AN INVESTIGATION OF HF DATA COMMUNICATION CIRCUITS AT HIGH LATITUDES

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

by

Baljinder Singh Dhanda Department of Engineering University of Leicester

April 1995

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Baljinder Singh Dhanda

ABSTRACT

The high latitude ionosphere forms a highly dynamic and disturbed medium which can severely degrade the performance of hf radio links. Characteristics of the signal which may be affected include signal strength, fading rate and the frequency range over which signals may propagate. Furthermore, large Doppler frequency shifts and spreads may be imposed on the signal due to movements in the ionosphere near to the reflection point.

To investigate these effects, signals from a transmitter located at Clyde River on Baffin Island in the Canadian North West Territories were received near Fairbanks, Alaska and at Alert, Elsmere Island. Doppler spread, signalling error rates and error distribution patterns occurring were measured during one month campaigns in summer 1988 and winter 1989.

Several interesting features were observed:

(a) Large Doppler spreads, often in excess of 10 Hz were frequently observed on the trans-auroral path and their occurrence was well correlated with the average position of the auroral oval relative to the path reflection points.

(b) The bit error rate of low speed FSK signals was not influenced by the level of Doppler spreading observed. Error rate was well correlated with the received signal to noise ratio and was in good agreement with theory. Signal to noise ratio was well correlated with predicted variations in ionisation due to changes in solar zenith angle.

(c) Distribution of errors were related to changes in Doppler spreading. Large Doppler spreads, were correlated with significantly shorter bursts of error was less than when Doppler spreading was small. However, there was no significant correlation with the length of guard space between errors.

This work is of particular relevance to researchers developing high latitude prediction programs and those employing channel simulators to assess communication systems.

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CHAPTER 1 Introduction

Ever since December 1901, when Marconi first successfully transmitted the letters 'SSS' in Morse code by a 313 kHz radio signal from Cornwall, England to Newfoundland, Canada, the ionosphere has played an increasingly important part in global communications. Originally, the propagation of radio waves was thought to be due to a diffraction process until both Kennelly (1902) and Heaviside (1902) independently suggested a conducting layer in the upper atmosphere which could reflect radio waves. This layer, which was for some time known as the Kennelly-Heaviside layer, is the ionosphere. In this chapter, the structure of the ionosphere and the basic equations of high frequency radio propagation within this medium are introduced.

1.1 The Earth's atmosphere

The Earth is surrounded by a layer of gas known as the atmosphere. Several criteria can be used to characterise the atmosphere, including temperature, composition and ionisation. At ground level the atmosphere consists mainly of a mixture of nitrogen and oxygen with small amounts of carbon dioxide, water vapour and inert gases such as argon and neon. This composition changes with altitude, becoming mostly atomic oxygen above about 150 km. At heights greater than 1000 km, gravitational separation becomes important and the proportion of lighter gases increases. In terms of temperature, five regions, illustrated in Figure 1.1, are generally identified.

The chemical processes in the atmosphere are very complex and are beyond the scope of this thesis. However, the affects of changes in the composition of the atmosphere with altitude are an important element in the formation and structure of the ionosphere. A complex, dynamic state of equilibrium exists between the constituent ions and molecules.

1.2 The ionosphere

Above about 50 km, solar radiation causes gases to dissociate. This is the primary source of free electrons in the atmosphere and results in the



Figure 1.1: Temperature distribution with height of the Earth's atmosphere. (After Rishbeth and Garriott, 1969)

formation of the ionosphere. There is a constantly changing equilibrium between production by solar radiation and losses due to recombination which varies with changes in altitude, solar conditions and several other parameters such as time of day, season and lunar tides. The ionosphere can be subdivided into regions associated with peaks in the electron density height profile. These regions are known as the D, E and F regions and are illustrated in Figure 1.2. This figure also illustrates the variation of electron density between day and night, and the affect of solar activity as indicated by sunspot number.

The D region extends from approximately 60 to 95 km with an electron number density typically of the order of 10^{10} m⁻³. This region is important in HF communications since it is the region in which much radio wave absorption occurs. As indicated in Figure 1.2, the electrons and positive ions in the D region usually recombine totally at night.

The E region extends from about 95 to 120 km and has an electron density of around 10^{11} m⁻³ by day with the peak electron density usually occurring at about 105 km. The electron density in this region varies with solar zenith angle, and therefore seasonal, as well as diurnal, changes are evident. Under certain conditions, a phenomenon known as sporadic E (Es) can also occur. At high latitudes the occurrence of sporadic E is associated with geomagnetic activity and can lead to an increase of an order of magnitude or more in electron density. At mid-latitudes, sporadic E is thought to be due to wind shears compressing the ionisation into an intense thin layer only a few kilometres thick. Sporadic E is generally considered to be a good reflector of radio waves but, as the name suggests, it occurrence is difficult to predict.

The F region, which occurs above about 120 km, is very sensitive to solar activity. Electron density in this region is of the order of 10^{12} m⁻³ during the day but can be smaller by a factor of about 10 during the night. The peak density occurs at about 300 km. During the summer, two peaks in electron density often occur, dividing the F region into the F1 and F2 regions. The F1 region always recombines at night and exhibits marked solar control.

The electron density in all regions varies with several parameters including solar activity, season, solar zenith angle (time of day) and even lunar tides



<u>Figure 1.2:</u> Typical electron density profiles for the mid-latitude ionosphere at sunspot maximum and minimum with D, E and F regions indicated. (*After Hargreaves, 1979*)

and is therefore difficult to predict. Figures 1.3 and 1.4 illustrate variations in the electron density profile with time of day and season respectively at a low latitude site. Variations in electron density at high latitudes and the affects of the high latitude ionosphere on propagation are more complex.

1.3 Radio propagation via the ionosphere

The electron density within the E and F regions is sufficiently large to reflect HF radio waves. In this section, the main equations governing the propagation of radio waves within the ionosphere are introduced. A detailed description of ionospheric radio wave propagation can be found in many text books, e.g. Davies (1990) and Hall and Barclay (1989).

1.3.1 Vertical propagation

When a radio wave travels through an ionised medium, the electromagnetic field subjects the free electrons and positive ions to forces which cause them to oscillate. As electrons are much less massive than atoms, they are displaced by a greater amount. The energy imparted to the electrons and ions as potential energy is restored to the wave, as an oscillating electric charge will radiate an electromagnetic wave. However, not all of the energy is reradiated as some energy is lost as heat due to non-elastic collisions between the electrons and ions and the neutral gas molecules.

Neglecting the effect of collisions and the influence of the geomagnetic field, the refractive index, μ , is given by:

$$\mu^2 = 1 - \frac{Ne^2}{\varepsilon_0 m\omega^2} = 1 - \frac{\omega_N^2}{\omega^2}$$
 Equation 1.1

where ω_N is the plasma frequency and is given by:

$$\omega_{N} = \sqrt{\frac{Ne^{2}}{\varepsilon_{0}m}}$$

and:

N is the electron density e is the electron charge m is the electron mass ω is the angular wave frequency (=2πf) $ε_o$ is the permittivity of free space



Figure 1.3: Diurnal changes in electron density profile at Grand Bahama on an average quiet day in March 1959. (After J. W. Wright, unpublished)





(After J. W. Wright, unpublished)

For a vertically propagating wave, the refractive index, μ , becomes equal to zero at the height where the wave frequency and the plasma frequency are equal and the wave is reflected. The maximum frequency of a vertically propagating radio wave which can be reflected by the ionosphere depends on the peak electron density and is known as the *critical* or *penetration* frequency, f_c.

If collisions are now taken into account, the refractive index is complex and is given by:

$$n^{2} = (\mu - i\chi)^{2} = 1 - \frac{\omega_{N}^{2}}{\omega^{2}(1 - i\frac{\upsilon}{\omega})}$$
 Equation 1.2

In this case, μ can never equal zero for any value of ω , but providing that the collision frequency, ν , is small, strong reflections will occur in regions when μ is close to zero. In the region where the radio wave is reflected, the signal is attenuated by a process known as *deviative absorption* given by:

$$\kappa \approx \frac{v}{2c} \left(\frac{1}{\mu} - \mu\right)$$
 (dB/km) Equation 1.3

A radio wave also suffers from *non-deviative absorption* in regions where the collision frequency is high. This is strongest in the D region. Under these circumstances, absorption is given by:

$$\kappa \approx \frac{e^2}{2\varepsilon_0 mc\mu} \cdot \frac{N\nu}{(\omega^2 + \nu^2)}$$
 (dB/km) Equation 1.4

A further important consideration is the influence of the Earth's magnetic field. When a charged particle moves in a magnetic field, it tends to spiral around the magnetic field lines with an angular frequency, known as the gyrofrequency, given by:

$$\omega_{\rm H} = \frac{\rm e}{\rm m} {\rm B}$$
 Equation 1.5

Typical values of gyrofrequency in the Earth's magnetic field are 1.4 MHz for

an electron, 770 Hz for a hydrogen ion, 28 Hz for a singly charged nitrogen molecule and 24 Hz for a singly charged oxygen molecule.

The refractive index when considering the affect of the Earth's magnetic field, but ignoring collisions, is given by:

$$\mu^{2} \approx 1 - \frac{2X(1-X)}{2(1-X) - (Y^{2} \pm Y^{2})}$$
Equation 1.6
Where : $X = \frac{\omega_{N}^{2}}{\omega^{2}}$
and $Y = \frac{\omega_{H}}{\omega}$

The positive sign solution to Equation 1.6 is associated with a wave reflected at normal incidence when X = 1 ($\omega_N = \omega$). This wave is known as the ordinary (O) wave and the height of reflection is independent of any effects due to the magnetic field. The two negative solutions to equation 1.6, at heights where X = 1 - Y and where X = 1 + Y, are associated with waves known as the extraordinary (X) and Z waves respectively. Although there are three possible reflection levels, there are only two possible polarisations, clockwise and anti-clockwise, and the O and Z waves have the same polarisation. At low and mid-latitudes, the extraordinary wave is reflected from the height where X = 1 - Y. At higher latitudes, energy can be coupled from the O to the Z mode allowing the wave to reach the height where X = 1 + Y.

The non-deviative absorption coefficient when both collisions and the magnetic field are considered is given by Equation 1.7. The ordinary wave (+ sign solution) suffers less absorption than the extraordinary wave (- sign solution) for a given electron density. This becomes more pronounced closer to the gyrofrequency as $\kappa \Rightarrow \infty$ when $\omega \Rightarrow \omega_{H}$.

$$\kappa \approx \frac{e^2}{2\varepsilon_0 mc} \frac{N\upsilon}{(\omega \pm \omega_{\rm H})^2 + \upsilon^2}$$
 (dB/km) Equation 1.7

1.3.2 Oblique propagation

There are several theorems, the secant law, Breit and Tuve's theorem and Martyn's equivalent path theorem, which relate certain characteristics of an obliquely propagating wave to those of a wave which, when propagating vertically, is reflected at the same real height. This wave is known as the equivalent vertical wave. The notations used in these theorems are illustrated in Figure 1.5.

<u>The secant law:</u> The relationship between the frequency, f_{ob} , of the wave incident obliquely on a flat ionosphere and the equivalent vertical frequency, $f_{v'}$ is given by:

 $f_{ob} = f_v \sec \phi_o$

Equation 1.8

Where:

 f_{ob} is the frequency of the obliquely propagating wave,

- f_v is the equivalent vertical frequency and
- $ø_0$ is the angle between the vertical and the ray at the bottom of the layer.

<u>Breit and Tuve's theorem</u>: The time taken to traverse the actual (curved) path, TBR, is the same as that which would be taken to traverse the (triangular) path, TAR, in free space.

<u>Martyn's equivalent path theorem</u>: The virtual heights of reflection, h'_r , of the obliquely propagating wave and the vertical wave are equal.

The secant law needs to be modified for distances greater than 500 km as effects due to the Earth's curvature become important. A correction factor, k, is introduced in Equation 1.9 to compensate for this. The correction factor has values between 1.0 and 1.2, depending on the electron density profile and path length.

 $f_{ob} = k f_v \sec \phi_o$

Equation 1.9



Figure 1.5: Diagram illustrating the geometry employed with the Secant Law. (After Davies, 1965)

1.3.3 Propagation modes

Radio signals may travel from the transmitter to the receiver via several paths, often involving intermediate ground reflections. Several possible paths are illustrated in Figure 1.6. Often, several such propagation modes may be simultaneously supported (e.g. Figure 1.7).

Ionospheric motion results in small Doppler shifts being imposed on the radio signals. When two or more signals are received due to multi-moded propagation, the varying phase relationship between the constituent signals causes amplitude fading.

At high latitudes, the ionosphere is very much more disturbed and cannot be considered as a smooth reflector. The signal from a single ionospheric reflection may be considered as the sum of a number of signals reflected from nearby points in the ionosphere (Figure 1.8). This is also true (to a lesser extent) at mid-latitudes, however, the generally more rapid movement of irregularities at high latitudes imposes large Doppler shifts on the signal resulting in rapid in-mode (flutter) fading.

1.4 The high latitude ionosphere

Interaction between the solar and geomagnetic fields gives rise to the magnetosphere (Figure 1.9). The magnetosphere is particularly important in influencing the characteristics of the high latitude ionosphere. Near the poles, the Earth's magnetic field lines extend thousands of kilometres into space where they connect with the interplanetary magnetic field (IMF) generated by the Sun. Protons ejected from the Sun are able to spiral down the field lines into the upper atmosphere where they interact with the atmosphere causing several effects, including the aurorae borealis and australis (northern and southern lights).

The region of open magnetic field lines is known as the polar cap and is effectively open to protons from the solar wind. The boundary of open field lines surrounding the cap which connect with the IMF and the closed field lines, approximately form an oval centred on the geomagnetic pole. This region is known as the auroral oval. Feldstein & Starkov (1967) demonstrated that the boundaries of the auroral oval varied depending on

1.7



<u>Figure 1.6:</u> Examples of different propagation paths. (*After Warrington, 1986*)



Figure 1.7: Example of two moded propagation. (After Warrington, 1986)



Figure 1.8: Representation of signals being reflected from nearby points in a rough reflector.

(After Warrington, 1986)





geomagnetic conditions. Their results are illustrated in Figure 1.10.

During times of high solar activity, the energy and concentration of incoming solar protons can increase, leading to an increase in electron density in the ionosphere. Consequently, during winter when the ionosphere may receive little or no direct solar illumination, the characteristics of the high latitude ionosphere are still influenced by solar activity. Particle precipitation augments the normal ionisation produced by solar illumination at all altitudes resulting in higher critical frequencies. However, the increase in ionisation in the D region can also increase absorption levels. Two different categories of absorption are caused by particle precipitation in the high latitude ionosphere: polar cap absorption (PCA) and auroral absorption (AA).

The high latitude ionosphere is discussed further in Chapter 2.

1.5 Aims of the present investigation

In this chapter, the basic characteristics of the ionosphere and the equations governing the propagation of radio waves within this medium have been briefly described. However, the propagation characteristics have not been related to the effects observed on communication systems. The aim of this investigation is to study the effects of the high latitude ionosphere on radio communication links; these topics will be considered in the following two chapters.





CHAPTER 2 Review of High Latitude Propagation Characteristics

Many researchers have attempted to correlate high latitude phenomena, particularly those associated with the auroral oval, to effects observed on radio links. In this chapter the results and conclusions of HF experiments reported in the literature are discussed. The locations of transmitting and receiving sites discussed with respect to particular experiments reviewed in this chapter are presented in Figure 2.1, together with an illustration of the mean position of the auroral oval at 12 UT for moderate geomagnetic conditions.

2.1 Absorption at high latitudes

Absorption is one of the main factors affecting HF propagation, and many of the results discussed in this chapter are due to this phenomenon. At high latitudes, there are two distinct forms of absorption, each with different characteristics: Polar Cap Absorption and Auroral absorption.

2.1.1 Polar Cap Absorption (PCA)

PCA events are due to protons with energies ranging from 1 to 400 MeV entering the atmosphere and producing ionisation by collisions with atmospheric gases. The protons usually originate from a solar flare and typically arrive 30 minutes to several hours after the flare. The ionisation generated by this effect is concentrated toward the end of the trail in the Earths atmosphere as air density is greater at lower altitudes. This enhanced ionisation occurs over most of the polar cap and causes intense absorption of HF radio signals at geomagnetic latitudes as low as 60° on some occasions.

Landmark (1968) correlated the occurrence of PCA events with solar activity as measured by sun spot number. This relationship is illustrated in Figure 2.2. A typical PCA event can last between 1 and 10 days and calculations by Hunsucker and Bates (1969), based on riometer observations, indicate that the absorption can exceed 100 dB at 12 MHz on a typical trans-polar path. The absorption is generally 4 to 5 times greater during the day since, at night, free electrons attach to neutral atoms or molecules to form stable negative ions



<u>Figure 2.1:</u> Locations of experimental sites discussed in Chapters 2 and 3 with a representation of the auroral oval at 12 UT during moderate geomagnetic conditions.

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Figure 2.2: Occurrence frequency of polar cap absorption events compared with smooth sun spot numbers. (After Landmark, 1968)

(Hargreaves (1979)). According to Jelly (1963), during all but the weakest PCAs, HF propagation is either not possible or is very difficult. Owren and Leif (1963), however, found that there were indications that weak PCA's affected propagation on a path between College, Alaska and Kiruna, Sweden more than stronger events. They reasoned that during times of stronger storms, a signal may propagate via a non-great-circle path (NGC), so avoiding the D region where absorption is taking place, and thus a circuit might be disrupted more by a weak storm.

NGC propagation is more prevalent at high latitudes where a multitude of small scale irregularities exist, particularly within the auroral oval. Frequently, a propagation mode via strong horizontal gradients in electron density away from the mean ray-path can provide an alternative path. This can result in an interfering signal degrading the communication link. However, NGC modes can provide the only path available when the direct path is affected by localised absorption.

2.1.2 Auroral Absorption (AA)

Unlike PCAs, which vary uniformly over a large area with time, auroral absorption is characterised by its rapidly varying intensity with time and space. AA is thought to be due to precipitated electrons with energies of approximately 10 keV which penetrate down to the D region where they cause increased ionisation. Holt *et al.* (1962) and Parthasarathy and Berkey (1965) reported that auroral absorption is a localised phenomenon, occurring only over a few hundred kilometres and, although auroral absorption usually accompanies visible aurora (Hunsucker and Bates (1969)), the two are not always correlated closely in position. Basler (1963) found that the peak in auroral absorption generally occurred 1° to 2° south of the peak of the auroral zone. Figure 2.3 illustrates the percentage of time that auroral absorption exceeded 1 dB measured by riometer at 30 MHz as a function of latitude and mean geomagnetic time.

Electron precipitation responsible for aurora in the morning zone can be divided into two groups characterised by energy (Sharp and Johnson (1968)). Electrons from 60° to 75° latitude typically have energies in excess of 10keV, whereas precipitating electrons between 75° and 80° are softer (around 1keV). Increased radio-wave absorption is therefore more likely to be encountered



Figure 2.3: Percentage of the time that auroral radio wave absorption of 1.0 dB or more occurred at 30 MHz. (Data plotted as a function of geomagnetic latitude and mean geomagnetic time.) (After Hartz et al., 1963)

between 60° and 70° magnetic latitude during mornings in disturbed periods.

2.2 Observed characteristics of signals propagating at high latitudes

Between March 1959 and June 1960, Egan and Peterson (1960) made signal amplitude recordings continuously on 12 and 18 MHz signals transmitted over several high latitude paths. They found that a link between College, Alaska and Boston, Massachusetts was the most sensitive to auroral zone absorption and critical frequency variations. This was not unexpected since a relatively long portion of the path lay within the auroral zone. However, a link between Thule, Greenland and Stanford, California tended to have an inverse correlation between the number of hours of successful signal reception and general geomagnetic disturbances. Overall, each circuit displayed different characteristics and generalisations could not be made between signal characteristics and the level of geomagnetic activity except at times of large disturbance.

In an investigation of HF propagation at high latitudes, Hunsucker (1964) measured the amplitude of an 18 MHz signal transmitted from Thule, Greenland and received at College, Alaska. These measurements were compared with data from a riometer operating at 27.6 MHz. Hunsucker expected riometer measurements to be indicative of auroral conditions and absorption levels, however, no apparent correlation was observed.

The signal behaviour in Hunsucker's and Egan and Peterson's measurements is mainly due to auroral effects being very localised in nature. Holt *et al* (1962) and Parthasarathy and Berkey (1965) found that auroral absorption occurred only over a few hundred kilometres. A more recent experiment was conducted by Thrane (1985). He demonstrated that during moderately disturbed conditions, when absorption as measured by riometer (A_r) was between 0.2 dB and 2 dB, the reliability of a medium distance path within the auroral oval in Northern Norway could be improved. This is illustrated in Figure 2.4. Thrane concluded that weak disturbances were absorbing interfering signals, leading to an increase in signal to noise ratio even though the signal strength was decreased.

In an experiment between Barrow, Alaska and Cedar Rapids, Nebraska,



Figure 2.4: Average reliability curves for a 450 km transmission path in the auroral zone for different degrees of disturbance.

IQuiet $A_r(30 \text{ MHz})<0.1 \text{ dB}$ IIModerately disturbed $0.2 < A_r < 2 \text{ dB}$ IIIDisturbed $A_r>2 \text{ dB}$ (After Thrane, 1985)

Roesler and Bliss (1988) measured many parameters including multipath delay spread, Doppler frequency spread, signal fade depths and rates, signal to noise ratio and bit error rates on FSK transmissions. Although a complete analysis of their data had not been completed in their report, their conclusions, like those of previous researchers, do not appear to be conclusive. They suggested that the most important factor in determining propagation conditions was the level of geomagnetic activity as indicated by the K index. Generally, high activity during the day resulted in propagation blackouts whereas at night, unexpectedly high frequencies sometimes propagated. The most important conclusion was that ionospheric phenomenon within the auroral oval had the potential to either enhance or degrade performance.

At high latitudes, the rate of fading tends to be higher than at mid-latitudes. On trans-auroral paths, fades with periods of less than 1 second, known as flutter fading, often occur. These are often associated with spread F conditions (Goodman (1992)). Koch & Petrie (1962) made measurements of fade rates on a trans-auroral path from Barrow, Alaska to Boulder, Colorado. They observed a small diurnal variation with higher fade rates during the early morning as well as generally higher fade rates during January 1960 than during October 1959 (see Figures 2.5 and 2.6). Fade rates were also generally higher on geomagnetically disturbed days with up to 20 fades per second being observed at times. The depth of fading was smaller during the fast auroral-type flutter fading indicating that there may have been a relatively steady component with a weaker fast fading component whereas the slow fading case could at times be characterised by a Rayleigh distribution.

Hatton (1968) believed that the fading characteristics were related to frequency dispersion and could affect the quality of data transmitted by a variety of modulation types e.g. CW, AM, SSB, FSK and differential phase systems. Measurements of frequency dispersion were undertaken by Lomax (1967) who observed that the spectra of received signals at high latitude paths had very large Doppler spreads when compared to temperate paths as illustrated in Figure 2.7.

Mather *et al.* (1972) found that signals propagating via the F region exhibited greater frequency dispersion than those propagating via E or E_s layers. This dispersion may have been due to multiple reflections within a single mode



Figure 2.5: Diurnal variations of hourly maximum fade rates on the Barrow to Boulder path, October 1959. (Hourly maximum fade rates are exceeded for percentage of time indicated by the curves). (After Koch and Petrie, 1962)



Figure 2.6: Diurnal variations of hourly maximum fade rates on the Barrow to Boulder path, January 1960. (Hourly maximum fade rates are exceeded for percentage of time indicated by the curves). (After Koch and Petrie, 1962)



Figure 2.7: Typical power spectra transmissions from Thule (trans-auroral) and Fort Monmouth (mid-latitude) monitored at Palo Alto. (After Lomax, 1967)

from spread F. However, there was no increase in frequency spread with an increase in geomagnetic activity as measured by K_p .

The concept of a channel scattering function, which relates frequency dispersion to propagation delay and received signal power, was developed by Vincent et al. (1968). A typical example of the channel scattering function, presented in Figure 2.8. Basler et al. (1988) also performed experiments and employed a channel scattering function to indicate the relationship between time delay, Doppler frequency and amplitude of a forward scattered signal. In their experiment, a transmitter and receiver were placed so that, at the frequency of intent, a signal would propagate only via a one hop F layer path. A number of experiments were performed over several paths including a polar cap path from Narssarssuaq, Greenland to Thule, Greenland (Autumn 1984 and Spring 1985) and one in the auroral region between Narssarssuaq and Winter Harbor, Maine (Spring 1986). Their results, presented in Figure 2.9, show that signals propagating via scattering modes away from the mean ray path were both delayed by the increased path length as well as undergoing a Doppler shift. Furthermore, there was a parabolic relationship between Doppler shift and time delay.

Using a specially developed wideband channel sounder, a 2300 km transauroral path from Iqaluit (Frobisher Bay), Canadian N.W.T to Rome, N.Y. was compard by Wagner et al. (1988) with the propagation characteristics of a mid-latitude path. Channel scattering functions were determined relating Doppler spread, Doppler shift, propagation delay and signal power for various propagating modes. The mid-latitude channel was found to be multi-modal but was usually characterised by a single specular return per mode with limited Doppler shift, or Doppler spread (see Figure 2.10(a)). However, the trans-auroral channel displayed variable characteristics, depending on the degree of magnetic disturbance, the position of the reflection point with respect to the auroral oval and the propagation mode. During quiet magnetic conditions and with the path mid-point to the south of the auroral oval, the channel resembled the mid-latitude path, but, at times, each mode was comprised of several multipath components (Figure 2.10(b)). In general, there was slightly more Doppler spread when compared with the midlatitude path. At night however, when the reflection point was located within the boundaries of the oval, much larger Doppler spreads were







Figure 2.9: Comparison of theory and polar data recorded at 1903 UT on October 8 1984 at 10.120 MHz illustrating the relationship between propagation delay and Doppler frequency.

(After Basler et al., 1988)



Figure 2.10: Scattering function obtained from: (a) a one hop F_2 mode for a short mid-latitude path (b) a trans-auroral channel one hop F_1 mode (c) a trans-auroral channel one hop F_1 high ray mode (After Wagner et al., 1988)
observed (Figure 2.10(c)).

2.3 Concluding remarks

The measurements reported in the literature and discussed in this chapter illustrate the difficulty in generalising the characteristic behaviour of HF circuits at high latitudes. Early research demonstrates that geomagnetic activity and absorption measured with riometers are not indicative of the quality of a channel. Absorption has been found on occasion to have enhancing effects when, due to the localised nature of auroral absorption effects, interfering signals are attenuated resulting in improved signal to noise ratio. More recent research indicates a correlation between frequency dispersion and the position of the path reflection point with respect to the auroral oval. There is also evidence of a diurnal variation in fading rate.

CHAPTER 3 Review of signal errors in HF communication systems

In Chapter 2, the characteristics of HF radio signals propagating at high latitudes were discussed. However, a propagating radio signal is of no value for communication purposes unless it conveys information. Various modulation techniques may be employed to include information in the signal, ranging from relatively simple amplitude modulation, which can be analogue or binary, to more complex techniques employing phase and frequency modulation.

Almost all modulation formats have some shortcomings, e.g. FM requires a relatively large bandwidth and phase modulation systems are unreliable over high latitude paths due to the phase fluctuations introduced by numerous rapidly moving irregularities. In the work presented in this thesis, signals from an FSK transmitter located at a high latitude site have been recorded and the signalling error rates and distributions investigated.

3.1 Causes of errors in HF links

Signalling errors may be caused by a variety of affects, the principle ones being poor synchronisation between the transmitter and the receiver, poor signal to noise ratio and inter-symbol interference. These causes are discussed further below. However, errors are also caused by interference from co-channel signals. This phenomenon is difficult to predict, although Gott *et al.* (1983) and Wong *et al* (1985) have attempted to model interference at a single site in the UK. Although co-channel interference is not discussed further in this thesis, provision was made to detect and eliminate its affects on results presented in later chapters.

3.1.1 Synchronisation

The ability to determine bit errors in a received data sequence is dependant upon two factors: (a) knowledge of and (b) synchronising with the transmitted data sequence. Synchronisation can be achieved by prior knowledge of the time of transmission, however, this is dependant on exact timing and is usually not practicable. The first bit of data received could be employed to indicate the start but this may be falsely recognised in a noisy environment. This system is commonly employed on teleprinters where each transmitted character begins with a space. In the investigation described in later chapters of this thesis, synchronisation was achieved by means of a Barker code sequence.

Barker (1953) discovered 3, 7 and 11 bit sequences that, when auto-correlated, produce an output from the correlator equal to n (the length of the sequence) with zero lag when synchronisation is achieved. When the sequences are not synchronised, the output is 0 ± 1 . Later, a longer sequence of 13 bits was discovered and is to date the longest known sequence to exhibit these properties. The four sequences are:

n = 3	+ + <i>=</i>
n = 7	* * * = = * =
n = 11	ф ф ф <i>и и и и</i> ф <i>и и</i> ф и
n = 13	

A longer sequence exhibiting some of these properties can be achieved by combining two sequences. For instance if the 13 bit sequence were denoted by X, then a 39 bit (3 x 13 bits) pseudo sequence could be produced by employing the properties of the 3 bit sequence (+ + -). The new sequence would be:

$x x \overline{x}$

٠٢ ٥٢

Although the output from the correlator is still equal to n when synchronisation is achieved, at other times the output is no longer 0 ± 1 . The auto-correlations for the 13 bit Barker sequence and the 39 bit pseudo Barker sequence are illustrated in Figures 3.1(a) and (b) respectively.

3.1.2 Affect of Signal to Noise Ratio

It has long been known that bit error rate (BER) is related to signal to noise ratio (Shannon (1963), Spaulding (1964)). BER is often defined as the probability, P(e), of any data bit being erroneously received. The relationship



Figure 3.1: Auto-correlation of:

- (a) 13 bit Barker sequence
- (b) 39 bit pseudo-Barker sequence

of P(e) to the received signal and noise powers has been investigated by many workers, for example Shanmugam (1976), Schwartz *et al.* (1966) and Couch II (1983). Their results indicate that P(e) is described by Equation 3.1 which is a function of E_b , the received signal energy per bit, and $N_o/2$, the double sided noise power density spectrum (W/Hz).

$$P(e) = \frac{1}{2} e^{-\frac{(E_b/N_0)}{2}}$$
 Eqn. 3.1

where

and:

S = the average received signal power
N = the average received noise power
T = the bit duration
W = the bandwidth in which the noise power is measured (Hz)

Therefore:

$$\frac{E_{b}}{N_{o}} = \frac{S}{N}WT$$

or,

$$\frac{E_{b}}{N_{o}}\Big|_{dB} = \frac{S}{N}\Big|_{dB} + \log(WT)$$

It should be noted that if WT≈1, then

 $E_b = S.T$, $N_o = \frac{N}{W}$

$$\frac{E_b}{N_o} \approx \frac{S}{N}$$

which is assumed in this thesis.

Equation 3.1 is only valid for the simplest case for binary non-coherent FSK signalling (as employed in the experiment discussed in this thesis) if the noise is assumed to be Gaussian and the the signal is assumed to have a Rician distribution (sinusoid + Gaussian noise). More complex models which assume the signal has a Rayleigh fading distribution, where signals propagating via several modes interfere, are also included in these texts. In these circumstances the error probability is given by Equation 3.2.

$$P(e) = \frac{1}{(2 + E_b/N_o)}$$

Equations 3.1 and 3.2 are presented in graphical form in Figure 3.2.

In both these examples, assumptions are made about the power density spectrum of the noise. Usually the noise is assumed to be Gaussian, however more complex models have been developed which assume different filter characteristics (which can influence the noise distribution), different forms of fading of the received signal and different noise functions. These models are described in detail by Turkmani and Parsons (1987) and Pejanovic *et al.* (1987) who developed similar equations relating P(e) to different filter models and noise functions, including impulse noise.

In practice, the probability of error does not continue to decrease with increasing signal to noise ratio but ultimately asymptotically approaches a limiting value as illustrated in Figure 3.3. Inter-symbol interference is caused by the different time delays in signals propagating along paths of different lengths, resulting in adjacent data segments (symbols) overlapping and interfering. Thus there is a deterioration in performance when the spread of path delays becomes comparable with the bit length. Frequency selective fading of one tone also causes large number of errors regardless of the signal to noise ratios. Further increases in signal power have minimal effect on errors due to inter-symbol interference or frequency selective fading.

3.2 Measurements of bit errors

Very few measurements of error rates have been published on HF FSK transmissions over high latitude paths, although it has long been known that performance on these circuits is inferior to comparable mid-latitude paths. Most researchers have instead attempted to characterise the propagation paths in terms of signal strength, frequency dispersion and fade rate, and have then used these parameters as the basis of prediction methods. One of the few experiments to have been conducted was performed by Roesler and Bliss (1988) on behalf of the Rockwell International company. Although they have compiled a large database of measurements, the results of their analysis have not yet been published.

Vincent et al. (1968) measured error rates on 14.360 MHz and 7.366 MHz



Figure 3.2: Comparison of optimum receiver performance for FSK signalling over fading and non-fading channels. (After Couch II, 1983)



Figure 3.3: Typical error performance for an hf digital communication system.

(After Walker, 1964)

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100 baud FSK signals on a mid-latitude path from Fort Monmouth, New Jersey to Palo Alto, California. These measurements conformed to the theoretical predictions, described earlier, demonstrating a logarithmic relationship between signal to noise ratio and bit error rate. Their results are reproduced in Figure 3.4 and it is noticeable that eventually bit error rate ceases to decrease with increasing signal to noise ratio. The errors at this point are due to inter-symbol interference.

Although the quality of a channel may be modelled in terms of bit error rate, the affect of the errors can be minimised by employing various error detection and correction schemes. The techniques and codes employed for error correction are numerous and often complex and are beyond the scope of this thesis. A detailed explanation of these methods can be found in many texts, for example Schwartz (1980), Shanmugam (1976) and Carlson (1986).

In order to apply error detection and correction techniques efficiently, some knowledge of the error distributions likely to occur on the communications link is desirable so that appropriate data formats can be developed. It is rare for consecutive errors to occur in a data stream. In a worst case scenario, when only noise is detected at the receiver, the probability that any given bit is correct or incorrect is 50%, and consequently it is unlikely for a long burst of erroneous bits to be received. Therefore, a burst of errors is not usually defined as being a number of consecutive errors but is more commonly defined as being a block of consecutive data bits with an error density greater than a specified value. Such a method of identifying and quantifying error distribution statistics was employed by Brayer (1968). Brayer defined an error burst as a block of data starting and ending with an erroneous bit and containing a minimum number of errors and a minimum error density, Δ . The error density is defined as the ratio of bits in error to the total number of bits in the block of data. An error burst is bounded by blocks with an error density less than Δ . Brayer gave the term "guard space" to the period between bursts.

These definitions are often employed in models produced to simulate HF channel. These definitions will also be employed in the ensuing chapters to describe error and guard space distributions observed during the course of the experiments reported in this thesis.



Figure 3.4: Error performance of mid-latitude link between Fort Monmouth, New Jersey to Palo Alto, California. FSK1 = Non-coherent FSK FSK2 = Dual diversity FSK

(After Vincent et al., 1968)

3.3 Concluding remarks

In this chapter, some of the causes of bit error rates in HF FSK data transmissions have been discussed. The work in the ensuing chapters of this thesis investigates the relationship between frequency dispersion, amplitude variations, error rates and error distributions and relates them to ionospheric propagation phenomena.

CHAPTER 4 Experimental Arrangement

4.1 Introduction

In order to investigate the affects of the high latitude ionosphere upon HF radio propagation, a frequency agile transmitter was installed north of the auroral oval on Baffin Island in the Canadian North West Territories. Receiving and data logging systems were deployed at a range of sites in the UK, USA and Canada to provide a variety of trans-auroral paths and one path contained entirely within the polar cap. Two receiving sites were chosen for the study presented in this thesis. The site locations, labelled Tx for the transmitter and A and B for the receiving sites, are illustrated in Figure 4.1. Also indicated on this diagram are the boundaries of the average auroral oval position as calculated from the Feldstein and Starkov model for moderate geomagnetic conditions (Kp=5) at 5UT. Further information related to the paths is provided in Table 4.1.

		Approx.	Great circle	Path type to
<u>Site</u>	<u>Location</u>	<u>Coordinates</u>	<u>path length</u>	<u>transmitter</u>
Transmitter	Clyde River	70°N,70°W		
	Baffin Is.			
А	Alert,	82°N, 62°W	1127km	Polar cap
·	Elsmere Is.			
В	Fairbanks,	71°N, 156°W	2780km	Polar cap/
	Alaska			Trans-auroral

Table 4.1 Details of experimental sites

Two experimental campaigns, each of approximately one month duration, were conducted during the period July/August 1988 and January/February 1989. During each campaign, measurements of signal strength and Doppler spread of an unmodulated (CW) signal, signalling error rate and error distribution of frequency shift keying (FSK) transmissions were made.



Figure 4.1: Location of transmitter (Tx) and receiver sites (Site A - Alert, Site B - Fairbanks).

4.2 The transmitter site

A transmitter controlled by an M6809 based microcomputer system, capable of operation on a predetermined frequency and modulation schedule, was installed at Clyde River on Baffin Island in the Canadian North West Territories. The transmitter system (Figure 4.2) was based on an amateur radio Icom 735 transceiver and an IC-2KL power amplifier which produced an average power of 350W into the antenna. Before deployment, modifications were made to the equipment to include a frequency stable reference oscillator to allow accurate measurements of the Doppler spread imposed on the CW signal by the reflection processes in the ionosphere. Different schedules were employed in the first two campaigns. These are presented in Table 4.2 and are described in more detail in Section 4.3.

Minutes	Frequency	Frequency	Data
<u>past hour</u>	(Summer 1988)	(Winter 1989)	<u>Format</u>
0	6.800 MHz	6.800 MHz	FSK
2	9.941 MHz	9.941 MHz	FSK
4	13.886 MHz	13.886 MHz	FSK
12	3.185 MHz	3.185 MHz	CW
15	4.900 MHz	4.900 MHz	CW
17	6.800 MHz	6.800 MHz	CW
19	9.941 MHz	9.941 MHz	CW
21	13.886 MHz	13.886 MHz	CW
23	18.204 MHz	18.204 MHz	CW
25	20.900 MHz	20.900 MHz	CW
30	6.905 MHz	6.905 MHz	FSK
32	10.195 MHz	10.195 MHz	FSK
34	14.373 MHz	14.373 MHz	FSK
38	3.230 MHz	4.455 MHz	CW
40	5.200 MHz	6.905 MHz	CW
42	6.905 MHz	10.195 MHz	CW
44	10.195 MHz	14.373 MHz	CW
46	14.373 MHz	17.515 MHz	CW
48	17.515 MHz	20.300 MHz	CW
50	20.300 MHz	23.169 MHz	CW

Table 4.2: Data transmission schedules

For the first experimental campaign, 18 July to 11 August 1988, two Butternut HF6V-X antennas were deployed. The fourteen frequencies allocated for the experiments by the Canadian authorities were divided into two similar



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Figure 4.2: Schematic of transmitter system employed in this experiment.

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groups, known as the primary and secondary frequencies, with each group covering the HF spectrum from approximately 3 to 20 MHz. Each antenna was tuned to one group of frequencies. The antennas were multi-band monopoles designed for transmitting on the HF amateur bands and had been re-tuned to operate on the experiment frequencies. The Butternut antennas operated well on frequencies above 7 MHz, however below this frequency, tuning was very critical and was affected by changes in the weather. Consequently, frequent re-tuning was necessary. For this reason a broadband whip antenna (APL V2000) was deployed for the second experiment (16 January to 10 February 1989).

The APL V2000 consisted of a 7m vertical whip above a heat sink structure containing a balun and loading resistor mounted on a 5m lattice work tower section . A series of test undertaken by Adler and Shaw (1984), indicated that this type of antenna was very inefficient when compared to a 'standard' US Navy 35 foot whip with antenna matching unit. The gain of the broadband antenna varied between +3dB and -37dB relative to the 35' whip. However, though inefficient, the antenna gave satisfactory performance.

4.3 Transmitted signal format

4.3.1 Sequence 1

This sequence (Figure 4.3a) was transmitted once per hour on each of 14 frequencies. In the event of interference on a particular frequency, another measurement could be taken again at a similar frequency approximately 30 minutes later. Each of these sequences incorporated:

(a) The call sign (CZB) transmitted in on/off keyed Morse code at 12 words per minute. This was repeated every 5 seconds for the period indicated and was intended for audio recognition of the signal.

(b) A 52 bit 0°/180° phase shift key (PSK) pseudo-Barker coded signal. The code sequence, where \uparrow and \downarrow indicate 0° and 180° phases and \diamond indicates an off period, was:



<u>Figure 4.3:</u> (a) The Barker and Doppler transmission format. (b) The FSK data transmission format.

Each bit was 250µs long and the sequence was repeated over the period indicated in Figure 4.3a. The Barker signal transmission was originally intended to provide information on the mode content of the received signal, however, this part of the experiment did not work very well and this signal format has not been utilised in the analysis presented in this thesis. This data will not be discussed further except where it relates to the data logging sequence.

(c) A 30 second period of unmodulated carrier (CW) included to enable the Doppler spreads, Doppler shifts and signal strength variations imposed on the signal by the ionosphere to be measured.

4.3.2 Sequence 2

This sequence (Figure 4.3b) was transmitted once per hour on 6 of the 14 allocated frequencies. Again the frequencies were divided into two similar groups. Each of these sequences incorporated (a) the call sign transmitted in Morse code for audio recognition of the signal and (b) three 30 second pseudo-random FSK data sequences transmitted at speeds of 50, 75 and 150 baud. The FSK data were divided into 168 bit blocks, each block starting with a 39 bit Barker coded segment to aid synchronisation followed by a 129 bit known random sequence. The complete code, in hex was:

F9AFCD41949EF94C779196390586AE93A44C233177

The low and high FSK tones were respectively 850 Hz and 1700 Hz above the nominal transmission frequency.

4.4 The receiver systems.

Each of the receiver systems (Figure 4.4) was based around a Racal RA6790/GM remotely programmable HF receiver provided with quadrature outputs at the modulation baseband and two outputs corresponding to the amplitudes of signals received at each of the two FSK tone frequencies. These outputs (one pair or the other) were simultaneously sampled by a microcomputer system and the data recorded onto magnetic tape for subsequent processing and analysis.



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Figure 4.4: Schematic of receiver system employed in this experiment

4.4.1 Recording of the CW signal and the Call Sign

Firstly, the receiver gain was set by monitoring the CW signal for 8 seconds. This gain setting was then maintained for 30.8 seconds, during which both the CW and call sign portions of the signal were recorded. The signal was mixed down in to the receiver to produce a nominal output frequency of +10 Hz. This offset was introduced to avoid confusion with any residual DC components produced by the receiver mixer system. 1530 real and imaginary samples of the signal were taken at 20 ms intervals with 12 bit A-D resolution and recorded onto magnetic tape.

4.4.2 Recording the FSK data

The signal was mixed down in the receiver to match the centre frequency of a chain of cascaded bandpass filters. The filter centre frequency for the low tone filter was 1277 Hz and 2128 Hz for the high tone. Depending on the baud rate, the signal amplitude was measured at different points along the chain. The frequency responses of the cascaded chain of filters at the tap off points for 150, 75 and 50 baud are presented in Figure 4.5, the average half power bandwidths are presented below.

150 baud filters:-	205 Hz
75 baud filters:-	124 Hz
50 baud filters:-	85 Hz

The output from the two tone filters were sampled simultaneously 300 times a second by two ADCs with 8 bit resolution. Unlike the CW case, the receiver AGC was operating throughout. The changes in the gain setting were not recorded and, therefore, signal strength variations could not be determined. But comparisons of relative variations between the two tones could be made.

4.4.3 Receiving antennas

A rhombic antenna was employed at Alert (site A). At Fairbanks (site B) a beam was produced from an array of vertical monopoles.

4.5 Concluding remarks

In this chapter, the experimental configuration has been described. Measurements have been made almost continuously over two one month



Figure 4.5: Frequency response of FSK tone filters

periods (July/August 1988 and January/February 1989). These measurements have been analysed and the results are presented in subsequent chapters of this thesis.

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CHAPTER 5 Analysis Techniques

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5.1 Introduction

Analysis has been performed on two distinct sets of data: (a) the CW and related signals and (b) the FSK signals. Analysis of the CW portion of the transmission involved spectral analysis of the received signal and yielded information concerning imposed Doppler spreads and variations in signal strength. As a large amount of data were collected, it was necessary to develop software routines to differentiate between signals from the Clyde River transmitter and background noise and interference. Recognition of a signal distorted by ionospheric propagation in a noisy environment can be subjective. However, an automatic recognition procedure was developed which agreed in the majority of cases with the decisions of human operators. These tests are discussed further in Section 5.2.

Analysis of the FSK transmissions involved synchronising with the data by means of a cross-correlation between the known 39 bit pseudo Barker sequence and the received code. The bit error rates and error distributions were then determined. These techniques are described in Section 5.3.

5.2 CW analysis procedure

The first stage of the analysis involved calculating the spectrum of the received CW signal. This was achieved by performing a 1000 point FFT (NAG C06EAF) on the complex signal samples after applying a cosine bell window function. Since the signal (real and imaginary components) was sampled 50 times per second, the resultant spectra covered a range of ± 25 Hz. Ignoring the effects of the window function, this gave a resolution of 0.05 Hz.

The signal strength at the receiver input was determined by multiplying the peak amplitude component in the spectrum by a receiver calibration factor. The signal strength calculated by this means was relative to 10μ V at the receiver input. The true signal strength could not be determined since the various antennas and associated distribution systems were not calibrated. A 3 point running mean was then applied to the calculated spectrum to speed up

the plotting process. A flow chart of the spectrum analysis procedure is supplied in Figure 5.1.

In order to speed up analysis and remove the need to manually examine all the data, two automatic recognition tests were developed. These tests were based on (a) the Doppler spreading imposed on the CW transmission and (b) recognition of the Morse coded call sign.

5.2.1 Doppler spread and the spread index (SI) test

In order to quantify the Doppler spreading of received signals, some researchers have fitted curves to spectra (Basler et al 1988) and quantified the Doppler spread in terms of one of the parameters of the fitted curve. Assumptions are made in this procedure about the shape of the spectrum. Good fits to the measurements are rarely achieved, particularly on high latitude signals where spreads can be large. Therefore, a simple technique was adopted in which the Doppler spread was quantified in terms of the area under the normalised amplitude spectrum.

In order to calculate the Doppler spread, the amplitude spectrum (an idealised spectrum of a typical signal plus noise is sketched in Figure 5.2(a)) was first normalised. The noise level occurring in the interval -25 Hz to -12.5 Hz was assumed to be representative of the mean noise level throughout the whole spectrum interval (-25 Hz to +25 Hz) (see Figure 5.2(b)). The base line noise level was then subtracted to yield a spectrum as indicated in Figure 5.2(c). The area under this remaining signal, which is approximately proportional to the width and hence the Doppler spreading of the signal, was then calculated. This area, multiplied by 20, is referred to as the Spread Index (SI).

Measurements of the SI and signal strength were employed in the following signal recognition tests:

- (1) If the spread index was large and the signal strength was above a preset minimum threshold, then the signal passed the recognition test. This was assumed to be a weak, spread signal. The preset minimum signal level was dependent on the environment at each site and was set by examining some of the data manually.
- (2) In the case where the SI was calculated to be zero or negative, the test



Figure 5.1: Flow diagram of the CW analysis procedure



Figure 5.2: Illustration of how the spread index is calculated

was failed regardless of signal strength. A negative SI could be due to either:

- (a) The presence of an interfering signal in the -25 Hz to -12.5 Hz range, or,
- (b) There was no detectable signal present and a negative spread index was calculated because of the purely random nature of the noise.

(3) A small positive SI could be due to either:

- (a) No detectable signal, but a small spread index was calculated from the noise. In this case, the signal strength would be below the threshold and the signal would fail the test.
- (b) A strong signal being present with very little spread. In this case the signal strength would be large and the signal would pass the recognition test.

Examples of each of these situations are given in Figure 5.3 and the conditions are summarised in Table 5.1:

<u>Spread Index</u>	<u>Signal strength</u>	<u>Decision</u>	<u>Comments</u>
Large	Large	Pass	Strong signal with large spread
Large	Small	Pass	Weak signal, but above preset
			minimum, with large spread
Negative	Large	Fail	Due to interference
Negative	Small	Fail	Due to random noise
Small	Small	Fail	Due to random noise
Small	Large	Pass	Signal with little spread

Table 5.1: Signal recognition tests involving SI

5.2.2 Recognising the call sign transmission

A further recognition test based on the Morse coded call sign (CZB) part of the transmission was also developed. The call sign was transmitted in slow speed Morse code as a 100% amplitude modulated sequence and was recorded along with the CW transmission as described in Chapter 4. The spectrum of the call sign portion of the sequence had a characteristic spectral content due to the modulation sidebands. A typical spectrum is presented in Figure 5.4. As indicated, the pattern differed from the unmodulated case by the presence of sidebands situated approximately 5 Hz either side of the carrier peak. The



Figure 5.3: Examples of signals that have passed and failed the recognition tests based on the measurements of the spread index.





following procedure was adopted in order to recognise the presence of the modulation:

- (a) The noise level within the frequency spectrum was calculated. This was done, as before, by examination of the frequency range -25 to -12.5 Hz, where the signal was not expected to occur. A threshold value of 2.5×10^{-12} x this noise level was set for the unambiguous detection of the spectral peaks due to the carrier and modulation sidebands.
- (b) The signal recognition routine searched within the frequency window from -5 to +20 Hz and attempted to find a pattern corresponding to the main signal peak together with two secondary peaks situated at frequencies 5 Hz above and below it. This was done by examining the frequency spectrum within 1 Hz wide bins 5 Hz either side of any signal greater than this threshold for subsidiary peaks greater in amplitude than the threshold value but less than that of the central peak. The position of the main signal peak within the spectrum could not be taken for granted as, not only could there be an imposed Doppler shift on the signal, but the transmitter and receivers tended to drift by a few Hertz.
- (c) The presence of amplitude minima 3 Hz either side of the central peak were also verified. If this pattern was found, the signal passed the test.

5.2.3 Signal categorisation

Signals that passed both the SI and call sign tests were assumed to be from the Clyde River transmitter. However, on occasion, one of the tests may have been passed while the other was failed. On these occasions, the signal was flagged as ambiguous. As the call sign test was more rigorous, signals failing this test rarely passed the SI test. Measurements failing both tests were assumed to be noise.

The presence of interference needed to be recognised and the measurement flagged as unreliable. Measurements could pass the SI test but fail the call sign FFT test if: (a) there was an interfering signal or, (b) the calls sign signal was weak and the sidebands could not be discerned from the noise. It was assumed that if the signal amplitude were 10 times greater than the noise level, determined from the spectra, the call sign sidebands should have been detectable. Therefore, if the sidebands were not detectable, but the signal amplitude was 10 times greater than the noise level, the signal measurement was assumed to be due to interference. Signal measurements where the signal amplitude was less than 10 times the noise level were flagged as ambiguous measurements.

The results of the signal recognition tests allowed the data to be divided into five different groups. Signals passing both test were adjudged to be from the Clyde River transmitter. Signals failing both tests were assumed to be measurements of noise due to the signal not being detectable. Two further categories were reserved for signals failing one or other of the tests. The final category was those signals adjudged to be interference. Signals in this final group were ignored in subsequent analysis.

In order to verify the accuracy of the two tests, comparisons were made with results from manual inspection of the signal spectra. The automatic recognition tests were found to agree with the judgment of persons familiar with the data more than 80% of the time.

5.3 FSK analysis procedure

Analysis of the FSK data transmission is described in the flow chart provided in Figure 5.5. In essence, the start and end of the data was determined by cross-correlating the received data with the known 39 bit pseudo Barker sequence. The samples were then averaged to determine the nature of each bit, '0' or '1', before the bit error rates, error distributions and signal to noise ratio was calculated.

5.3.1 Synchronisation

Synchronisation with the FSK sequence was achieved by cross-correlating the embedded 39 bit Barker sequence with the known (correct) sequence by means of applying a matched filter. As the data was sampled 300 times per second, there were 2 samples per data bit at 150 baud, 4 samples per data bit at 75 baud, and 6 samples per data bit at 50 baud. However, until the start of the data, and the first sample of the first data bit is determined, it is not possible to average the data samples. Therefore, only one sample from each bit of data was used, initially, to determine the start of the data.





Comparison started at the first sample and continued with every other N sample, where N was the number of samples per bit for the relevant baud rate. In this way, one sample from each bit of data was checked. An example of this technique is illustrated for a 75 baud data sequence with 4 samples per bit in Figure 5.6. At each sample, if the sample matched the corresponding sample in the known Barker sequence, one was added to an accumulator. If the sample did not match, one was subtracted from the accumulated value. For a perfect match, i.e. perfect synchronisation with no bits in error, a total of 39 would have been recorded. An arbitrary threshold of 25 was set for the matched filter output for acceptable synchronisation. Perfect synchronisation was not expected every time as some of the bits would have been erroneously received due to propagation affects and the presence of interference.

Upon completing the correlation with the first 39 bits of the data sequence, the process was repeated starting at the next sample. Synchronisation was only assumed to have been achieved if the output from the match filter equalled or exceeded 25 for N-1 consecutive samples, i.e. synchronisation was achieved with all but one sample in each of the 39 bits of the pseudo-Barker sequence. This assumed that one sample per bit of data could have been at the crossover between two received data bits as illustrated in Figure 5.7. If this criterion was met, the N-1 samples were averaged to determine the average amplitude of the data bit and the two tones were compared to determine whether a 1 or 0 was transmitted.

The synchronisation routine was also employed to re-synchronise with the data at the end of each 168 bit block of data to compensate for any drift in the receiver or transmitter. Re-synchronisation occurred if the output from the match filter was both greater than the current match filter output and also greater than the threshold (25) if the routine was applied 30 samples in each direction from the current position in the data stream.

5.3.2 Analysing the FSK data

Once synchronisation has been achieved, the samples within each bit were averaged to reduce the affect of noise and the value of each bit determined. The received sequence was then compared with the expected sequence and a record was made of which bits were in error and, when an error was detected, whether a 1 had been received instead of a 0, or whether a 0 had been received instead of a 1.



Figure 5.6: Illustration of how a match filter is applied to synchronise with the data.





Signal to noise ratio (SNR) for each received bit was determined by comparing the signal amplitude from the filter in which the signal was expected to appear along with additive noise with the amplitude from the other tone filter which was expected to be a measurement of background noise alone. The signal to noise ratio was defined as:

$(A - B)^2 / B^2$ Equation 5.1

Where A represents the amplitude output of the filter containing the signal and additive noise, and B represents the amplitude output from the filter containing noise only.

At times the signal amplitude in the noise channel (B) could be low enough for the ADC to read zero. As the ADC had an error range of ± 0.5 , SNR in these cases was defined as:

$A^{-} / 0.5$ Equation 5.	A2
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5.3.3 Error distribution

The definition of an error burst employed in this analysis is similar to that defined by Brayer (1988). His method defined an error burst as a period containing a minimum number of errors, M_e , and a minimum density of errors in that period, Δ . For the purposes of the analysis discussed in this thesis, M_e was set to 1 and Δ set to one error in every four bits, i.e. a burst of errors is defined as a period bounded by at least four correct bits, and no more than three bits of consecutive data are received without error. This definition differs from Brayers in that an individual error is accepted as an error burst. The period bounding an error burst is defined as the guard space. This definition of an error burst is discussed further in Chapter 7.

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5.4 Concluding remarks

Automatic signal recognition routines have been developed for the CW signal. There is good agreement between the automatic recognition routines and decisions made on the basis of manual examination of the measurements. The computer based routines agree with the manual

observations more than 80% of the time. The routines divide the data into four main groups: signals identified as being from the Clyde River transmitter; noise; ambiguous/unsure and interference.

Analysis routines have also been developed for the FSK signal. The FSK analysis routines synchronise with the data and then determine error rates, error distributions and signal to noise ratio for each data bit.

The following two chapters are concerned with the analysis of measurements made employing the techniques described in this chapter for signals received over two high latitude paths.

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CHAPTER 6 Measurements of the CW signal

6.1 Introduction

In this chapter, the results derived from measurements of the CW portions of the transmissions are presented. In particular, variations in Doppler spreading imposed on the signal by the ionospheric reflection process and diurnal changes in signal and noise strength are discussed. The measurements were made during two experimental campaigns, one during a summer period (18 July 1988 to 11 August 1988) and the second during a winter period (16 January 1989 to 10 February 1989).

The measurements have been related to various geophysical parameters, e.g. the position of the auroral oval (an estimate based on the work of Feldstein and Starkov (1967)) and the level of geomagnetic activity. The level of geomagnetic activity was particularly low during the summer campaign with A_p rarely exceeding 10 (see Figure 6.1(a)). A_p was higher during the winter campaign (Figure 6.1(b)), exceeding 40 on occasion (average 21.6). Overall the level of geomagnetic activity during the two experimental campaigns varied between levels that would normally be categorised as low to moderate. Therefore, significant ionospheric disturbances were not expected.

6.2 Clyde River to Alert (Site A), summer 1988

6.2.1 Observations

As measurements of spread index will be unfamiliar to most, and a ready comparison cannot be made with the degree of Doppler spreading, examples of typical spectra and their corresponding SI value are presented in Figure 6.2. A typical low spread signal of up to 5 Hz can be characterised by an SI value of 30 or less, a medium spread of between approximately 5 Hz to 10 Hz can be characterised by SI between 30 and 100, and a large spread signal of more than 10 Hz by SI in excess of 100. (It should be noted that SI measurements at times of sporadic propagation or when signal to noise ratio is low can be misleading as the measurements may be of noise.)







Figure 6.2: Examples of spectra of varying Doppler spreads with corresponding spread index measurements.

In order to compare the occurrence of any observed phenomena with solar affects, the functions $\cos(\chi)$ and $1-\cos(\chi)$, where χ is the solar zenith angle, are plotted in Figure 6.3. Any solar related affects are expected to correlate with these functions. The justification for these functions is discussed in Section 6.2.2.

The spread, index, signal strength and noise strength measurements derived from the CW portion of the transmissions are averaged and presented in graphical form, as in Figure 6.4(a). Each plot contains three frames. The frames are:

Bottom frame: The averaged peak signal and noise strengths measured over the campaign from the data pre-selected as described earlier. The grey bars represent the signal strength measured in decibels relative to a 10μ V signal at the receiver, the black bar is a measure of the average noise in the first quarter of the spectrum, -25Hz to -12.5Hz as described in Chapter 4.

Middle frame: The peak signal to average noise ratio (in decibels) calculated from the values in the lower frame.

Top frame: Averaged Spread Index (SI) measurements of spectra.

Over the Clyde River to Alert path, during the summer experimental campaign, the lower frequencies propagated particularly well around local midnight when D-region absorption is expected to be at its minimum. The 3.185 MHz signal (Figure 6.4(a)) displays characteristics which are typical of those observed at the lower frequencies. Although there is little diurnal variation in Doppler spread, which is low (below a spread index of 30) and approximately constant, a strong diurnal variation (approximately 30 dB) in signal strength and noise strength (approximately 15 dB) is evident. The signal strength is well correlated with the $1-\cos(\chi)$ function illustrated in Figure 6.3. However, the noise does not follow the same trend. Between 0 and 9UT, the noise level follows a similar trend to that observed in the signal strength variation, but between approximately 10UT and 23UT the noise reaches a minimum. As noise strength no longer decreases, but signal strength continues to so, there is a sharp degradation in signal to noise ratio.



Figure 6.3: The average variation of $cos(\chi)$ at the Clyde River to Alert (Site A) path mid-point during the Summer 1988 experimental campaign, and the expected form of signal strength variation $(1-cos(\chi))$.



Figure 6.4(a): The average variation in spread index, signal to noise ratio and signal and noise strengths measured on at Alert (Site A) during the Summer 1988 experimental campaign at 3.185 MHz.



Figure 6.4(b): The average variation in spread index, signal to noise ratio and signal and noise strengths measured on at Alert (Site A) during the Summer 1988 experimental campaign at 6.800 MHz.



Figure 6.4(c): The average variation in spread index, signal to noise ratio and signal and noise strengths measured on at Alert (Site A) during the Summer 1988 experimental campaign at 10.195 MHz.



Figure 6.4(d): The average variation in spread index, signal to noise ratio and signal and noise strengths measured on at Alert (Site A) during the Summer 1988 experimental campaign at 13.886 MHz.

At higher frequencies, Doppler spread remains low (SI below 30) with no discernible diurnal variation. As the noise strength rises above the noise floor and begins to vary in a similar manner to the signal strength, there is less variation in signal to noise ratio. As indicated by the measurements of the 6.800 MHz signal in Figure 6.4(b), there is a marked diurnal variation of approximately 25 dB in both signal and noise strengths, both correlating well with the 1- $\cos(\chi)$ function suggesting solar control, but there is very little diurnal variation in the signal to noise ratio which remains constant at approximately 32 dB.

The effects of D-region absorption are minimal on the 10.195 MHz signal (Figure 6.4(c)). The diurnal variation in signal and noise strengths evident at the lower frequencies is not evident with both signal and noise strengths remaining constant at 5dB and 35dB respectively. The degree of Doppler spreading remains low with spread index values less than 30. At higher frequencies, the propagation characteristics change as the MUF is exceeded. The measurements presented in Figure 6.4(d) of the signal received at 13.886 MHz are typical of the general behaviour observed. Although there is no change in Doppler spreading, which remains low, around local midnight the signal frequency exceeds the MUF and the signal penetrates the ionosphere. The averaged peak signal strength measurements at around local midnight are therefore mainly of noise and are low.

It should be noted that the signal strength at 9UT on the 13.886 MHz transmission is lower than expected due to the regular presence of an interfering source resulting in the elimination of the majority of the signals. The value presented is of the few uncontaminated noise only measurements.

6.2.2 Discussion

As the Clyde River to Alert path was contained entirely within the polar cap, no auroral affects were expected. Any observed variations in signal characteristics were therefore expected, in the main, to be solar driven and, as the path was sunlit throughout the campaign period, these were expected to be minimal but correlated with the diurnal variation in solar zenith angle, χ .

Non-deviative absorption, L, is proportional to the inverse of the square of the propagating frequency and is, therefore, a major controlling influence on signal strength at the lower propagating frequencies. Furthermore, nondeviative absorption of a signal passing at oblique incidence through a Chapman layer has a marked dependance on solar zenith angle, χ , as illustrated in Equation 6.1 (Piggott, 1968):

L ∝ cosⁿχ

Equation 6.1

Where n is an unknown exponent varying between 0.2 and 1.0 (Davies, 1965).

Therefore, the received signal strength can be calculated employing Equation 6.2:

 $S = S_0 - A.cos^n \chi$ Equation 6.2

Where: S is the received signal strength (dB) S_0 is the signal strength without absorption (dB) A is an unknown constant

These equations are inappropriate for solar zenith angles greater than about 80°. At large zenith angles the inverse of the Chapman function should be employed, but as this function requires information on the reflection height of the signal which is not available, it cannot be employed. Furthermore, the assumptions employed in the derivation of the Chapman theory are unrealistic at high latitudes due to electron precipitation in to the D-region which can enhance absorption. Milan (1994), using some of the same data collected for this experiment, demonstrated that the relationship between signal strength and solar zenith angle, as described in Equations 6.2 and 6.3, are not particularly sensitive to the value of n. High correlation (coefficient of correlation greater than 0.95) has been achieved for values of n between 0.3 and 1.35. An arbitrary value of 1.0 has been chosen for n in this analysis, i.e it has been assumed that L $\alpha \cos \chi$. Signal strength is therefore expected to follow a 1-cos χ form.

The propagation characteristics observed on this circuit agreed with those expected. Non-deviative absorption was the dominant affect on the variation in signal strength at the lower propagating frequencies, and this affect reduced

at the higher propagating frequencies. At the higher propagating frequencies, average signal strength variation, as expected, was dominated by MUF penetration at times of lower ionospheric electron density (local midnight).

6.3 Clyde River to Fairbanks (Site B), summer 1988

The path from Clyde River to Fairbanks alternates between being contained entirely within the polar-cap path and being trans-auroral. This is illustrated in Figure 6.5 where the statistical diurnal variation of the auroral oval position for moderate geomagnetic conditions, as calculated from the Feldstein and Starkov (1967) model, is indicated with reference to the path reflection points. Although the path mid-point is always located within the polar-cap, the second 2-hop reflection point is within the boundaries of the mean auroral oval between approximately 16UT and 5UT. The functions $\cos(\chi)$ and $1-\cos(\chi)$ relating to the variation of the solar zenith angle at the path midpoint are presented in Figure 6.6 for comparison purposes.

6.3.1 Observations

There is little evidence of propagation below 6 MHz, and only erratic propagation at 6.800 MHz (Figure 6.7(a)), the measurements of SI, therefore, are not valid as they are mainly measurements of noise. However, diurnal variation in the signal and noise strength, peaking at around 8UT (local midnight at the path mid-point) can be observed with a corresponding variation in signal to noise ratio.

At 10.195 MHz (Figure 6.7(b)), there is a clear diurnal variation in signal to noise ratio. Signal to noise ratio starts to increase at 18UT (local noon at the first of the two hop reflection points) from about 22 dB to 30 dB before starting to decrease at approximately 12UT. There is also a diurnal variation in SI which correlates well with the times at which the second hop reflection point is expected to be located in the auroral oval. This effect is more evident at the higher frequencies.

The diurnal solar controlled variation in signal strength, evident at the lower frequencies, is less apparent at higher frequencies. At 13.886 MHz (Figure 6.7(c)), the signal and noise strengths follow no obvious trends.



Figure 6.5: Predicted average position of the auroral oval relative to the Clyde River to Fairbanks (Site B) path.



Figure 6.6: The average variation of $cos(\chi)$ at the Clyde River to Fairbanks (Site B) path mid-point during the Summer 1988 experimental campaign, and the expected form of signal strength variation $(1-cos(\chi))$.



Figure 6.7(a): The average variation in spread index, signal to noise ratio and signal and noise strengths measured on at Fairbanks (Site B) during the Summer 1988 experimental campaign at 6.800 MHz.



Figure 6.7(b): The average variation in spread index, signal to noise ratio and signal and noise strengths measured on at Fairbanks (Site B) during the Summer 1988 experimental campaign at 10.195 MHz.



Figure 6.7(c): The average variation in spread index, signal to noise ratio and signal and noise strengths measured on at Fairbanks (Site B) during the Summer 1988 experimental campaign at 13.886 MHz.



Figure 6.7(d): The average variation in spread index, signal to noise ratio and signal and noise strengths measured on at Fairbanks (Site B) during the Summer 1988 experimental campaign at 18.204 MHz.

However, there is a good correlation between Doppler spreading as measured by SI and the position of the second reflection point with respect to the auroral oval. The signal is significantly more spread when the reflection point is within the oval (SI>60) as compared to when it is outside (SI<30) (8UT to 13UT). Most of these trends continue to be observed on signals up to approximately 18 MHz (Figure 6.7(d)) after which the MUF is exceeded and propagation ceases. However, as the propagating frequency increases, the extent of Doppler spreading is smaller.

6.3.2 Discussion

Diurnal solar control on this predominantly two hop circuit (as predicted by the IONCAP and ICEPAC prediction programs) was expected to correlate with the variation of solar zenith angle, even though the mid-point was in sunlight for 24 hours each day. Local noon at the path mid-point was at 20UT and local midnight was at 8UT. Ignoring the effects of auroral absorption, signal strength was expected to follow the S₀ - A.cosⁿ χ type function presented in Figure 6.6. This generally matches the observations.

Although auroral absorption may have been expected, its occurrence is not easy to predict. Significant auroral absorption or PCA events were not expected due to the generally low geomagnetic activity prevalent throughout this experimental campaign and there is no clear evidence of either of these phenomena occurring.

There is a strong correlation between Doppler spread and the position of the second hop reflection point with respect to the expected position of the auroral oval. Doppler spreading is significantly larger when the reflection point is within the boundaries of the oval.

6.4 Clyde River to Alert (Site A), winter 1989

As the Clyde River to Alert path was in darkness throughout the winter experimental campaign, no direct solar production of ionisation was expected. However, a degree of ionisation was expected due to plasma convection from lower latitudes, as predicted by the Fuller-Rowell and Rees (1980, 1983) model. A typical example of the results produced by this model is presented in Figure 6.8. The signal measurements were compared with these



Figure 6.8: Polar ionospheric structure predicted by the Fuller-Rowell model centred on the longitude of the mid-point of the Clyde River to Alert path (mid-point latitude is approximately 70°).

predicted trends in the variation of electron density.

6.4.1 Observations

The measurements of the 3.185 MHz signal presented in Figure 6.9(a) illustrate the typical trends observed on the lower frequencies propagating over the Clyde River to Alert path. There is diurnal variation in signal to noise ratio: a decrease in signal strength of 10dB is evident around local noon. There is also evidence of a slight decrease in Doppler spreading around local noon (17UT). However, this measurement is unreliable due to the poor signal to noise ratio at this time.

At higher frequencies, such as 6.905 MHz in Figure 6.9(b) (very few 6.800 MHz signals passed the signal recognition tests due to interference) no diurnal variation in signal strength is apparent and signal to noise ratio is constant at approximately 30 dB. Doppler spreading is also relatively large (SI between 30 and 60) with no diurnal trends evident. There is erratic propagation at 10.195 MHz (Figure 6.9(c)) and little evidence of any propagation at higher frequencies, e.g. 13.886 MHz, see Figure 6.9(d).

6.4.2 Discussion

Although there was no direct solar produced ionisation on this path, sufficient plasma can be convected up from lower latitudes to support HF propagation. Such convection has been modelled by Fuller-Rowell and Rees (1980, 1983) (Figure 6.8). This model takes into account global coupling between the neutral thermosphere and the ionosphere as well as considering neutral winds, chemical composition, temperature, solar production of ions and particle precipitation.

Output from the Fuller-Rowell model is not available for the dates of this campaign or for the geomagnetic conditions prevalent during the campaigns conducted. Therefore, it has not been possible been to make a direct comparison between a prediction from this method and observed propagating characteristics. However, assuming that the results in Figure 6.8 are representative, the Fuller-Rowell model would appear to indicate a general trend of plasma convection at around local noon (17UT), and a depletion in electron density around local midnight (5UT). Therefore, the magnitude of non-deviative absorption and MUF at these times can be



Figure 6.9(a): The average variation in spread index, signal to noise ratio and signal and noise strengths measured on at Alert (Site A) during the Winter 1989 experimental campaign at 3.185 MHz.



Figure 6.9(b): The average variation in spread index, signal to noise ratio and signal and noise strengths measured on at Alert (Site A) during the Winter 1989 experimental campaign at 6.905 MHz.



Figure 6.9(c): The average variation in spread index, signal to noise ratio and signal and noise strengths measured on at Alert (Site A) during the Winter 1989 experimental campaign at 10.195 MHz.



Figure 6.9(d): The average variation in spread index, signal to noise ratio and signal and noise strengths measured on at Alert (Site A) during the Winter 1989 experimental campaign at 13.886 MHz.

compared with the actual results obtained (the corrected geomagnetic latitude of the Clyde River to Site A path mid-point is approximately 85°N).

The diurnal trends expected in signal to noise ratio are present. A decrease in signal strength of 10 dB is evident around local noon on the 6.800 MHz signal when plasma would be expected to flow across the polar-cap, increasing the electron density, and hence the magnitude of non-deviative absorption. There is also evidence of a slight decrease in Doppler spreading, as indicated by SI, around local noon. However, this is probably due to the poor signal to noise ratio at this time and the measurements are likely to be of noise.

Overall, the magnitude of Doppler spread is generally higher on propagating frequencies during the winter than in the summer (SI typically between 30 and 60) but the MUF is lower due to the lack of direct solar ionisation.

Due to different antennas being deployed at the transmitter site during the summer and winter campaigns, and the possibility of different noise characteristics at the receiver site, direct comparisons of signal strength, noise strength and signal to noise ratio cannot be made between the summer and winter campaigns.

6.5 Clyde River to Fairbanks (Site B), winter 1989

6.5.1 Observations

There is no evidence of consistent propagation below 6 MHz and only weak propagation at 6.800 MHz (Figure 6.10(a)). Although signal to noise ratio is poor (approximately 20 dB), there is some indication of diurnal variation, reaching a minima at around local noon (20UT). Due to the poor signal to noise ratio at the lower frequencies, the Doppler spread measurements are unreliable.

There is no discernible trend in variations at higher frequencies, the results from the 10.195 MHz (Figure 6.10(b)) and 13.886 MHz transmissions being typical (Figure 6.10(c)). However, at the highest consistently propagating frequency of 18.204 MHz (Figure 6.10(d)), a clear variation is present in the signal and noise strengths (15 dB) and in the Doppler spreading (from in



Figure 6.10(a): The average variation in spread index, signal to noise ratio and signal and noise strengths measured on at Fairbanks (Site B) during the Winter 1989 experimental campaign at 6.800 MHz.



Figure 6.10(b): The average variation in spread index, signal to noise ratio and signal and noise strengths measured on at Fairbanks (Site B) during the Winter 1989 experimental campaign at 10.195 MHz.



Figure 6.10(c): The average variation in spread index, signal to noise ratio and signal and noise strengths measured on at Fairbanks (Site B) during the Winter 1989 experimental campaign at 13.885 MHz.



Figure 6.10(d): The average variation in spread index, signal to noise ratio and signal and noise strengths measured on at Fairbanks (Site B) during the Winter 1989 experimental campaign at 18.204 MHz.

excess of 60 to below 10), both correlating with times when the second reflection point is located within the auroral oval. Doppler spreading is at its greatest between 16UT and 5UT when average signal and noise strengths are also at their greatest.

6.5.2 Discussion

The path to Fairbanks was in darkness throughout the winter 1989 experimental campaign. Therefore, ionisation to support HF propagation was expected to be from plasma convection from lower latitudes and also due to particle precipitation in the auroral zone. The results from the Fuller-Rowell model, presented in Figure 6.8, took into account both of these phenomena. Assuming that the model is approximately valid at all longitudes, by shifting the time axis these results can be taken to indicate trends in electron density variation over the path to Site B. Based on this assumption, peak electron density at the path mid-point points would still be expected to occur at local noon (20UT) and a depletion at local midnight (8UT). This is broadly consistent with the characteristics observed.

Auroral effects between 16 and 5UT would be expected, though whether they would enhance or degrade propagation is dependant on the energy associated with the precipitating particles. While high energy particles may reach the D region and increase the magnitude of non-deviative absorption, lower energy particles are likely to only reach the E or F region where they may augment ionisation and enhance the MUF. The increased signal and noise strengths observed on the 18.204 MHz signal (Figure 6.10(d)) between 16UT and 5UT may be due to enhanced MUF as a result of augmentation in ionisation by particle precipitation.

6.6 Summary

Results derived from measurement of the CW signal over the Clyde River to Alert and Clyde River to Fairbanks paths have been presented for two experimental campaigns (summer 1988 and winter 1989). These results indicate that there are solar, auroral and plasma convection controlled variations in signal and noise strength and in Doppler spreading.

During the summer campaign, signal and noise strength is well correlated

6.9

with solar zenith angle over both paths, but during the winter campaign, signal and noise strength is well correlated with plasma convected from lower latitudes as predicted by Fuller-Rowell and Rees. Increased ionisation due to plasma convection appears to result in increased non-deviative absorption at the lower propagating frequencies, but simultaneously enhanced the MUF.

Increased Doppler spreading on the Clyde River to Fairbanks (trans-auroral) path correlates with times when the second hop reflection point is expected to be within the boundaries of the auroral oval. The signal can be spread over 20 Hz or more. However, the magnitude of the spreading reduces as the signal frequency approaches the MUF. These effects are summarised in Tables 6.1 and 6.2. The general propagation characteristics observed for each path are summarised in Table 6.3.

Clyde River	Frequency	Occurrence	of Doppler spr	eads
to Alert		0 <si<30< td=""><td>30<si<100< td=""><td>SI>100</td></si<100<></td></si<30<>	30 <si<100< td=""><td>SI>100</td></si<100<>	SI>100
∞	3.185 MHz	74%	25%	1%
ler 198	6.800 MHz	75%	24%	1%
Sumn	10.195 MHz	80%	18%	2%
	13.886 MHz	98%	2%	0%
	3.185 MHz	14%	81%	5%
er 1989	6.905 MHz	24%	67%	9%
Wint	10.195 MHz	34%	57%	9%
	13.886 MHz	Few signals	Few signals	Few signals

<u>Table 6.1:</u> Occurrence of Doppler spreads observed on the Clyde River to Alert path expressed as a percentage of all signals recognised.

Clyde River to	Frequency	Occurrenc when i	e of Dopple n oval (16-:	r spreads 5 UT)	Occurrence when out	e of Dopple side oval (6	r spreads -15 UT)
F'banks		0 <si<30< td=""><td>30<si<100< td=""><td>SI>100</td><td>0<si<30< td=""><td>30<SI<100</td><td>SI>100</td></si<30<></td></si<100<></td></si<30<>	30 <si<100< td=""><td>SI>100</td><td>0<si<30< td=""><td>30<SI<100</td><td>SI>100</td></si<30<></td></si<100<>	SI>100	0 <si<30< td=""><td>30<SI<100</td><td>SI>100</td></si<30<>	30 < SI<100	SI>100
988	10.195 MHz	19%	53%	74%	34%	56%	10%
immer 1	13.886 MHz	22%	62%	16%	57%	42%	1%
Sı	18.204 MHz	28%	58%	14%	64%	36%	0%
989	10.195 MHz	1%	61%	38%	0%	67%	33%
Vinter 1	13.886 MHz	2%	63%	35%	3%	59%	38%
Ň	18.204 MHz	5%	55%	40%	4%	69%	27%

<u>Table 6.2:</u> Occurrence of Doppler spreads observed on the Clyde River to Fairbanks path when the second hop reflection point is located both within and outside the expected boundaries of the auroral oval.

Path	Frequency Range	Characteristics observed during Summer 1988 experimental campaign	Characteristics observed during Winter 1989 experimental campaign
	<4 MHz	Signal and noise strengths in good agreement with changes in χ . Decrease in signal to noise ratio at local noon. (From SNR>30dB to SNR<20dB) Little Doppler spreading (SI<30).	Signal and noise strength correlates with plasma convection model. Decrease in signal to noise ratio at local noon. (From SNR≈25dB to SNR≈10dB) Unreliable Doppler spread measurements.
Clyde River to Alert Polar cap	4 - 11 MHz	Some diurnal variation in signal and noise strengths. Little variation in signal to noise ratio. (SNR>30dB). Little Doppler spreading (SI<30).	No obvious diurnal variation in signal to noise ratio (SNR 20-30dB). Relatively large Doppler spreads (SI from 30-60 on 6.905 MHz).
	>11 MHz	Signal exceeds the MUF at local midnight, high signal to noise ratio at other times (SNR>40dB). Little Doppler spreading (SI<30).	Little evidence of propagation.
	<7 MHz	Sporadic propagation below 6 MHz.Signal strength and SNR in good agreement with changes in χ . (SNR \approx 25dB local midnight, SNR \approx 10dB local noon.)Unreliable Doppler spread measurements at times of low SNR.	Sporadic propagation below 6 MHz. Signal to noise ratio correlates with plasma convection model (SNR≈20dB local midnight, SNR≈15dB at local noon). Large Doppler spreads (SI 60 to 90).
Clyde River to Fairbanks Polar cap/Irans-auroral	7 -15 MHz	Some diurnal variation in signal to noise ratio at 10 MHz (35-25dB), little at 14 MHz (SNR=30dB). Increased Doppler spreading when second reflection point within autoral oval. (SI>60) when in oval, SI<30 when outside oval.)	Little variation in signal to noise ratio (SNR between 15dB and 20dB). Large Doppler spreads (Si≂60).
	>15 MHz	No obvious trend in signal to noise ratio variation (SNR≈25dB). Increased Doppler spreading when second reflection point within auroral oval. (SI>30 when in oval, SI<15 when outside oval.)	Signal and noise strength enhanced when reflection point in auroral oval $RNR\approx20dB$. Larger Doppler spreading when reflection point in auroral oval. (SI>60 when in oval, SI<30 when outside oval.)

<u>Table 6.3</u>: Summary of the observed characteristics of the signals recieved over the two paths during the Summer 1988 and Winter 1989 experimental campaigns.

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CHAPTER 7 Measurements of the FSK signal

7.1 Introduction

In Chapter 6, the effects of solar and auroral control on HF CW transmissions across polar and trans-auroral paths were presented. In particular, the received signal strength and signal to noise ratio was shown to be related to changes in solar zenith angle. On the trans-auroral path, the magnitude of Doppler spreading was found to be related to the position of the reflection points with respect to the auroral oval. In this chapter, these effects are related to the signalling error rates and bit error distributions observed on an 850 Hz shift FSK data signal transmitted over the same paths. However, it should be noted that this signal format was not developed specifically for the analysis presented here and, consequently, the modulation type, shift and other parameters could not be varied.

7.2 The affects of signal to noise ratio (SNR) on bit error rate

The theoretical affects of signal to noise ratio on bit error rate (defined as bits in error/bits transmitted), or the probability of a bit being in error, P(e) (essentially the same as bit error rate in this context and therefore interchangeable), were discussed briefly in Chapter 3. The models discussed did not take into account different noise models or interference characteristics, although such models do exist. Instead, the noise characteristics were assumed to be Gaussian. As noise characteristics are often unique to each site, it was not considered worthwhile to investigate and compare more complex models here. Instead, comparison is limited to the simplest model discussed in Chapter 3 (Equation 7.1). Figure 7.1 illustrates the relationship between SNR and P(e) as predicted by this model for binary non-coherent wide-band FSK (as in this experiment).

$$P(e) = \frac{1}{2} e^{-\frac{E_b}{2N_o}}$$
 Eqn. 7.1

Where E_b/N_o represents the signal to noise power ratio expressed as a numerical ratio.



Figure 7.1: Predicted relationship between P(e) and signal to noise ratio.
The error rate recorded over the polar cap path from Clyde River to Alert (Site A) and the trans-auroral path from Clyde River to Fairbanks (Site B) on 25 July 1988 (a typical day) at 50, 75 and 150 baud are presented in Figures 7.2 and 7.3 respectively. In general, the plotted results follow a trend similar to that predicted by the model. However, at low signal to noise ratio (below 0 dB), the measured results are significantly better than predicted. This is attributed to the pre-selection of the data as discussed in Chapter 5. Although poor performance would be expected, the analysis algorithm is not capable of synchronising with severely corrupted data and the data is discarded, thereby biasing the recorded results toward better than expected performance.

When SNR is above 0 dB, the 50 and 75 baud data closely approximates to the predicted characteristics. The 150 baud data performs worse than predicted at SNR above 10 dB due to the greater likelihood of inter-symbol interference at this transmission rate. This could be due to off great-circle propagation, particularly reflections from the auroral oval which could be delayed by the order of milli-seconds. Such delays were observed by Basler *et al.* (1988) on the Narssarssuaq, Greenland to Winter Harbor, Main path as described in the discussion in Chapter 2. However, it is not possible to attribute this effect with any great certainty to inter-symbol interference due to the lack of data on the mode structure of the received signal.

Comparison of results recorded at the same baud rates in Figures 7.2 and 7.3 indicate that there is no difference in the relationship between signal to noise ratio and P(e) across the two paths.

7.3 Error rate measurements

7.3.1 Clyde River to Alert (Site A), summer 1988

In Chapter 3 it was established that P(e) is a function of SNR, and in Chapter 6 that SNR correlates well with expected variation in solar produced ionisation at the lower propagating frequencies, that SNR is approximately constant at the mid propagating frequencies and that SNR is a function of the MUF at the highest propagating frequencies. These effects would be expected to influence P(e) in predictable ways throughout the day. Figure 7.4 illustrates the average variation of bit error rate (P(e)) observed on three frequencies over the Clyde











Figure 7.4(a): Average bit error rates (P(e)) measured on the Clyde River to Alert path during the Summer 1988 experimental campaign at 6.800 MHz.







Figure 7.4(c): Average bit error rates (P(e)) measured on the Clyde River to Alert path during the Summer 1988 experimental campaign at 13.886 MHz.

River to Alert path during the summer 1988 experimental campaign. Each bar indicating the averaged bit error rate is composed of two segments: the grey segment represents the number of data 1's received when 0's were expected and vice versa for the black segment. In the absence of co-channel interference, these two segments should be approximately equal. However, when an interfering signal is present on one of the tone frequencies, the distribution of errors will be unequal. Typically, there are in excess of 25,000 bits sampled for each hourly segment at 50 baud, in excess of 40,000 bits at 75 baud and in excess of 80,000 bits of data at 150 baud.

Although direct comparisons cannot be made between the results presented in Chapter 6 and those presented here for a variety of reasons: (a) the time difference of approximately 15 minutes between the recording of CW and FSK data; (b) the different filter bandwidths employed in the receiver hardware; (c) the different pre-selection techniques and slightly different frequencies (the FSK tones are shifted by 850 Hz and 1700 Hz for the low and high tones respectively from the base CW frequency), the general trends are expected to be similar. The results in Chapter 6 (Figure 6.4) indicated that, at frequencies around 6 MHz over the Clyde River to Alert path, there is very little diurnal variation in SNR which remains high (in excess of 30 dB) and approximately constant. Similarly, there is little diurnal variation in the average bit error rate observed on the 6.800 MHz FSK data transmission (Figure 7.4(a)). Due to narrower filter bandwidths on the lower baud channels, and therefore less noise and superior SNR, P(e) is lower on the 50 baud transmission than the 75 baud, which in turn is lower than the 150 baud. There is some evidence of a slight diurnal variation in P(e) on the 150 baud data as there is a slight increase in bit error rate between 13 to 0UT. This corresponds with the expected occurrence of peak absorption on this path (Figure 6.3).

At 10.195 MHz (the 9.941 MHz transmission was not recorded at this site during the summer 1988 campaign due to an omission in the recording schedule), similarly to the results observed on the 6.800 MHz signal, error rates on the faster baud rates are higher than on the slower baud rates. Although the bit error rate is still low (Figure 7.4(b)), there appears to be a slight increase in error rate at approximately local midnight (5UT). This trend is clearer on the 13.886 MHz data (Figure 7.4(c)) where the average error rate is significantly higher (approximately 30% on the 150 baud data at around local midnight) since the frequency often exceeds the path MUF at this time.

7.3.2 Clyde River to Fairbanks (Site B), summer 1988

A correlation is apparent between the FSK and CW data recorded over the Clyde River to Fairbanks path during the Summer 1988 experimental campaign. At 6.800 MHz (Figure 7.5(a)) there is a strong diurnal variation in bit error rate which is well correlated with changes in SNR illustrated in Figure 6.6. However, at this site, there are consistently more errors in one tone than the other. This may have been due to interference within the passband of one of the FSK detection filters.

At 10.195 MHz (Figure 7.5(b)), the error rate is lower than at 6.800 MHz and exhibits very little diurnal variation. At 13.886 MHz (Figure 7.5(c)) the average bit error rate is lower still (typically below 0.05 at 150 baud) and approximately constant.

7.3.3 Clyde River to Alert (Site A), winter 1989

During the Winter campaign, no FSK data was discernible at Alert due to the poor SNR. This may have been due to higher noise levels at the site, lower signal strength or associated with the change in transmitter antenna (Chapter 4). CW signals were analysed from this campaign in Chapter 6, but the FSK portion of the system is more susceptible to noise due to the wider filter bandwidths which result in poorer SNR. Consequently, no analysis was conducted on FSK data transmitted over this path during the winter 1989 campaign.

7.3.4 Clyde River to Fairbanks (Site B), winter 1989

The SNR on the Clyde River to Fairbanks path was lower during the winter campaign than the summer campaign as indicated by the higher average bit error rates that occurred (as illustrated in Figure 7.6). However, as with the Clyde River to Alert path, no direct comparison is possible between the summer and winter campaigns due to the changes in the transmitter antenna, but the main source of ionisation is, once again, assumed to be plasma convection from lower latitudes.

There was no clearly discernible relationship between variation in SNR and the position of the reflection point relative to the auroral oval in the results



Figure 7.5(a): Average bit error rates (P(e)) measured on the Clyde River to Fairbanks path during the Summer 1988 experimental campaign at 6.800 MHz.



Figure 7.5(b): Average bit error rates (P(e)) measured on the Clyde River to Fairbanks path during the Summer 1988 experimental campaign at 10.195 MHz.



Figure 7.5(c): Average bit error rates (P(e)) measured on the Clyde River to Fairbanks path during the Summer 1988 experimental campaign at 13.886 MHz.







Figure 7.6(b): Average bit error rates (P(e)) measured on the Clyde River to Fairbanks path during the Winter 1989 experimental campaign at 10.195 MHz.



Figure 7.6(c): Average bit error rates (P(e)) measured on the Clyde River to Fairbanks path during the Winter 1989 experimental campaign at 13.886 MHz.

discussed in Chapter 6. The results from the FSK data transmissions on similar frequencies (Figure 7.6) suggest that, at these times, the average bit error rate is significantly lower. On the 6.800 MHz 150 baud transmission (Figure 7.6(a)), P(e) is approximately 0.15 between 18UT and 6UT, rising to approximately 0.28 at 13UT. There are also variations evident in the 50 and 75 baud transmissions, though not as large. There is some evidence of this trend continuing on the 10.195 MHz data set (Figure 7.6(b)) and is clearer still on the 13.886 MHz transmission (Figure 7.6(c)).

Between approximately 18UT and 6UT, ionisation at F region heights may be enhanced by the precipitation of weak particles at auroral latitudes. This may support propagation at higher frequencies and thus reduce the bit error rate.

7.4 Error distribution measurements

A preliminary manual examination of the data described above indicated that errors appeared to be more likely to occur in clusters when Doppler spreading of the CW signal is small on the Clyde River to Fairbanks path during the summer 1988 campaign. The distribution of errors on the Clyde River to Fairbanks path during the winter, and the Clyde River to Alert path during the summer, was apparently random and there was no recognisable correlation with Doppler spreading. However, this was probably due to a larger average Doppler spreading during the winter campaign on the Clyde River to Fairbanks path and little variation in Doppler spreading on the path to Alert make comparison between Doppler spread variation and error distribution measurements difficult..

The following detailed analysis of the error distributions concentrates on the 13.886 MHz and 14.373 MHz data recorded during the summer 1988 campaign over the Clyde River to Fairbanks path. These frequencies were selected as the effects due to the position of the auroral oval with respect to the propagation path and diurnal effects could be differentiated as they peak at different times on this path. As indicated in the results discussed in Chapter 6, solar affects (variations in signal strength and signal to noise ratio) peak at 8UT (local midnight) and 20UT (local noon) whereas auroral affects (variation in Doppler spreading) are expected to occur between 16UT and

5UT. The two frequencies selected propagate nearly continuously and have low, and approximately constant, error rate. These frequencies also best illustrate the variation in Doppler spreading. Therefore, the effects solely due to the Doppler spreading (which correlate with the position of the auroral oval relative to the propagation path) can be investigated as opposed to other affects due to signal to noise ratio variations (which correlate with solar production of ions).

7.4.1 Initial observations

Initial analysis was conducted manually. The occurrence of errors were plotted against time and compared to the spectrum of the corresponding CW transmission. Examples of the errors observed on the 150 baud, 13,886 MHz transmission between Clyde River and Fairbanks on Monday 25 July 1988, at times of low Doppler and high Doppler spreading have been plotted in Figures 7.7 and 7.8 respectively. The errors are plotted in segments of 100 bits, and each plot covers 2000 bits of data. The spectra of the CW signals recorded on the same day are presented in Figure 7.9. The initial observations demonstrate that errors are more randomly distributed at times of high Doppler spread, and more likely to cluster at times of low Doppler spread.

Comparison of the spectra of the CW signals with the corresponding amplitude plots (Figure 7.10) indicates a clear relationship between fade duration and the extent of Doppler spreading: large spreads are associated with fades of short duration and small Doppler spreads are associated with fades of longer duration. This is due to large Doppler spreading being associated with multiple sub-modes which are summed at the receiver antenna. These components move in and out of phase causing rapid fading, and more importantly, fades of short duration. As errors occur when fades in signal amplitude are of a depth sufficient to take the signal strength below the level of the noise, when Doppler spreading is large, these fades will be of short duration and hence few errors will occur in a continuous burst. Similarly, during periods of slow fades (small Doppler spread) errors are expected to occur in longer bursts. This is illustrated in Figure 7.11.

7.4.2 Diurnal variation of error distributions

In order to quantify the observations discussed above, the method of characterising errors in to bursts previously described briefly in Chapters 3 and 5 was applied. Individual errors were sorted from errors that occurred in



<u>Figure 7.7</u>: Bit errors observed on the Clyde River to Fairbanks path on 25 July 1988 on the 13.886 MHz transmission at (a) 10 UT (SI = 13), (b) 11 UT (SI = 19) and (c) 17 UT (SI = 28).



Figure 7.8: Bit errors observed on the Clyde River to Fairbanks path on 25 July 1988 on the 13.886 MHz transmission at (a) 20 UT (SI = 120), (b) 21 UT (SI = 159) and (c) 22 UT (SI = 94).



Figure 7.9: Spectra of CW transmissions logged at 13.886 MHz on 25 July 1988 over the Clyde River to Fairbanks paths.



Figure 7.10: Spectra of CW transmissions (left) with corresponding amplitude plots (right).



Figure 7.11: Illustration of the effects on error distributions of (a) long fades and (b) short fades.

clusters (or bursts). A single, individual error is classified as any error bounded by four or more error free bits. Therefore, a burst is any group of errors with less than four error free bits between erroneous bits (i.e. an error density greater than 25%). The periods bounding the error bursts (periods with no errors) are referred to as the guard space. Examples explaining illustrating this are presented in Figure 7.12.

Averaged error distributions for the 13.886 MHz and 14.373 MHz 50, 75 and 150 baud signals as a function of time of day are presented in Figures 7.13 and 7.14. There is evidence of an increase in errors bursts of 2 or more bits (as opposed to individual errors) around 12UT when the second reflection point is expected to be furthest away from the auroral oval. This is clearest on the 13.886 MHz measurements. The largest variation is observed at 50 baud where the probability of a burst of 2 or more errors increases from approximately 5% to 20%.

The variation of guard space with time of day are presented in Figures 7.15 and 7.16. The guard spaces measured at 50, 75 and 150 baud on both the 13.886 MHz and 14.373 MHz transmissions were grouped into periods of 10 bits or more without error, 50 bits or more without error and 100 bits or more without error. Figures 7.15 and 7.16 indicate that there is no obvious correlation between time of day and the length of guard space Overall, the guard space appears to remain approximately constant and there is a likelihood of approximately 95% that an error will be followed by 10 or more error free bits of data on both frequencies analysed, regardless of baud rate.

7.4.3 Relationship of error distribution to Doppler spread

The measured error distributions were also plotted against the corresponding SI values calculated from the CW transmissions and a best fit line added to determine a clearer relationship. These plots are presented in Figures 7.17 and 7.18. Figures 7.17 and 7.18 demonstrate that there is a clear relationship between error distribution and Doppler spreading. An increase in Doppler spreading is correlated with an increasing likelihood of individually occurring errors and a decreasing likelihood of bursts of errors of any given length. This relationship is more pronounced on the lower baud rates, as evidenced by the greater gradients of the best fit lines. However, the function relating error distribution and SI is different for each frequency and baud rate



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Figure 7.12: Examples of error bursts and guard spaces.



Figure 7.13: Average number of errors occurring individually or in bursts as a percentage of the total number of errors recorded on the 13.886 MHz FSK data transmission during the Summer 1988 experimental campaign.





- O Error bursts of 2 or more
- △ Error bursts of 3 or more
- Error bursts of 4 or more

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Error bursts of 5 or more











Figure 7.16: Average length of guard space as a percentage of the total number of guard spaces recorded on the 14.373 MHz FSK data transmission during the Summer 1988 experimental campaign.



Figure 7.17: Average number of errors occurring individually or in bursts as a percentage of the total number of errors recorded on the 13.886 MHz FSK data transmission during the Summer 1988 experimental campaign plotted against the corresponding spread index measurement.



Figure 7.18: Average number of errors occurring individually or in bursts as a percentage of the total number of errors recorded on the 14.373 MHz FSK data transmission during the Summer 1988 experimental campaign plotted against the corresponding spread index measurement. due to the dependency on the overall error rate, which in turn is a function of signal to noise ratio. At times of high bit error rate, there will be a greater percentage of errors occurring in bursts of all lengths, regardless of the extent of Doppler spreading. Similarly, if the error rate is very low, or there are no errors occurring at all, naturally, the probability of a burst of any given length will be much lower.

Plots of guard space as a function of SI (Figures 7.19 and 7.20) indicate that the probability of a guard space of up to 100 bits at 150 baud remains constant, regardless of the extent of Doppler spreading. For guard spaces longer than 100 bits, this may not hold true. Given that the overall bit error rate is a function of the average signal to noise ratio, and not the rate of fading, for a given error rate if errors occur in shorter bursts, the bursts could be expected to occur more frequently.

7.5 Summary

The results described in this chapter demonstrate that bit error rate is a function of signal to noise ratio which, at the lower propagating frequencies, was demonstrated to correlate with the solar production of ionisation in Chapter 6. When there is no direct solar illumination, as in the winter 1989 experimental campaign, propagation conditions are governed by plasma convected from lower latitudes around local noon and this in turn relates to the bit error rates observed. Particle precipitation in the auroral zones can also augment the electron density and enhance propagation conditions, thus the reliability of a communications links may improve when a reflection point is located within the auroral oval.

Doppler spreading has been demonstrated to relate to the duration of fades. Fades are of short duration when Doppler spreading is large, and fades are of longer duration when Doppler spreading is small. When fades are short (large Doppler spreads), the probability of an error occurring in a burst of any given length is reduced. The probability of occurrence and length of bursts of errors can thus be related to the position of the reflection point with respect to the auroral oval. When the reflection point is within the oval, errors tend to occur in shorter bursts. The probability of a guard space of any length (up to 100 bits), however, is independent of Doppler spreading.

7.8



Figure 7.19: Average length of guard space as a percentage of the total number of guard spaces recorded on the 13.886 MHz FSK data transmission during the Summer 1988 experimental campaign plotted against the corresponding spread index measurement.

lakini.



Figure 7.20: Average length of guard space as a percentage of the total number of guard spaces recorded on the 14.373 MHz FSK data transmission during the Summer 1988 experimental campaign plotted against the corresponding spread index measurement.

CHAPTER 8 Summary, discussion and conclusions

8.1 Summary

In the preceding chapters, the characteristics of signals received during the course of two experimental campaigns (18 July to 11 August and 16 January to 10 February) over two paths (Clyde River to Alert and Clyde River to Fairbanks) have been described. The main factors controlling the observed characteristics have been identified. These factors were: solar production of ions during the summer months, plasma convection from lower to higher latitudes during the winter, and the influence of the auroral oval. The results presented in this thesis demonstrate that the effects of each of these factors can be treated independently.

8.1.1 Solar affects

Variations in solar zenith angle, χ , affects the production of ions over both paths discussed in this thesis and therefore the received signal strength. The general relationship between signal strength and the solar zenith angle, χ , is indicated by Equation 8.1 which assumes that the received signal strength is a function of the degree of non-deviative absorption the signal undergoes on passing at oblique incidence through a Chapman layer.

$S = S_0 - A.cos^n \chi$	Equation 8.1
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Where:

S is the received signal strength (dB) S₀ is the signal strength without absorption (dB) A is an unknown constant n is an unknown constant

There was good correlation between the observed signal strength variations on the lower propagating frequencies, on which the affect of non-deviative absorption would be greatest, and the variation in signal strength predicted by Equation 8.1 when the value of n was assumed to equal 1.

The noise strength varied in a similar manner to the signal strength.

8.1

However, at the lowest propagating frequencies, the noise strength reached a minimum value whereas the signal strength continued to decrease, there is therefore a greater effect on signal to noise ratio on the lower propagating frequencies. The major factor affecting received signal to noise ratio on the higher propagating frequencies is penetration of the ionosphere when the signal frequency exceeds the MUF at local midnight.

The general relationship between signal to noise ratio and received bit error rates on non-coherent FSK transmitted data is indicated by Equation 8.2.

 $P(e) = \frac{1}{2} e^{\frac{E_b}{2N_o}}$

Equation 8.2

Where E_b/N_o represents the signal to noise power ratio expressed as a numerical ratio.

The observed error rates in the 50, 75 and 150 baud 850 Hz shifted FSK transmitted data was better than predicted at low signal to noise ratios (below 0 dB) due to a bias introduced by the pre-selection of data. At higher signal to noise ratios, the observed results at 50 and 75 baud approximate the predicted characteristics. The 150 baud data was worse than predicted, possibly due to inter-symbol interference caused by off great-circle propagation.

The variation in bit error rates correlated well with the expected variation predicted by the model relating solar zenith angle to the production of ionisation (Equation 8.1).

8.1.2 Plasma convection affects

Both experimental paths were in darkness throughout the winter 1989 campaign but HF propagation was still possible. The model developed by Fuller-Rowell and Rees (1980, 1983) indicates that this could be achieved due to the convection of plasma from lower latitudes around local noon. At this time, a decrease in signal strength is observed on the lower propagating frequencies over both paths (Chapter 6). This could be due to an increase in D-region absorption associated with the plasma flows predicted. Overall, the increased ionisation due to plasma convection is insufficient to raise MUF levels to those observed during the summer.

Signal to noise ratio was lower on both paths during the winter. This resulted in the FSK data being indiscernible from the noise at Alert and higher bit error rates (than the summer campaign) at Fairbanks. There were no obvious trends discernible in the observed error rates at this site that could be associated with the predicted pattern of convection flow.

8.1.3 Auroral affects

As the Clyde River to Alert path was a polar cap path, no effects due to interaction with the auroral oval were observed. The Clyde River to Fairbanks path alternated between being a polar cap and a trans-auroral path. When the second hop reflection point of the path to Fairbanks was expected to be within the boundaries of the oval (as calculated from the Feldstein and Starkov (1967) model), spectral analysis of the received CW signal showed a marked increase in Doppler spreading, with Doppler spreading exceeding 20 Hz at times.

The extent of Doppler spreading was demonstrated to be related to the duration of fades in the received signal strength. Large Doppler spreads are synonymous with fades of short duration, and similarly, small Doppler spreads are related to fades of longer duration. The duration of fades in signal strength and Doppler spreading, were in turn demonstrated to be related to the distribution of errors observed in the received FSK data, but not to the number, or rate, of errors.

During periods of small Doppler spreading, errors in the FSK data are more likely to occur in groups, or bursts. Whereas, during periods of large Doppler spreading, errors are more likely to occur on their own or in shorter bursts. The length of error free data between errors (guard space) is independent of Doppler spreading for guard spaces of up to 100 bits. The distribution of errors has thus been demonstrated to correlate with the position of the reflection point with respect to the auroral oval.

8.2 Discussion

Contrary to expectations, the results in this thesis demonstrate that communication circuits with a reflection point within the auroral oval can

have their characteristics enhanced. The more random distribution of errors when Doppler spreading is large can allow the use of simple and efficient forward error correction codes. Furthermore, the selection of the best propagating frequency is not significantly affected by auroral effects (on the paths analysed). The most important factor in selecting the best frequency for the least number of bit errors is solar control of the MUF, and of D-region absorption which affects the signal to noise ratio.

However, it should be noted that the results in this thesis relate particularly to an 850 Hz shifted FSK data transmission. This system was immune to the extent of Doppler spreading measured during the course of this experiment because of the wide separation between the two tones. A system employing a smaller shift between the two tones on a trans-auroral circuit could be susceptible to energy spilling over between the two channels as a result of the large Doppler spreads observed. Systems employing Phase Shift Keying (PSK) would be susceptible to large phase fluctuations associated with Doppler spreads.

8.3 Concluding remarks

The results presented here are of particular relevance to researchers developing programs to predict the characteristics of radio communication circuits at high latitudes and those employing channel simulators to assess communication systems. Affects on bit error rates and error distributions on FSK data transmissions are of particular importance to the communications engineer. Prior knowledge of the likely characteristics that will occur over a link can be valuable in the selection of an appropriate transmission format. Further work should enable the prediction of bit errors and error patterns to be made from a knowledge of the geophysical conditions and path geometry. This will enable the selection of the appropriate frequency and transmission format for any given polar cap or trans-auroral path. For those employing high latitude communication links, it may prove possible to employ a simple measure of Doppler spreading, such as the spread index, to determine the most efficient transmission format to use (e.g. forward error correction codes, automatic repeat requests, etc.).

Further experiments are required to compile a database of results for analysis.
It may be desirable to modify the equipment for future experiments to enable absolute measurements of signal strength so that the affects on signal strength can be determined quantitatively. A change in the transmission schedule, or modifications to the equipment could also allow the measurement of Doppler spreading at, or nearly at, the same time as, as the FSK signal. Measurements also need to be made over a wide variety of paths at a range of geomagnetic condition. Other workers (Davies and Cannon (1993), Roesler and Bliss (1988)) are also developing systems and making measurements that would also be relevant to this work and could similarly be incorporated into future prediction programs.

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