undersampling. Figure 6.6a shows the fitted spectral width values for CUTLASS Finland, beam 9 and Figure 6.6b below it shows an estimate of the number of peaks in the spectra (colour coded) in comparison. Both plots have axes of range gate against time. The spectra used to produce Figure 6.6b were calculated using the first 15 lags of the ACF modified by a Hanning window to reduce ringing effects. The algorithm used to identify the number of peaks is simple but remarkably effective. The spectra are scanned for changes in the sign of the gradient above some threshold in the power value (here chosen to be half of the power of the largest peak in each spectrum). From this analysis the region of low spectral width is seen to be almost exclusively single-peak spectra. The area of high spectral width appears to have two different regimes of spectra, firstly a cluster of multiple-peak spectra with up to seven or eight peaks in places poleward of ~72°N from approximately 0155 UT to 0235 UT. The rest of the high spectral width appears to be dominated by single-peak spectra with a few two or three-peak spectra widely dispersed.

Figure 6.7 shows a zoomed in section (0218 UT to 0233 UT, range gates 27 to 37 of beam 9) of the previous figure with the colour coding showing the fitted spectral width (FITACF was applied to the raw data from which the spectra were produced) with the corresponding normalised spectrum overlaying each observation. The horizontal dashed lines show the half maximum power level for each spectrum and the vertical dashed lines indicate the 0 m s⁻¹ position. The lowest spectral widths are all narrow, single-peak
Figure 6.6. (a) Spectral width for 20 December 1998 plotted for range gate against UT. (b) The number of peaks identified in the power spectra for the same data (a peak being identified if it is larger than 1/2 the power of the largest peak).
Figure 6.7. A zoomed in section of the spectral width range gate against UT plot from Figure 6.6a. Overlaid on each radar scan for each cell is the corresponding normalised power spectrum for comparison.
spectra. The complexity of the spectra tends to increase as the fitted spectral width does, particularly above ~250 m s⁻¹.

6.3.3 Meridian scanning photometer data

The optical data for two wavelengths, 630.0 nm and 557.7 nm, taken from the Longyearbyen MSP (see Chapter 4) for the interval 0100 UT to 0600 UT on 20th December 1998 are shown in Figure 6.3d and e, respectively. These have been plotted as a function of magnetic latitude assuming an altitude of 250 km for the emission at 630.0 nm and 110 km for 557.7 nm. The assumed altitudes are seen to be reasonable in the discussion.

There was structure in both the 630.0 nm and 557.7 nm emissions from 0100 UT until 0140 UT when a sudden decrease to very low intensity emission occurred. This lack of emission lasted until 0240 UT. Coincidentally, the time-span of this marked drop in intensity was the same as the density decrease observed by WIND when a time lag of 20 minutes from the spacecraft is included. It may be possible that the two events are related in some way, with the additional delay of 10 minutes a result of the reaction time in the nightside ionosphere to the change at the magnetopause. The optical intensity decreased between 0140 UT and 0240 UT, this time marked the beginning of the region of ionospheric scatter observed by the Finland HF radar. The region of ionospheric scatter expanded quickly to cover latitudes from 67°N up to 83°N, then the poleward edge of it contracts dramatically just before 0240 UT to 76°N. The 630.0 nm emission then took the form of a narrow band of high intensity, >3 kR, which was approximately 2° wide in latitude at 0240 UT. The peak intensity of the main emission moved equatorward from 75°N to 71°N, during the interval 0240 UT to 0420 UT. After this the peak emission moved poleward to 77°N, once again becoming narrow, reaching its maximum latitude at 0540 UT. Above the main latitude of emission there were several equatorward moving features starting at 0310 UT, 0345 UT, 0355 UT and 0400 UT. The first and last of these moved from 76°N to 73°N, whilst the intermediate features moved from 75°N to 73°N. The approximate rate of motion was 0.1° ± 0.05° per minute (~170 m s⁻¹).
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The 557.7 nm emission, although active simultaneously with the 630.0 nm emission, had a constant poleward edge at 73°N with a broader region of high intensity, above 3 kR, and variable structure equatorward of this latitude. The same reduction in luminosity between 0140 UT and 0240 UT was observed in the 557.7 nm emission, as were the same equatorward moving features from 0310 UT to 0400 UT. The peak of the of the 557.7 nm emission was located at approximately 72°N from 0240 UT until 0410 UT, when it moved southwards to 70°N at 0500 UT at which point the intensity started to decrease until it was beyond the interval of interest. The equatorward edge of the emission was south of the field of view from 0250 UT until the end of the interval.

6.3.4 Magnetometer data

A 150 nT negative bay was observed in the X-component (North-South) data from Sørøya (SOR, 67.1°N, 106.7°E) to Pello (PEL, 63.3°N, 105.4°E) in the IMAGE chain from 0000 UT to 0110 UT (data not shown). This enhanced westward electrojet decayed to previous levels by 0110 UT and was therefore assumed to have no effect on the spectral width boundary indicated in Figure 6.3a. Data from five of the magnetometers of the IMAGE chain for the period 0100 UT to 0600 UT on 20th December 1998 are shown in Figure 6.8. The magnetometer data have been band pass filtered using a range of 100 s to 1000 s. A wave, matching the frequency of the one observed by the Hankasalmi radar (~2 mHz) was recorded by magnetometers of the IMAGE chain starting at 0220 UT. The amplitude of the wave observed by the magnetometers is largest at the stations of Bear Island (BJN, 71.3°N, 108.9°E) and Hopen Island (HOP, 72.9°N, 115.9°E). There was a sharp decrease in the amplitude of the wave between HOP and Longyearbyen (LYR, 75.0°N, 113.0°E) and a slower decrease to the south of HOP. Measurements of the latitudinal variation of the amplitude and phase of the wave were consistent with the wave being a field line resonance (FLR, see Chapter 4) with the resonating field line poleward of SOR and equatorward of BJN. As FLRs only occur on closed field lines a lower limit for the OCFLB can be set at 72.9°N.
Figure 6.8. The north-south component measurements from five of the IMAGE magnetometer stations filtered between 100 s and 1000 s, for 20th December 1998.
6.3.5 Incoherent scatter data

The first three panels of Figure 6.9 show the electron density, electron temperature and ion line-of-sight velocity respectively observed by the ESR from 0100 UT to 0600 UT. The panels (d) and (e) of Figure 6.9 present the line-of-sight velocity and spectral width from beam 9 of CUTLASS Finland for the same range of magnetic latitudes. The last panel shows the 630.0 nm optical emission for the same latitude range as the other panels. The ESR UHF beam was pointing in the same vertical plane as beam 9 of CUTLASS Finland, in the opposite sense during this interval, at an elevation of 30°. The altitude range covered by the data in Figure 6.9 is from approximately 90 km at 74°N to 390 km at 70°N. Although not shown here, the data from the EISCAT VHF beams showed very similar results to those from the ESR. It is evident from Figure 6.9c and d that the line-of-sight ion velocities from the incoherent radar agree well with the irregularity drift velocities observed by CUTLASS Finland. (Note that all the data shown has positive velocities towards the HF radar at Finland. Also that the range of magnetic latitudes shown here is a subset of those in Figure 6.3). This is consistent with previous results that the phase speed of F-region irregularities is equal to the component of the ambient plasma flow in their direction of propagation [Davies et al., 2000 and references therein]. One can observe the same field line resonance signature as seen from Hankasalmi and the same flow bursts at 0310 UT and 0350 UT.

Equatorward moving structures are evident in the electron density and electron temperature data, Figures 6.9a and b respectively, from 0340 UT to 0410 UT. These structures were observed by the ESR whilst equatorward moving structures were also observed by the MSP although not simultaneously and at a lower latitude. The equatorward motion was observed at the same time as strong velocity towards Hankasalmi, and also in the latter part of the interval when the spectral width gradient moved equatorward.

The ESR observed two pronounced regions of structured, elevated electron temperature in the F-region, Figure 6.9b, and this was replicated by the two VHF beams from Tromsø, from 0100 UT and 0145 UT, and 0310 UT and 0420 UT. The ESR beam was at F-region altitudes equatorward of approximately 73°N. These regions are clearly seen to be co-located with the areas of high spectral width observed by CUTLASS
Figure 6.9. Data from the EISCAT Svalbard Radar, 20th December 1998, a) electron density, b) electron temperature, c) ion line-of-sight velocity. Data from CUTLASS Finland on a reduced latitude scale from Figure 3, d) line-of-sight velocity and e) spectral width. All negative velocities are away from the Finland radar. Panel f) is the 630.0 nm optical emission from the Longyearbyen MSP.
Finland at these times, Figure 6.9e. Figure 6.10 shows a comparison of the electron temperature from the incoherent scatter radars and spectral width from the Finland radar in the region 71° to 72°, which restricts the altitude range of observation to a small slice of the F-region around 300 km. This is done for two reasons, firstly to ensure the values are solely from the F-region and secondly to avoid any effects due to the underlying increase of electron temperature with altitude found in the F-region. Panels (a) through (c) of Figure 6.10 show scatter plots of electron temperature from the ESR and beams 1 and 2 of the EISCAT VHF system respectively versus co-located and simultaneous HF spectral width. The data has been collected into bins of 50 m s⁻¹ and 100 K, with the colouring indicating the number of observations in each bin. Figure 6.10 shows that high spectral width values measured by CUTLASS Finland were co-located with elevated electron temperatures although the reverse was not the case. Figure 6.11 shows a direct comparison of simultaneous, co-located observations for the ESR UHF beam and beams 1 and 2 of the mainland VHF system ((a) to (c) respectively) with the HF radar data. The analysis from both Figures 6.8 and 6.9 shows that although high spectral widths from the HF radar were associated with high electron temperatures, there were also regions of elevated electron temperature associated with very low spectral width. Also note that the elevated electron temperature features were spatially extended in longitude as they occurred in all three incoherent scatter radar beams.

6.4 Discussion

A previous case study in the pre-midnight sector [Lester et al., 2001] concluded that the well-defined gradient between low (<200 m s⁻¹) and high (>200 m s⁻¹) spectral width can be used, with caution, as an ionospheric proxy for the OCFLB. This conclusion was based on the fact that the gradient would at times follow the poleward edge of the 630.0 nm optical emission which has been proposed as a proxy for the OCFLB [Blanchard et al., 1995]. Blanchard et al. had established that the poleward edge of the 630.0 nm emission can be used as the ionospheric footprint of the OCFLB with an accuracy of ± 0.9° in the pre-midnight sector. Lester and colleagues did note that during dynamic intervals, e.g. a weak substorm, the relationship between the spectral width gradient and the poleward border of the red line emission broke down. Although there
Figure 6.10. Scatter plots of electron temperature against spectral width, (a) ESR, (b) VHF beam 1, and (c) VHF beam 2 against CUTLASS Finland respectively. The data used has been restricted to between 71°N and 72°N.
Figure 6.11. Line plots comparing co-located and simultaneous measurements of electron temperature (in black) from the three incoherent scatter beams and spectral width (in red) from Finland beam 9, a) ESR UHF, b) EISCAT VHF beam 1, c) EISCAT VHF beam 2. The locations of these intersecting measurements have been chosen within the range 71°N to 72°N, and at an altitude of ~300 km.
were no substorm signatures in the interval presented in this chapter it would seem that other transient features such as enhancements in the electron temperature and the regions of increased flow speed caused the relationship between the spectral width gradient and the poleward edge of the 630.0 nm emission to break down.

In general the motion in time of the location of the gradient did not follow either the main poleward boundary, or the equatorward moving arcs. This could be a result of the altitude structure of the optical emission changing with time, nevertheless the spectral width gradient stays equatorward of the emission at 0° to the zenith. Thus the assumption is valid that the non-correspondence of the spectral width boundary and poleward edge of the 630.0 nm emission is not a result of the assumed altitude applied to the observations of the 630.0 nm emission in order to map it to magnetic latitude. The electrojet activity in the vicinity of Scandinavia seen at 0000 UT, prior to the interval discussed here has been assumed to have no long lasting effect that would affect the alignment of the spectral width gradient and poleward edge of the 630.0 nm emission over Scandinavia. If one imagines a line drawn between the peaks of the oscillations in the location of the spectral width gradient from 0300 to 0430 UT then the poleward edge of the main 630.0 nm emission agrees well with the spectral width gradient. The transient optical emissions poleward of this would be expected to be on closed field lines, although this would contradict the magnetometer estimation of the OCFLB location. The final deviation of the spectral width gradient from the poleward edge of the main 630.0 nm emission between 0430 and 0500 UT occurs where the identification of the width gradient is dubious and should therefore be ignored. The increases in velocity at the poleward edge of the region of backscatter could be another cause of the breakdown in the red line/spectral width gradient relationship. The increases in velocity are towards the radar in the same direction as the spectral width gradient then moves. It does not appear to be the case that the high widths are associated with high velocities though.

Another interesting feature is that the general trend of the most equatorward location of the spectral width gradient follows the equatorward extent of the 630.0 nm emission. This is not an exact correspondence but could be an indicator that precipitation is having an effect on the spectral width values.

If one looks at the comparison between the optical and spectral width gradients in this way, then there is a similarity to the conclusions of Lester et al. [2001]. The work of
Blanchard et al. [1995; 1997] did not extend into the post-midnight sector, however the discrete 630.0 nm emission within which the spectral width gradient should be on closed field lines. The observations shown in this paper indicate that much of the high spectral width region is actually located on closed field lines. Hence one can conclude that Lester et al. [2001] were correct in advising caution in using the gradient between high and low spectral width as a proxy for the OCFLB. Furthermore in the post-midnight sector the gradient between large and small spectral width values was exclusively on closed field lines during this case study.

During this interval there was another means of finding the minimum latitude for the OCFLB, namely the field line resonance seen in both the IMAGE magnetometer data and the Finland and EISCAT radar line-of-sight velocity data, Figures 6.8 and 6.9. These observations set a lower limit for the OCFLB at 72.9°N since a FLR is expected to occur only on closed field lines. This lower limit for the OCFLB was poleward of the majority of the spectral width gradient's location, which reached 71°N at its lowest point. This would indicate that if the gradient is related to a magnetospheric boundary then it is more likely to be an indicator of the boundary between the CPS and BPS [Dudeney et al., 1998] since both of these regions are assumed to be on closed field lines.

The incoherent scatter radar data from the EISCAT facilities show an interesting effect to consider further. A first look at Figure 6.9b and e seems to indicate a correspondence between regions of elevated electron temperature and high spectral width. Upon further comparison of the F-region electron temperature data from the EISCAT and ESR data with the spectral width values, it was found that regions of high spectral width were associated with regions of high electron temperature, but not vice-versa. Only data between 71°N and 72°N were used to eliminate the underlying change in the electron temperature with altitude that is present in the F-region. This latitude range also restricts the CUTLASS, EISCAT and ESR observations to F-region altitudes. Upon closer inspection of Figure 6.11 the increases in spectral width appear to be triggered by features in the electron temperature. This could be some threshold value of electron temperature but the spectral width increases seem to be more related to sudden elevations in the electron temperature. If this is the case then the spectral width values decrease more quickly than the electron temperature does. Since the electron temperature decay is very quick, a few seconds or less (certainly less than time between CUTLASS scans) the
source elevating the electron temperature must still be present in order to maintain the high temperature. This implies that the spectral width parameter is sensitive to the onset of the electron heating mechanism. This agrees with the analysis of Figure 6.10 which shows that high electron temperatures are associated with both low and high spectral widths, but high spectral widths only occur in conjunction with high electron temperatures.

If one assumes that elevated electron temperatures are linked to electron precipitation then there is a relationship here between F-region electron precipitation and high spectral widths in the F-region. Following from this interpretation it is possible that the relationship between elevated electron temperature and high spectral width on closed field lines is a signature of small scale vortex activity resulting from precipitation. The work of Newell et al., [1996] has characterised the change from structured to unstructured electron precipitation (on a scale of > 5-10 km) as boundary "b4s" as observed by DMSP satellites. The decrease in correlation between successive electron spectra above this boundary means that there are spatial structures <5-10 km at the satellite altitude on closed field lines. These could be the signature of filamentary electron precipitation which could generate small scales vortices. This case study cannot, however, directly demonstrate this.

The estimates of the number of peaks in the spectra related to the fitted spectral widths appears to indicate two types of high spectral width, 'A' where there are clusters of many multiple peak spectra and 'B' high widths where there are mostly single-peak spectra with a few double or triple-peak spectra widely dispersed. The low widths are almost solely single-peak spectra. The majority of the type B widths appear to be co-located with the discrete optical emissions which might lead one to conclude that perhaps the high width is a result of the suggested vortex mechanism arising from filamentary precipitation. However, the region of optical emission extends substantially equatorward of the type B widths meaning there must be some other factor controlling where the spectral width gradient occurs.

From Figure 6.6 it appears that the type A widths were poleward of the type B widths and none of the type A were within the 71°N to 72°N region investigated for the correlation between spectral width and elevated electron temperatures. Unfortunately at the latitudes required to test the relationship of electron temperature and spectral width the
altitude difference between the incoherent and coherent radar beams is large. The
differences in the spectra are either showing up different mechanisms or different
intensities of the same mechanism. The former explanation seems more likely since the
type A widths extend poleward to over 80°N and are therefore almost certainly on open
field lines whereas the type B widths are seen more equatorward with at least part on
closed field lines (using the 630.0 nm emission as a guide). It is therefore possible,
although difficult to prove in this case, that the type A widths are all on open field lines
and type B on closed field lines. This idea requires further investigation since this
subdivision of the high spectral widths could prove to be a more useful proxy of the
OCFLB than the previously investigated spectral width gradient on the nightside. The
type A widths and spectra also resemble more the description of the spectral widths in the
cusp which could indicate that they are an open field line phenomena. Chapter 7 will
investigate further this possible new proxy for the OCFLB.

The case study presented in this chapter contradicts in part the statistical study of
the previous chapter. In Chapter 5 (specifically Figure 5.11) it appears that the average
high spectral widths from the Finland radar were almost exclusively on open field lines in
the post-midnight sector. However, in this case study the high spectral widths occur on
both open and closed field lines. The averaged data would seem to indicate that high
spectral widths on closed field lines are a comparatively rare occurrence in the Finland
data. Perhaps the conditions (geophysical and propagation) required for the closed field
line high spectral width are more often met using the Iceland East and Syowa East radars
where a significant proportion of the average high spectral width appears to be on closed
field lines.

6.5 Summary

Contrary to the statistical observations from the Finland radar presented in the
previous chapter, where the average spectral width gradient appeared to be very close to
the OCFLB, the boundary between large and small values of HF radar spectral width for
the data in this case study is located exclusively on closed field lines. The observations
presented in this chapter agree to some extent with those of Lester et al. [2001] and
Parkinson et al. [2002]. It should be noted the data from the current study is from the
post-midnight sector and these two published cases were based in the pre-midnight sector.
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The statistical results of Chapter 5 indicate that these two MLT sectors show very different spectral width behaviour on average. It therefore seems plausible that the spectral width gradient may be a more effective proxy for the OCFLB in the pre-midnight rather than post-midnight sector, although care is still required even in the pre-midnight range as stated by Lester et al. [2001]. Overall it appears that the spectral width gradient can at times be used as a proxy for the OCFLB but its susceptibility to transient phenomena mean that as an automated method for locating the OCFLB the spectral width gradient is too unreliable.

There is evidence for a relationship between high spectral width and elevated electron temperature in the F-region during this interval leading to the conclusion that there could be a link between electron precipitation and high spectral width. High electron temperature appears to be a necessary but not sufficient condition for the presence of large spectral width on the closed field lines investigated in this study. The trigger for high spectral widths appears to be a sudden increase in the electron temperature. However, the continued elevation of the temperature is not sufficient to sustain the high widths.

It is also demonstrated in this chapter that large spectral width on the nightside may be split into two types, 'A' where all the spectra have many peaks and 'B' where the majority of the spectra have one peak with a few double or triple-peak spectra here and there. This would appear to show the presence of more than one generating mechanism for large spectral widths on the nightside, possibly the two mechanisms already suggested in relation to the dayside. The type A widths show the characteristics expected as a result of undersampling of electric field variations as proposed by André et al. [1999; 2000a; 2000b]. It is more difficult to tell if the type B widths correspond to the vortex mechanism suggested by Schiﬀler et al. [1997] and Huber and Sofko [2000]. Most of the type A widths occurred on open field lines, although the equatorward extent was such that some of the type A data may have been on closed field lines. The type B widths seem to be present more on closed field lines, possibly extending into the open field line region. However, without an accurate and continuous location for the OCLFB it is very hard to say if the two types are separated by the OCFLB. This interesting possibility requires further investigation.
CHAPTER 7

Two further case studies under different geophysical conditions

7.1 Introduction

The case study presented in Chapter 6 found an interesting relationship between high spectral width measured by the CUTLASS Finland HF radar and elevated electron temperatures observed by the EISCAT and ESR incoherent scatter radars on closed field lines in the post-midnight sector of magnetic local time. This chapter expands that work by looking in depth at two further case studies. In all three cases a region of high HF spectral width (>200 m s\(^{-1}\)) exists poleward of a region of low width (<200 m s\(^{-1}\)). Each case occurs under quite different geomagnetic conditions. The case study in Chapter 6 occurred during an interval with no observed electrojet activity, the first study in this chapter during a transition from quiet to active conditions with a clear band of ion frictional heating indicating the location of the flow reversal boundary, and the final case during an isolated substorm. These case studies indicate that the relationship between elevated electron temperature and high HF radar spectral width appears on closed field lines after 0300 magnetic local time (MLT) on the nightside. It is not clear whether the same relationship would hold on open field lines, since our analysis of this relationship is restricted in latitude.

The previous study also found two types of high spectral width, one consisted of almost all multiple-peak spectra with up to seven or eight peaks (type A), and the other had a majority of single-peak spectra with a few widely dispersed double- or triple-peak spectra (type B). The two cases presented in this chapter will investigate the possibility that these two types of large spectral width could represent two different generating mechanisms.
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### 7.2 CUTLASS and EISCAT modes used

Two case studies are presented in this chapter both of which make use of both coherent HF radar data from the Finland radar of the CUTLASS, and low elevation incoherent scatter data from the EISCAT mainland VHF system. One of the studies also uses low-elevation data from the EISCAT Svalbard Radar (ESR).

Only CUTLASS Finland (see Chapter 2) data will be presented in these cases and the locations of the field-of-view and beams 7 and 9 are shown in Figure 6.1 as for the previous case study. The operating modes used in the two case studies both used range gates of 45 km with the distance to the first range at 180 km. On 22\textsuperscript{nd}/23\textsuperscript{rd} November 1999 the radar was running common mode, which has a dwell time of 7 s on each beam and the scans are synchronised to start at beam 15 every two minutes. On 21\textsuperscript{st}/22\textsuperscript{nd} August 1998 beam 9 was run in high time resolution mode to coincide with the ESR beam. The dwell time was 2 s with the beams scanned in the following order: 15, 9, 14, 9, 13, 9, 12, etc, thus the temporal resolution of beam 9 was 4 s and for the whole scan 64 s.

Both of the case studies presented herein utilise the EISCAT mainland VHF radar (see Chapter 4) in a CP4 type mode. This consists of two low-elevation beams from the VHF radar, beam one has an azimuth to geographic north of 345° and beam two has an azimuth of 359°, Figure 6.1. The elevation of both beams is 30°. Only long pulse data has been included in these studies, which for the elevation of the beam used covers altitudes from approximately 280 km to 1050 km in 20 gates. The ESR, which was running for 2 of the events studied, was directed at an azimuth of 161.6° with an elevation of 30° on 20\textsuperscript{th} December 1998 and 31° on 21\textsuperscript{st} to 22\textsuperscript{nd} August 1998, see Figure 6.1. The long pulse code from the ESR for this scan covers altitudes from approximately 90 km to 470 km in 27 gates.

### 7.3 22\textsuperscript{nd} to 23\textsuperscript{rd} November 1999

#### 7.3.1 WIND magnetic field and solar wind particle observations

During the interval 2000 UT on 22\textsuperscript{nd} November 1999 to 0600 UT on 23\textsuperscript{rd} November 1999 the WIND spacecraft was located at approximately (-13, -67, 15) R\textsubscript{E} in
(X, Y, Z) GSM coordinates. Data from the WIND MFI and SWE instruments are shown in Figure 7.1 (see Chapter 4 for details). The time delay from the data at the spacecraft to be incident on the magnetopause is estimated at 3 ± 15 minutes, no delay has been added to the times described below or on the figure. From 2000 UT to 0330 UT the IMF $B_Z$ (GSM) varied between 0 and +6 nT. From 0330 UT $B_Z$ moved almost linearly from 1 nT to −8 nT at 0600 UT when it turned sharply northwards again within a few minutes. The IMF $B_Y$ component was positive and relatively large (4 to 7 nT) from 2000 UT to 0200 UT when it became ~ 0 nT for 30 minutes before rising steadily to 7 nT at 0330 UT. It remained at 7 nT until 0430 UT when it decreased to −4 nT at 0600 UT then turned sharply in a few minutes to 8 nT. $B_X$ remained negative throughout the interval except for one very brief positive excursion at ~ 0230 UT.

The solar wind velocity was 450 m s$^{-1}$ ± 20 m s$^{-1}$ throughout the interval. The proton density was steady at ~6 cm$^{-3}$ from 2000 UT to 0300 UT after which 3 bursts of enhanced density occurred, each approximately one hour in duration and 12 cm$^{-3}$ in magnitude, starting at ~0310 UT, 0430 UT and 0530 UT. In summary, the solar wind and interplanetary magnetic field (IMF) conditions were relatively stable with $B_Z$ northwards from 2000 UT until ~0330 UT when there was a steady change to $B_Z$ southwards passing 0 nT at 0400 UT.

7.3.2 IMAGE ground magnetometer measurements

Data from the X-component of the IMAGE network shown in Figure 7.2 indicates mainly quiet conditions. There were two small disturbances (~50 nT) in the stations from Sørøya (SOR, ~67.1°N, all coordinates in this chapter are given in AACGM based on Baker and Wing [1989]) to Kilpisjarvi (KIL, ~65.7°N) around ~2045 UT, and again at ~0000 UT both lasting approximately one hour. At ~0045 UT there was a deflection in the magnetic signature at the Bear Island station (BJN, 71.3°N) of -100 nT from the mean field value. This was the station where the largest deflection was seen, smaller deflections were seen poleward and equatorward, decreasing in magnitude the further in latitude away from BJN. The X-component at BJN returned to previous values at 0230 UT when wave activity with an amplitude of ~25 nT and frequency of ~2 mHz ensued in the stations from BJN to Ny Alesund (NAL, 76.0°N). Similar patterns were seen in the stations south of
Figure 7.1. WIND IMF Bx, By, Bz, and solar wind velocity, density and pressure data from 22nd to 23rd November 1999.
Figure 7.2. X-component magnetometer data from the IMAGE array for 22nd to 23rd November 1999. The latitudes are given in magnetic coordinates. The scales are all the same.
BJN but of smaller amplitude of ~10 nT. This wave activity continued around a constant, and small 0-25 nT, offset from the mean field, until 0520 UT when a sharp, short-lived (~5 minutes) bay in the X-component occurred. The bay was negative from Hankasalmi (HAN, ~58.5°N) to SOR and positive from BJN to NAL. Following this bay, all of the measured X-components steadily decreased, the magnitude of the change was largest at BJN where the deflection started at ~0 nT at 0520 UT to ~100nT at 0600 UT and then increased in the same manner from the minimum at 0600 UT. During this decrease, the stations from SOR to Oulujärvi (OUJ, ~60.8°N) observed a wave signature (~30 nT amplitude from 0520 to 0530 UT, then with a smaller amplitude to 0600 UT) with a frequency of ~ 4 mHz in all three components. The amplitude of this wave was much reduced at all the stations north of SOR, similar to the wave signature observed in the first case study. It seems likely that this was another FLR, although not as clear an example as the previous case making it harder to identify where the last closed field line was. Fortunately, as will be described shortly, there was another signature of the OCFLB available in the EISCAT data which was obtained.

7.3.3 EISCAT and CUTLASS radar data

Figure 7.3 presents data from this interval from beam two of the EISCAT VHF radar and beam 9 of CUTLASS Finland for the latitude range 70°N to 78°N. Panels (a) to (d) of Figure 7.3 present the electron density, electron temperature, ion temperature and line-of-sight ion velocity from the EISCAT VHF beam 2 respectively (equivalent to altitudes of approximately 280 km to 510 km). From 2000 UT to 2300 UT the electron density in the latitude range 70.5°N to 74°N was large (>2.7x10¹¹ m⁻³). At 2300 UT the electron density decreased, although remaining structured, until 0200 UT when it returned to levels prior to 2300 UT. The electron temperature observations (Figure 7.3b) exhibited complex structuring from 2300 UT until the end of the interval at all latitudes. The electron temperature enhancements at 2300 UT coincided with the first evidence of enhanced ion temperature which appeared to move equatorward (panel (c)). The subsequent electron temperature enhancements (after 0200 UT) were particularly large.

Three strong and consistent ion frictional heating events were observed, apparent from Figure 7.3c. Ion frictional heating occurs when the imposed electric field changes
Figure 7.3. Data from 22nd to 23rd November 1999. Panels (a) to (d) incoherent scatter data from EISCAT VHF beam 2, electron density, electron temperature, ion temperature and ion line-of-sight velocity (negative values are away from the radar) respectively. Panels (e) and (f) are the CUTLASS Finland beam 9 (e) spectral width and (f) line-of-sight velocity (negative values away from the radar). The data has been separated into three intervals, labelled I, II and III.
direction or magnitude. This changes the ion flow vector $V_i$, but has little immediate effect on the velocity of the more numerous neutral atoms, $V_n$. The ions then collide with the neutrals causing an ion temperature enhancement that is proportional to the square of the vector difference $(V_i - V_n)^2$. Momentum transfer from ions to neutrals (ion drag) causes the neutral velocity $V_n$ to become more aligned (in both magnitude and direction) with the new velocity and thus $(V_i - V_n)^2$ and therefore the ion heating effect is reduced [e.g. Rees and Walker, 1968; St-Maurice and Hanson, 1982; Davies et al., 1999]. The first of the ion frictional heating signatures was the equatorward moving feature that moved from 76°N at 2300 UT to 70.5°N at 2330 UT. This was a weak signature that was collocated with a velocity shear presented in panel (d). The second ion frictional heating signature started at 70.5°N at 0045 UT and moved steadily poleward reaching 75°N at 0130 UT. The third ion frictional heating signature moved equatorward from 76.0°N at 0415 UT to 70.5°N at 0600 UT. These last two features were in the same region as shearing in the velocity and also depletions in the F-region electron density. In general in this interval the line-of-sight ion velocities were highly structured and variable.

Lockwood et al., [1988] demonstrated that such moving bands of ion frictional heating associated with velocity shear such as those identified above, follow the motion of the FRB. The width of the ion frictional heating region is controlled by the length of time for which the difference in velocity between the ions and neutrals is significant and hence $(V_i - V_n)^2$ is large. If the electric field conditions remain stable then the width of the ion frictional heating band will reflect the length of time it takes the neutrals to align with the ions. When the polar cap is contracting (expanding) the FRB is the poleward (equatorward) edge of the region of hot ions [Lockwood and Fuller-Rowell, 1987a; 1987b]. In this case study it seems reasonable to use these ion frictional heating signatures (particularly the last two) as ionospheric proxies for the FRB.

The FRB can in turn be used as a representation of the OCFLB. The FRB will always be equatorward of or equal to the latitude of the OCFLB with two possibilities to cause separation of the two. Regions of high conductivity, which can occur in the auroral region equatorward of the OCFLB, tend to cause a deviation in the plasma flow such that it avoids the high conductivity region and thus moving the FRB equatorward also. The second possibility is viscous interaction with a convection cell on closed field lines, close
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to the OCFLB [e.g. Lockwood et al., 1988]. Fox et al. [1994] demonstrated how such viscous cells could actually often be driven by nightside reconnection, as suggested by Lockwood and Cowley [1992]. Therefore, when the polar cap is contracting the poleward edge of the region of hot ions is a reasonable proxy for the OCFLB, but when the polar cap is expanding the equatorward edge of the hot ions can be on closed field lines and so can be considered as the minimum latitude limit for the OCFLB.

Figure 7.3f presents the line-of-sight velocity from CUTLASS Finland beam 9. The overall form of the CUTLASS velocity data was similar to that from the VHF system in Figure 7.3(d). The CUTLASS and VHF velocity data both show very complex flows from 2000 UT to 0015 UT. An investigation of the global plasma velocity pattern during this time was performed using the spherical harmonic potential fitting of the 'potential map' technique [Ruohoniemi and Baker, 1998], utilising all the northern hemisphere SuperDARN radars. The flow patterns from 2000 UT to 2300 UT were highly complex, although it appeared that the locations of the EISCAT and CUTLASS radar beams were essentially in the region of anti-sunward flow out of the polar cap and as such the location of the FRB could not be located unambiguously during this time. The CUTLASS data indicated that the FRB was close to 70°N shortly after 2330 UT and remained there until the majority of the ionospheric scatter disappeared at 0015 UT. When the ionospheric scatter returned at 0030 UT the FRB identified from spatial plots of the CUTLASS line-of-sight velocities from both radars moved poleward following the motion of the second ion frictional heating signature.

The latitude range of particular interest is 71°N to 72°N as this is the range in which direct comparison between electron temperature and spectral width is made. The OCFLB was likely located poleward of 72°N from 2000 UT to ~2315 UT (reasonable since the prevailing IMF, solar wind and geomagnetic conditions would indicate that the polar cap was reasonably small at this time), from 2315 UT to ~0115 UT the OCFLB was equatorward of 72°N, then for the remainder of the interval (0115 UT to 0600 UT) the OCFLB was located poleward of 72°N. This interpretation agrees with that obtained from the ion frictional heating signatures, namely that in the latitude range 71°N to 72°N the field lines are closed from 2000 UT to 2315 UT, open from 2315 UT to 0115 UT and closed again from 0115 UT to 0600 UT.

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To consider the HF spectral width data in Figure 7.3e the dataset has been split into three distinct subintervals, I - 2000 to 2315 UT, II - 2315 to 0115 UT and III - 0115 to 0600 UT, each of these is delineated by the crossing of a heating signature through the latitude range 71°N to 72°N. The first of these subintervals contained a large region of high spectral width with an ill-defined boundary. In the second, the HF data was patchy and the spectral width data was high where they occurred. In interval III a very definite boundary between high and low spectral width existed and moved in latitude with time. Only interval II had open field lines from 71°N to 72°N assuming the ion frictional heating signatures identified the OCFLB reasonably well. The HF spectral width in interval I did not appear to be related to any elevated electron temperatures. In the third subinterval a well defined gradient in the spectral width was evident, with high values poleward of low values. The equatorward boundary of the region of high spectral width followed the motion of the velocity shear and previously identified ion frictional heating features where they were present. In between the last two ion frictional heating features the high values of spectral width appear to be related more to the electron temperature enhancements, as in the case study in Chapter 6. These transient high spectral width signatures seem (as in the previous case study, and Lester et al. [2001]) to be on closed field lines.

The very different nature of subintervals I and III in spectral width behaviour becomes apparent when comparing the time series for collocated EISCAT and CUTLASS Finland data. This has been done for both the VHF beams and is presented in Figure 7.4a beam 1 (gate 1, ~71.4°N corresponding to beam 7, gate 29 of CUTLASS Finland) and (b) beam 2 (gate 1, ~71.3°N corresponding to beam 8, gate 28 of CUTLASS Finland). As in the first study a height of 300 km is assumed since the elevation angle is indicative of F-region scatter. As before the spectral width is in red, electron temperature is in black and ion temperature is in blue (dotted). At 0115 UT in both VHF beams there is a large spike in the ion temperature corresponding to the poleward motion of the region of ion frictional heating. As this passes through the latitude from which these cells are taken, the spectral width behaviour changes distinctly from being high to being generally low. Then a few minutes after 0530 UT when the ion frictional heating returned equatorward, the spectral width appeared to be returning to its former wider behaviour just before 0600 UT. Within
Figure 7.4. Line plots from overlapping radar cells between (a) EISCAT VHF beam 1, and (b) EISCAT VHF beam 2, and appropriate CUTLASS Finland range cells, within the 71°N to 72°N latitude range. Electron temperature is in black, ion temperature in dotted blue and spectral width in red. The dashed vertical lines indicate the same three intervals as in Figure 7.3.
interval III the OCFLB is poleward of the cells from which the data in Figure 7.4 is taken, thus the observations were again made on closed field lines.

The scatter plots for electron temperature and HF spectral width generated in the same way as for the case in Chapter 6 are presented in Figure 7.5 for the three subintervals. The ion temperature comparison in the region 71°N to 72°N shows no clear effect on spectral width and is therefore not shown here. The ion frictional heating signatures pass through this region only briefly and thus the observed correspondence between large spectral width and the ion frictional heating does not show up in a scatter plot analysis. Figures 7.5a and 7.5b show the relationship during interval I, Figures 7.5c and 7.5d interval II, and Figures 7.5e and 7.5f show the data from interval III. The upper panels are for EISCAT beam 1, the lower panels are for beam 2. There are two different relationships demonstrated by these figures. The data from interval III, when the observations were from a closed field line region, show a similar pattern to that found in the first case study, while the data from interval I show virtually no relationship with HF spectral widths: spectral widths (low and high) are seen but at low electron temperatures. Interval II, the only time when the range of latitudes investigated was on open field lines shows a wide, uncorrelated scattering of data points indicating no relationship between electron temperature and spectral width.

Figure 7.6 presents data from CUTLASS Finland beam 9, (a) spectral width and (b) the estimated number of peaks in the associated power spectra (with a threshold of half the maximum power in the spectrum as in Chapter 6). The first two and a half hours of the interval show very few multiple peak spectra despite a large region of high widths between range gates ~20 to ~40. For this time range the large widths are thought to be on closed field lines for the reasons described previously. The three ion frictional heating signatures have been marked approximately on Figure 7.6 they are shown in black on Panel (a) and red in Panel (b). The first signature is thin and therefore the line represents the middle of it, the second line follows the poleward edge of the second heating signature and the third line shows the equatorward edge of the third signature. Thus the first two lines indicate the approximate location of the OCFLB and the third line shows the most equatorward position the OCFLB could be in. A small extrapolation of the first line indicates that the cluster of multiple-peak spectra with typically four or more peaks (type
Figure 7.5. Electron temperature from the EISCAT VHF against spectral width from CUTLASS Finland. Left column, data from interval I, centre, interval II, and right column interval III. Top row, VHF beam 1, bottom row, VHF beam 2. The data is restricted to 71°N to 72°N.
Figure 7.6. (a) Spectral width for 22nd to 23rd November 1999 plotted for range gate against UT. (b) The number of peaks identified in the power spectra for the same data (a peak being identified if it is larger than 1/2 the power of the largest peak). The three diagonal lines (black on (a) and red on (b)) show the approximate motion of the three ion frictional heating signatures from Figure 7.3.
A) between gates 40 and 55 just before 2300 UT was probably on open field lines. The small cluster of double- and triple-peak spectra at the same time but between gates 20 to 35 was on closed field lines. Between the first two ion frictional heating signatures where the field lines are most likely open, there are many multiple-peak spectra. Within the second heating signature (just below the line showing the location of its poleward edge) there are four or five double peak spectra but mostly single-peak, from Figure 7.3f it can be seen that some of this low width, single-peak data has been identified as ground scatter. Poleward of the second heating signature there are more multiple-peak spectra particularly from 0100 to 0130 UT. Between 0130 UT and 0415 UT it is not clear where the OCFLB is located although no signatures of a significant motion of the OCFLB occurred until the third heating event and the data equatorward of range gate 40 (at least) is therefore probably on closed field lines. The high widths at gates less than 40 appear to consist mainly of single-peak spectra with a few two or three-peak spectra widely dispersed – as referred to in Chapter 6 as type B.

The final heating signature appeared at 0415 UT and including the change in the rate of motion of the equatorward edge of the signature at ~0430 UT the line delineates the region of high widths very clearly. The very high spectral widths at the end of the interval from ~0430 UT could be related to the cusp since the strongly positive $B_y$ component in the IMF would shift the cusp to earlier MLT. There are several indicators that this could be cusp data even at this early MLT (0430 – 0600 UT corresponds to about 0645 – 0815 MLT): the presence of large and variable spectral widths in the CUTLASS data [e.g. Baker et al., 1995], the poleward moving forms in the velocity data (this is clearer in the EISCAT ion velocity data) [e.g. Thorolfsson et al., 2000; Lockwood et al., 2000], the increase in electron density following the depletion due to the passage of the ion frictional heating region (likely due to cusp precipitation [Yeoman et al., 1997; Newell and Meng, 1992]). Perhaps most indicative is the oppositely directed motion of the FRB and the ions from ~0430 UT. This behaviour is consistent with a non-adiaroic OCFLB (adiaroic means no flow across the boundary, i.e. no particles moving from the closed region to the open region of magnetic field) implying that there is reconnection occurring in this local time sector which opens field lines and moves them into the polar cap. The equatorward motion of the OCFLB as depicted by the ion frictional heating also indicates that the size of the polar cap is increasing, consistent with more open flux being
added to it. It is hard to separate the spectra found in the presence of ion frictional heating and those located in the cusp in this final part of the data, indeed some of the ion frictional heating may be due to large flows observed in the cusp.

The high widths in the last hour and three-quarters appear to be split into two regions, one from 0415 UT to 0530 UT separated from the other region which starts at 0445 UT at higher latitudes. These two regions are partly separated by a small area of ground scatter and could all be part of the same feature. The second, more poleward region has a distribution of the number of peaks similar to that one might expect from the cusp in the description of André et al. [1999; 2000a, 2000b]. The more poleward in the region of hot ions one looks the more clustered the multiple-peak spectra are and the more peaks they have. It seems likely therefore that the truly multiple-peak spectra are related to the cusp, and in the region of ion frictional heating the spectra are single, double and occasionally triple-peak.

Figure 7.7 shows a section of the final region of high spectral widths from range gates 30 to 40, 0501 UT to 0517 UT with the normalised power spectral overlaid on each observation. As in Chapter 6 the lowest spectral widths have simple, narrow spectra, but as the fitted widths increase so in general does the complexity of the spectra.

### 7.4 21st to 22nd August 1998

The final case study presented here is taken from 2100 UT on 21st August 1998 to 0100 UT on 22nd August 1998. The ionospheric flows in this interval have been studied previously as an example of isolated substorm plasma flow behaviour [Yeoman et al., 2000]. The CUTLASS Finland radar was running a high time resolution mode on beam 9 which is ideal for comparison with the low elevation mode of the ESR that was running during the SP-UK-CSUB EISCAT and ESR campaign at that time. The mainland EISCAT VHF system was running in split beam, CP4 type mode during the night time experiments undertaken.

Data from the ESR are presented in Figure 7.8 along with the high time resolution observations from beam 9 of CUTLASS Finland. Panels (a) to(d) show electron density, electron temperature, ion temperature and line-of-sight ion velocity from the ESR data.
Figure 7.7. A zoomed in section of the spectral width range gate against UT plot from Figure 7.6. Overlaid on each radar scan for each cell is the corresponding normalised power spectrum for comparison.
Figure 7.8. Data from 21st to 22nd August 1998. Panels (a) to (d) are observations from the ESR radar, electron density, electron temperature, ion temperature and ion line-of-sight velocity (negative values are toward the radar) respectively. Panels (e) and (f) are from beam 9 of CUTLASS Finland, (e) spectral width and (f) line-of-sight velocity (negative values are away from the radar).
respectively. Panels (e) and (f) show the spectral width and line-of-sight velocity from CUTLASS Finland beam 9. The onset of the substorm growth phase begins at ~2115 UT, with expansion onset from 2250 UT and full recovery by ~2340 UT [Yeoman et al., 2000]. There are two equatorward moving auroral forms observed between 2120 and 2220 UT in the electron and ion temperature data (panels (b) and (c) of Figure 7.8). These features are typical of the growth phase of an isolated substorm [Persson et al., 1994]. Then after the expansion phase onset at 2250 UT (identified by Pi2 pulsations in the IMAGE ground magnetometer network [Yeoman et al., 2000]) there is a poleward expanding auroral form seen in the electron and ion temperature, the substorm associated auroral bulge. Given the large line-of-sight ion velocities and F-region density depletion the elevated ion temperature was thought to be due to ion frictional heating. The ion frictional heating could indicate (as in the November 1999 case study) the motion of the FRB as the substorm expansion phase destroys open flux in the polar cap.

Once the CUTLASS Finland ionospheric scatter becomes dominant over the ground scatter at ~2140 UT the equatorward edge of the region of scatter moves equatorward in accordance with previous substorm growth phase studies [Lewis et al., 1997], (although this is out of the latitude range of Figure 7.8e and 7.8f). The line-of-sight velocities (where there is ionospheric scatter) are comparable to those seen by the ESR and VHF radar as shown by Davies et al. [2000] (the ESR data is presented in Figure 7.8d). Yeoman et al. [2000] ascribed the first dropout of ionospheric data (at 2300 UT) to a reduced number of irregularities due to suppressed electric fields. The second (at 2310 UT) they assumed was due to the changing HF propagation conditions as the substorm progressed [Gauld et al., 2002]. Then as the substorm subsided the ionospheric scatter returned and moved poleward.

The beam-swinging analysis performed by Yeoman et al., [2000] on the data from the two VHF beams indicates the location of the FRB for the majority of the interval from 2230 to 2330 UT. The FRB moves equatorward of 72°N at approximately 2245 UT and then returns poleward of 72°N at about 2305 UT, for the rest of the interval it would seem to be above 72°N given the absence of magnetic activity before the substorm onset and the expanded auroral bulge later on. Little backscatter is observed between 71°N and 72°N during these 20 minutes, thus for the majority of the interval which is analysed and
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presented as a scatter plot of electron temperature and HF spectral widths as for the other two cases (Figure 7.9) the data are from regions of the ionosphere threaded by closed field lines: Figure 7.9a is for the EISCAT beam 1 data, 7.9b for the EISCAT beam 2 and 7.9c for the ESR. F-region scatter is assumed from the range of the data although the elevation angle data in this interval is unclear. The form of the relationship between electron temperature and spectral width does not resemble that of case study one at all. Firstly the overall electron temperature level is \( \sim 1000 \) K higher than previously. This could be attributed to the increase in solar radiation due to the time of year although the electron density is not increased. Secondly there is no distinct absence of low spectral widths at high electron temperatures, as in the pre-midnight UT half of the second case study. If there is any dependence, it is that spectral widths decrease slightly with increased electron temperature.

A section of the interval is presented in Figure 7.10, showing (a) fitted line-of-sight velocity, (b) fitted spectral width, and (c) the number of peaks (above half the maximum power). There appear to be distinct regions of multiple-peak spectra in Panel (c), notably between 2250 UT and 2255 UT, between gates 20 and 25, and also from \( \sim 2345 \) UT between gates 30 and 40. Also many of the spectra from 2200 UT to 2240 UT in the range gates from 30 to 55 have more than one peak, but these are more dispersed among the single-peak spectra. What might be causing the multiple-peak spectra in this interval is much less clear than for the other two cases studied. The velocities are variable, in particular the small stripe of multiple-peak spectra from 2250 UT to 2255 UT seems to be associated with a small region of localised rapid plasma motion which appears quite structured.

The multiple-peak spectra from 2345 UT seem to be related to very variable velocity measurements located at the poleward edge of the main scatter region. Figure 7.11 shows some of the spectra from this time overlaid on the fitted widths. Note that the different sizes of each scan of beam 9 are a result of the resolution with which the time of each scan is saved, to the nearest second, however each scan integration time is consistent to millisecond accuracy (2 s in this mode). The multiple-peak spectra are not restricted to the very highest fitted widths, they seem to occur from 200 m s\(^{-1}\) upwards. There are also some very large fitted widths with only a single peak as well. The sudden change from
Electron temperature

Figure 7.9. Electron temperature from the EISCAT and ESR radars against spectral width from CUTLASS Finland for the entire interval. (a) EISCAT VHF beam 1, (b) EISCAT VHF beam 2, and (c) ESR. The data is restricted to 71°N to 72°N.
Figure 7.10. (a) Line-of-sight velocity for 21 August 1998 plotted for range gate against UT, (b) spectral width, and (c) the number of peaks identified in the power spectra for the same data (a peak being identified if it is larger than 1/2 the power of the largest peak).
Figure 7.11. A zoomed in section of the spectral width range gate against UT plot from Figure 7.10. Overlaid on each radar scan for each cell is the corresponding normalised power spectrum for comparison.
smoothly varying flow to the rapidly fluctuating velocities associated with the large widths and multiple-peaks could mean one of two things, either the region generating the scatter is significantly different or some physical change has occurred within one region of scatter. There is a plausible physical explanation, i.e. that the more poleward, more variable data is the result of a temporally varying electric field as suggested by André et al. [1999; 2000a; 2000b] since this is capable of producing widely varying widths and velocities and multiple-peak spectra. The elevation angle data indicates that there is no sudden change in the scatter producing region at this time. It therefore seems likely that these multiple-peak spectra have been produced by undersampling as suggested by André et al.

7.5 Discussion

The two case studies presented in this chapter and the original case study in Chapter 6 cover a varied set of geophysical conditions all of which have high spectral width data from the CUTLASS Finland coherent HF radar. There is evidence that the turbulence creating these large widths is generated by more than one physical mechanism, although it is possible to have a dominant mechanism. The evidence presented in the three case studies can be summarised in three key points, (i) high widths (>200 m s⁻¹) originate from both single and multiple-peak spectra, (ii) the relationship between electron temperature and high spectral width is not consistent in the different intervals, and (iii) high spectral width can occur on both open and closed field lines. That more than one generating mechanism probably exists is unsurprising in such a dynamically complex region as the ionosphere. The question following on from this is can one associate particular mechanisms with specific geophysical conditions and/or locations and perhaps specific forms of the power spectra. This has been done on the dayside with multiple-peak spectra associated with the cusp [Baker et al., 1995; André et al., 1999; 2000a] and for double-peak spectra associated with the LLBL [Schiffler et al., 1997; Huber and Sofko, 2000]. The aim here is to apply similar procedures on the nightside. The physical mechanisms proposed for the dayside, namely temporal electric field variations in the Pc1/Pc2 frequency band [André et al., 1999; 2000a] and small scale vortices in the plasma
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[Schiffler et al., 1997; Huber and Sofko., 2000; André et al., 2000b] are equally applicable to the nightside.

The analysis of the 20th December 1998 case study indicated a relationship between electron temperature and spectral width, namely that high spectral width is associated with elevated electron temperatures, but not vice versa. This analysis took place at ~300 km altitude, 71°N to 72°N and on closed field lines in the post-midnight sector. The spectra that were observed in the region of high spectral width were primarily single-peak spectra with a cluster of multiple-peak spectra between 0200 to 0230 UT and ~73°N to ~83°N. There were more observations of multiple-peak spectra in the high spectral width region than in the low spectral width region. In the region of detailed investigation between 71°N and 72°N there are virtually no multiple-peak spectra. Elevated electron temperature in incoherent scatter radar data is a good indicator that there is particle precipitation present [Kofinan and Wickwar, 1984] and this is often also related to field aligned currents. Since high spectral widths are associated with high electron temperatures in this interval in the region 71°N to 72°N it is reasonable to say that the large spectral widths could be related to precipitation. It should be noted that this is not a straightforward conclusion since there are many low spectral widths at high electron temperatures, but there are no high spectral widths at low electron temperatures. The lifetime and drift of the backscatter targets could have an effect on the data that were observed, however the lifetimes of the irregularities are short, of the order of seconds and will not have a large effect. Thus at this time elevated electron temperature appears to be necessary, but not sufficient, to give high spectral widths. This perhaps shows us that several processes are in progress that have different effects on the ionospheric plasma.

If for example the high electron temperature is indicative of precipitation then there could be vortices caused by the mechanism suggested by Schiffler et al. [1997] and Huber and Sofko, [2000]. These would be discrete objects and may not cause large widths in every range cell analysed but would all be within the region of high electron temperature. There is also optical auroral activity in this region at this time verifying the presence of particle precipitation (see Chapter 6). Whether there is likely to be filamentary particle precipitation, suitable for the generation of vortices of a scale size less than that of the radar cell, remains unclear, but the fact that precipitation is present is supporting
evidence that high spectral widths may be generated in this fashion. The fact that there are almost no multiple-peak spectra in the region 71°N to 72°N however, does not support the vortex idea and also the region of optical activity extends equatorward of the high spectral width values. The comparison with ion temperatures is unrevealing except to say that there is no obvious correlation between the spectral width and the ion temperatures in this interval. As the second case shows this is not always the case.

The second case study, 22nd to 23rd November 1999 is split into three parts, the first (2000 UT to 2315 UT) has a poorly defined boundary between high and low spectral width. The line-of-sight velocities in this interval are also highly variable indicating a highly turbulent plasma environment. The vast majority of the coherent power spectra in this part of the interval have only one peak indicating that neither the temporal electric field, nor the vortex mechanism for generating high spectral width is likely to be present. It seems that the high spectral width for the most part is due simply to the variation of the line-of-sight velocity about a central value during the integration time in a regime where the velocity is very variable. The analysis of electron temperature and spectral width for this part of the interval indicates no clear relationship between the two parameters. This is not to say that there is no precipitation going on as the structure in the electron density and electron temperature indicate that there most likely is precipitation. The first interval of this case study is probably on closed field lines given the geophysical conditions and the possible FRB motion equatorward at ~2300 UT (shown in the ion temperature) during this time. This conflicts with the first case study electron temperature comparison results since that was also on closed field lines. The main difference between these two intervals is the data location in MLT, in this case the data are from the pre-midnight sector.

The analysis of the second subinterval (from 2315 UT to 0115 UT) is the only time in any of the case studies when the latitude range tested (71°N to 72°N) is thought to be on open field lines. The electron temperature and spectral width show no correlation at all during this short interval.

The third subinterval (from 0115 UT to 0600 UT) has a clear example of ion frictional heating at a velocity shear indicating the location of the FRB. This in turn gives an approximate location for the OCFLB. The behaviour of the spectral width parameter changes dramatically as the FRB passes poleward of the region being analysed. Once the
analysis is on closed field lines again (0115 UT to 0600 UT) the relationship of electron
temperature to spectral width is similar to the first case study. The power spectra at the
latitudes being analysed for this relationship again have mainly single peaks. Therefore as
in the first interval there is no evidence for the presence of vortices in the region where
large spectral widths were found to be related to high electron temperatures. However,
the power spectra in the region around and above the second ion frictional heating event
and FRB have more than one peak (typically two peaks) and such a velocity shear could
cause vortices by the Kelvin-Helmholtz instability. The velocity shear itself could also
introduce double-peak spectra.

In the last hour and a half of the data it is difficult to tell which of the spectra are
related to ion frictional heating and which are due to the cusp, most of the spectra in this
region have several peaks. The spectral width parameter from the FITACF software in
this last section of the data is very large as FITACF reaches the limits of its ability to fit to
these difficult spectra. It is likely that part of this is early cusp activity due to the large,
positive $B_Y$ at this time. Other indications that these data are from the cusp are the
presence of poleward moving forms [e.g. Thorolfsson et al., 2000; Lockwood et al.,
2000], the increase in electron density probably due to soft precipitation such as is
observed in the cusp region [Yeoman et al., 1997; Newell and Meng, 1992], and the
opposite motion of the FRB and plasma flow at this time, indicating a non-adiaroic
OCFLB.

The final case study is an example of spectral width behaviour during an isolated
substorm following a prolonged period of northward IMF. The previous two case studies
considered alone would lead one towards the conclusion that the electron temperature to
spectral width relationship found in the first case study happens on closed field lines after
~0300 MLT. In the third case study there is no obvious relationship between the two
parameters, despite the analysis being performed on closed field lines for the vast majority
of the data. However the third case is before the 0300 MLT limit and also the electron
temperature is much higher than in either of the two previous studies, in general nearly
1000K larger. This could be due to the time of year in which this case study occurs. The
solar illumination, and hence atmospheric ionisation, is high in August whereas in the
other two studies, conducted in late November and December, the illumination is low.
Although one might expect the observed electron density to also be increased in summer this need not be the case since other processes may deplete the electron density. In particular in this case there is ion frictional heating also present and this is known to reduce the electron density.

The HF power spectra are also somewhat different in the final case with regions of many multiple-peak spectra occurring sporadically within areas where single-peak spectral dominate. The final burst of multiple peak spectra starting at 2345 UT occurs in conjunction with both large widths and rapidly fluctuating velocity measurements suggesting that this could be a result of the mechanism suggested by André et al. [1999; 2000a; 2000b]. The elevation angle data suggests that the sudden change with latitude from single to multiple component spectra is the result of the location of the generating mechanism, not the effect of observing two different scattering regions.

The first case study and the final part of the second study are the times during which there is a coincidence between elevated electron temperature and the high HF spectral width. These intervals are both approximately located between 0300 and 0800 MLT whereas the other intervals are in the range 2200 to 0300 MLT. The discriminating factor seems to be whether the data are from before or after ~0300 MLT on the nightside. The statistical analysis of the Finland spectral widths in Chapter 5 also indicated a split in the behaviour of the spectral width, although this was closer to 2200 MLT, the difference from 0300 MLT could be a result of the averaging process. The one brief interval of open field line data analysed indicated no relationship between electron temperature and spectral width.

7.6 Summary
Two intervals of data with combined measurements from the CUTLASS Finland coherent HF radar and the EISCAT and ESR radars have been investigated. A comparative analysis of electron temperature data from the incoherent scatter radars and spectral width data from the Finland coherent radar performed at an altitude of ~300 km, 71°N to 72°N finds a relationship between the two parameters in two of the case studies. The following key points have been identified:
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(1) The relationship between electron temperature from the incoherent radar data and spectral width from the coherent radar data is not unique, nor is it universal. It appears to occur on closed field lines in the range 0300 to 0800 MLT (0800 MLT is the limit of the observations presented here).

(2) The power spectra from the coherent radar in the regions of high spectral width have both single and multiple-peaks. In general the single, wide peaks dominate, particularly at lower latitudes.

(3) The regions of high spectral width occur on both open and closed field lines. The appearance of high widths on closed field lines seems to be related to transient phenomena as suggested by Lester et al. [2001] and further reinforced with the current case studies.

(4) The ion frictional heating in the November 1999 case is associated with large spectral widths in coherent radar data with more multiple-peaked spectra.

(5) Several causes of high spectral width on the nightside seem to exist, therefore its use as an ionospheric proxy must be approached with caution.
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The phenomenon of large HF Doppler spectral widths in the dayside ionosphere has already received much attention. Indeed the large spectral widths on the dayside are often used as a proxy for the low altitude cusp. Similar high spectral widths are also frequently present on the nightside but significant investigation into this related phenomenon has not so far been carried out. Suggestions have been made for the mechanisms generating high spectral widths in the cusp region. Similarly the gradient between low and high spectral width on the dayside has been associated with the OCFLB. So far no specific mechanism has been identified as the cause of high spectral width on the nightside, although both of the mechanisms identified for the dayside are applicable to the nightside as well. Electric field variations of the appropriate frequency for the André and co-workers undersampling mechanism [André et al., 1999; 2000a; 2000b] have been observed in the auroral region [Gurnett et al., 1984; Gurnett, 1991]. Also the precipitation and field-aligned currents that are observed on the nightside could create conditions for the formation of small plasma vortices, the mechanism for generating double-peak spectra suggested by Schiffler et al. [1997] and Huber and Sofko [2000]. The frequently observed sharp gradient between low and high spectral width on the nightside would lend itself well for use as an ionospheric proxy for tracking some part of magnetospheric dynamics. Two suggestions have been put forward to explain the nightside spectral width gradient, one that it represents the OCFLB and the other that it shows the change from the central plasma sheet to the boundary plasma sheet. If it were to be proven that the spectral width gradient on the nightside shows the change from open to closed field lines, it could be a very useful tool in studies of reconnection, and polar cap size. As yet there has not been enough investigation to determine which if either of these proposals is the correct interpretation. This thesis aims to redress the imbalance between the knowledge of the spectral width parameter in the dayside and nightside ionosphere.
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8.1 Conclusions regarding nightside spectral width

Following the statistical results presented in Chapter 5 six key observations regarding the behaviour of the spectral width in the southern and northern hemispheres on the nightside have been made: i) radars with the same pointing directions observe similar characteristics on a statistical basis; ii) a latitudinal dependence related to magnetic local time is found in both hemispheres for both azimuthal and meridional radar beams; iii) a seasonal dependence of the spectral width is observed by all the radars investigated, which show a marked absence of latitudinal dependence during the summer months on the nightside; iv) in general the Syowa East spectral width tends to be larger than that from Iceland East; v) all three radars used observe a decrease in the average spectral width values in all or part of the pre-midnight sector, and vi) the highest spectral widths seem to appear on both open and closed field lines.

Points (i) and (ii) indicate that the cause of high spectral width is magnetospheric in origin rather than a local phenomenon in the ionosphere. Point (iii) suggests that either the propagation of the HF radio waves to regions of high spectral width or the generating mechanism(s) for high spectral width is affected by solar illumination or other seasonal effects. Point (iv) suggests that the radar beams from each of these two radars are subject either to different instrumental or propagation effects, or different geophysical conditions due to their locations, although this result has been shown to be most likely due to geophysical effects. Point (v) shows a distinct difference in the pre- and post-midnight sector spectral widths. Point (vi) leads to the conclusion that, in general on the nightside, the boundary between low and high spectral width will not be a good proxy for the open/closed field line boundary. In addition to this the post-midnight average spectral widths for Iceland East and Finland are also different, with the Iceland East data showing a large proportion of the highest widths on closed field lines. This has been attributed to the different orientation of the two radars.

The fifth and sixth observations mentioned above are reflected in the case study data presented in Chapters 6 and 7. The case studies show that large spectral widths are indeed observed on both open and closed field lines and in conjunction with the incoherent scatter measurements it would seem that there is a change in the relationship of spectral width to electron temperature on closed field lines (and therefore possibly to
precipitating particles) at some point between the pre- and post-midnight sectors. These case studies also show that although at times the spectral width gradient does appear to be a reasonable proxy for the OCFLB, the use of the spectral width gradient as an ionospheric proxy for the OCFLB is not possible in all circumstances. Transient events such as enhancements in electron temperature, increases in flow and velocity shears have been shown to affect the location of the spectral width gradient. Thus utilising the nightside spectral width gradient as an automated proxy for the OCFLB seems to have little future, however in individual cases it may prove useful if applied with care. The conclusions from the case studies presented here suggest that it may be possible to understand the location of the spectral width gradient by following the particle loss processes in the inner magnetosphere, for example with substorms (as in Lester et al. [2001]).

In terms of the mechanisms that are causing the large spectral widths the observations in Chapter 5 indicate that there is probably more than one mechanism present, perhaps one on open field lines and another on closed. The observations also imply that whatever the mechanism(s), it (they) is (are) more prominent, or occur(s) more often in the post-midnight sector. The seasonal variation in the value of the average spectral widths found in Chapter 5 indicates that the mechanism(s) are either less active or more attenuated during the summer months of a given hemisphere. Given that the origin of the high spectral widths appears to be magnetospheric in origin it would seem that it is the summer ionospheric conditions that reduce the effect of the mechanism(s) on the spectral width values.

The observations in Chapters 6 and 7 regarding the form of the Doppler power spectra also indicate two different mechanisms for spectral width. One which produces clusters of spectra with many peaks (type A spectral width) and one which creates mainly single-peak spectra with two or three-peak spectra widely dispersed (type B spectral width). The two mechanisms already proposed for the dayside could create these two different types of large spectral width. Type A fits the description of power spectra resulting from the undersampling of temporally varying electric fields as described by André et al. [1999; 2000a; 2000b]. At least two examples of large and variable spectral width coincident with variable velocity and multiple-peak spectra were found. Type B appears to fit the mechanism of Schipfer et al. [1997] and Huber and Sofko [2000]
better, where the presence of small vortices within the radar range cells cause double-peak spectra although there is little direct evidence to support this here. This tentative differentiation between large spectral widths of different types could prove very useful in identifying the cause of the high spectral width with further investigation.

8.2 Future investigations of the spectral width parameter

There remain several questions to be solved in the area of nightside spectral width values. Can the number of peaks in the power spectrum be used to help identify the presence of temporally varying electric fields (0.1 to 5 Hz) or small plasma vortices, or perhaps even as a better proxy for the OCFLB? What is the significance of the nightside spectral width gradient, can it be used as a general proxy or only in specific, carefully identified cases? Why does the azimuthally pointing Iceland East radar observe large, average spectral widths at different latitudes to the Finland radar in the post-midnight sector? What is the origin of the larger spectral widths in the southern hemisphere?

To answer the first two problems the use of satellite data is required. There has, as yet, been no long term comparison of the nightside spectral width gradient to satellite measurements of magnetospheric boundary locations although individual cases have been investigated [Lewis et al., 1997; Dudeney et al., 1998; Lester et al., 2001; Parkinson et al., 2002]. There are two main aims that this comparison would address. (i) The spectral width gradient has been linked to two mutually exclusive proposals for its use as an ionospheric proxy using individual cases of satellite data: that it shows the open/closed field line boundary [Lester et al., 2001], and the central plasma sheet/boundary plasma sheet boundary [Dudeney et al., 1998]. The first aim of this proposed research is therefore to resolve this inconsistency and identify which, if any, magnetospheric boundary the spectral width gradient maps to and under what geophysical conditions. (ii) The root cause of the regions of high spectral width on the nightside is unproven at this time.

Several mechanisms for generating high spectral widths have been suggested, André et al., [1999; 2000a; 2000b] propose that the presence of low frequency (0.1 to 5 Hz) electric field variations causes multiply-peaked power spectra, which results in a large
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and variable spectral width. Schiffler et al., [1997] and Huber and Sofko [2000] suggest that vortices in the plasma velocity, smaller than the spatial and temporal resolution of the radars, create doubly-peaked power spectra. These could also enlarge spectral width values. Identifying where the high spectral width occurs in relation to the possible sources of these mechanisms using satellite measurements will help to find the underlying physical mechanism(s).

It is proposed that SuperDARN data be compared in as many cases as can be found to appropriate satellite particle, wave, electric and magnetic field measurements. The SuperDARN dataset contains measurements for many years and continues to grow with the number of radars in the network increasing as the years progress. There are currently nine operational SuperDARN radars in the northern hemisphere and 6 in the southern hemisphere. There are several sources for low-altitude, polar-orbiting satellite measurements, in the first instance a search would be conducted for DMSP conjunctions with radar fields of view on the nightside using the SSCWeb facility to identify possible times. The FAST satellite would provide two sets of measurements for investigation, both particles and also the DC electric and magnetic fields instruments would be useful in terms of confirming the electric field variation mechanism for generating high spectral width. If possible, use of the NOAA-POES data in collaboration with the Space Environment Centre would be incorporated to locate the auroral oval as identified through particle measurements. The POLAR and CLUSTER spacecraft are other possible sources of suitable measurements.

Once suitable conjunctions with the many radar fields of view were identified a search would then be carried out using the online summary plots from the SuperDARN radars to eliminate those cases where there is no spectral width gradient when the satellite overpass maps to in the radar field of view. It is anticipated that there would be a statistically significant number of conjunctions with nightside spectral width gradients being available. Identification of the magnetospheric boundaries would follow the definitions in Newell et al., [1996]. The cases would be investigated in light of the global geophysical activity (in terms of geomagnetic indices) and IMF conditions prevalent at the time. Given the conclusions of Chapter 5 some dependence on season and MLT may be
discovered. The work in Chapter 5 may also be extended to investigate the effect of the IMF orientation and geomagnetic indices.

The relationship found between elevated electron temperature and high spectral width in Chapters 6 and 7 may perhaps be due to particle precipitation. More direct evidence of the presence of precipitation is required and is likely to be provided by satellite measurements, possibly including satellite auroral imagers. Is the relationship restricted to closed field lines in the 0300 to 0800 MLT sector? The statistical results of Chapter 5 would seem to suggest not. It is proposed that multi-instrument case studies including satellite data be performed to investigate these problems. The specific aims of this work are: (i) to find or eliminate a relationship between particle precipitation and high spectral widths, (ii) to understand the relationship between electron temperature and high spectral width in terms of possible mechanisms and when and where the relationship exists. Incoherent radar, optical imagers and riometers would be used to assess the level and form of precipitation present and pulsation magnetometers would be employed in looking for Pc1/Pc2 pulsations from the ground. An experimental campaign could be organised to give the best conjunction of instruments on the ground and in space. As with any radar experiment, care would be required to identify the most likely time for the occurrence of a suitably located region of high spectral. A winter campaign would be a pre-requisite to allow the possibility of optical measurements (this will also enhance the probability of good HF radar scatter and regions of high spectral width). Arrangements would be made for a high time/space resolution mode to be run on the HF radars to coincide with the location of the incoherent scatter beam.

The remaining problem of how the radar pointing direction and hemisphere affects the spectral width values needs to be investigated in individual cases. Initial investigations indicate that the two radars often observe clearly related spectral width gradients, but by no means always. Such cases need thorough investigation to determine why the average spectral widths in the post-midnight sector are higher at lower latitudes for the Iceland East radar than for the Finland radar. An ideal opportunity to further the interhemispheric spectral width comparison is now available with the presence of the Kerguelen radar conjugate to the Finland radar. Kerguelen has been running for sufficient
time to perform a small statistical study and the possibility for an Iceland East, Finland, Syowa East and Kerguelen case study is now available.
References


Egeland, A., N.C. Maynard, and J. Holtet, Variational electric fields in the polar cusp, paper presented at Conference on Origins of Plasmas and Electric Fields, Sponsored by National Aeronautics and

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Greenspan, M.E., P.B. Anderson, and J.M. Pelagatti, Characteristics of the thermal plasma monitor (SSIES) for the Defense meteorological Satellite Program (DMSP) spacecraft S8 through S10,


La Hoz, C., EISCAT meetings 82/7, 1982.


