Effect of geomagnetic activity on the channel scattering functions of HF signals propagating in the region of the midlatitude trough and the auroral zone

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[1] The morphology of the auroral and subauroral ionosphere is strongly dependent on the interplanetary magnetic field and the level of geomagnetic activity. This change in the morphology impacts on the characteristics of signals received after propagation through these regions of the ionosphere. In order to develop a better understanding of these effects, a number of experiments have recently been undertaken in which the time of flight, Doppler frequency, and direction of arrival of HF signals have been measured over several northerly paths. In this paper, parameters derived from the observations of the channel scattering functions and direction of arrival for HF signals propagating over two paths (one in the auroral zone, and one at latitudes affected by the midlatitude trough) are presented.

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1. Introduction

[2] The morphology of the auroral and subauroral ionosphere is strongly dependent on the interplanetary magnetic field and the level of geomagnetic activity. For example, as the geomagnetic activity increases, the size of the polar cap tends to increase and the auroral oval moves equatorwards. This change in the morphology impacts on the characteristics (e.g., Doppler and delay spreads, and direction of arrival) of signals received after propagation through these regions of the ionosphere. In order to develop a better understanding of these effects, a number of experiments have recently been undertaken by the University of Leicester in which the time of flight, Doppler frequency, and direction of arrival of HF signals have been measured over several northerly paths. Measurements from Uppsala, Sweden to Leicester, U.K. and Kirkenes, Norway to Kiruna, Sweden are considered in this paper.

[3] This paper is primarily concerned with the effect of geomagnetic activity on the channel scattering functions (i.e., the variation of signal amplitude with delay time, Doppler and, in this paper, direction of arrival). An

understanding of the influence of geophysical parameters on the characteristics of HF signals is important for the development of prediction techniques required for new systems.

2. Experimental Details

[4] Measurements made over two paths (Figure 1 shows their position relative to the modeled position of the midlatitude ionospheric trough [Halcrow and Nisbet, 1977] for a time of 0200 UT with Kp values of 0 and 6) on frequencies in the range 4–20 MHz are presented in this paper: (a) a 1400 km link along the midlatitude trough with the transmitter located in Uppsala, Sweden and the receiver in Leicester, U.K., and (b) a 450 km link located predominantly in auroral zone between Kirkenes, Norway and Kiruna, Sweden. The Uppsala transmitter operated on a 3 minute cycle during which time transmissions were made in sequence on six frequencies in the range 4 to 18 MHz, whereas the Kirkenes transmitter operated on a similar range of frequencies but on a 20 minute cycle. In addition, an oblique ionospheric sounder was operated over the Uppsala to Leicester path to aid interpretation of the measurements. The systems were operated throughout the day over the course of just over a year.

[5] The radiated signals comprised 2 second sequences of 13-bit Barker coded PSK pulses modulated at (usually)

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Figure 1. Map illustrating the two propagation paths considered in this paper, together with the modeled position [Halcrow and Nisbet, 1977] of the midlatitude trough at 0200 UT for Kp values of 0 (top) and 6 (bottom).

1667 baud with a repetition rate of 80 coded pulses per second for the Uppsala transmitter, and 2000 baud with a repetition rate of 66.7 coded pulses per second for the Kirkenes transmitter. Since the transmitter and receiver systems were synchronized to GPS, the absolute time of flight of the signals could be determined. The signals were received with a large sampled aperture antenna array, each element of which was connected to a separate receiver. The complex amplitudes of the signals received on each antenna within the array were sampled simultaneously 10000 times per second and the data processed to provide a measure of the relative times of flight of the propagating modes and their associated Doppler spectra (see the method employed by the DAMSON system, described by Davies and Cannon [1993]). In this way, the signal was split into components distinguished by time of flight, Doppler frequency and by antenna position in the receiving array. A direction finding algorithm (usually a modified version of the Capon algorithm

[Featherstone *et al.*, 1997]) was then applied to each signal component in turn in order to estimate the directional characteristics of the received signal. Although the modified Capon algorithm was usually employed in the processing of the experimental data, the choice of algorithm is not particularly critical (see Warrington *et al.* [2000] for a discussion of the behavior of various algorithms in the presence of diffuse signal energy). Note that when several signal components closely separated in direction of arrival are present in a single delay-Doppler cell, the DF algorithm may produce a single estimate of the direction of arrival. This arises from the limited resolving capability of the DF algorithm and it is expected that the estimated direction of arrival will usually be bounded by the limits of the direction of arrival spread within the cell. The precise value of the estimated direction of arrival will vary with time as the relative phases and amplitudes of the constituent components within the delay-Doppler cell change.

3. Observations

3.1. Uppsala to Leicester Path, 6.95 MHz

[6] The Uppsala to Leicester path is about 1400 km long with a great circle bearing at the receiver of approximately 46° , and is often located under the expected position of the midlatitude trough. Warrington and Stocker [2003] and Siddle *et al.* [2004a, 2004b] have previously reported the statistical variations of Doppler and delay spread, and of time of flight and direction of arrival as a function of time of day and of season for this path. Further interpretation of these measurements from the point of view of variations in the channel scattering function with geomagnetic activity is presented in this paper.

[7] An example nighttime scattering function for this path is presented in Figure 2. The signal was received on great circle ($\sim 46^\circ$ azimuth) via a reflection from a sporadic E layer at a delay of around 5 ms and Doppler frequency of 0 Hz (note that there may be a small systematic offset in this particular parameter) and off great circle ($20\text{--}30^\circ$ azimuth) at a delay of about 7 ms. It is interesting to note that, in this instance, the signal arriving at the longer delay (probably via a reflection or scattering from the northward trough wall) is separated into two parts distinguished by different Doppler shifts and azimuthal directions of arrival. For further analysis, the scattering function is characterized by identifying each of the active regions by setting a threshold of (in this case) -6dB relative to the peak and determining the delay, Doppler and direction of arrival of the resulting modes and their associated spreads.

[8] The most striking features in these measurements are the off-great circle modes with increased times of

Figure 2. Scattering function for the Uppsala–Leicester path, 6.95 MHz, 26 December 2001, 2118 UT. Note that the elevation angle measurements are not accurate for low elevation angles. This has resulted in a cluster of points close to 0° elevation in the delay versus elevation angle plot.

flight observed at night (see *Siddle et al.* [2004a, 2004b] for more examples).

[9] Approximately six weeks of measurements have been aggregated and plotted as a function of time of day in Figure 3. During the day, the measurements indicate that propagation is largely on-great circle at delays of less than 6 ms and elevation angles of about 20° and 35° , corresponding to 1F and 2F modes respectively. However, the most striking features in these measurements are the off-great circle modes with increased times of flight observed at night. For example, around midnight (UT), the signal arrives up to about 40° to the north of the great circle direction accompanied by significantly larger delays (up to around 9 ms), and elevation angles of about 15° . Previous work [*Siddle et al.*, 2004a, 2004b; *Warrington and Stocker*, 2003; *Warrington et al.*, 2006; *Zaakov et al.*, 2005] has established that this off great circle propagation is consistent with the signal scattering from irregularities in the auroral oval or embedded in the poleward wall of the trough, accompanied by refraction in the trough wall when the electron density depletion in the trough is such as not to support on-great circle propagation.

[10] Since the position of the northern wall of the trough and southern border of the auroral oval depend on the level of geomagnetic activity, the scattering function distributions have also been plotted as a function of K_p (Figure 4). The K_p values for individual measurements of delay and azimuth plotted in this figure have been derived from the 3-hourly values of K_p using a spline interpolation. For these measurements, the azimuth deviation from the great circle direction decreases as K_p increases, and there is a less marked trend in delay with K_p , although larger delays do occur for values of K_p of about 0.5, just under 1.5, and at around 3. This behavior is consistent with changes in the position in relation to the path of the auroral oval and the midlatitude trough with K_p (see Figure 1), since as geomagnetic activity increases the poleward wall of the trough moves southward, and therefore the reflection or scattering region moves to lower latitudes consequently reducing the azimuthal deviation from the great circle direction.

[11] However, the equatorward border of the auroral oval is not fixed in latitude with time even in the case when K_p is fixed. In order account for this, the scattering

Figure 3. Diurnal dependence of the scattering function for the Uppsala–Leicester path, 6.95 MHz, 1 December 2001 to 13 January 2002. The contours represent the fraction of the number of observations with values of 0.2, 0.5, 0.7, and 0.9 (these values are used in all figures). Note: data within 3° of the great circle azimuth have been excluded from the analysis to highlight off-great circle features.

function parameters have been displayed (Figure 5) as a function of the geomagnetic colatitude of the northern wall of the trough at longitudes corresponding to either the path midpoint, the receiver or the transmitter depending on the most likely value based on the direction of arrival and the delay of the received signal (this is clearly an approximation). The model of *Halcrow and Nisbet*

[1977] was used to determine the position of the poleward wall of the trough and it was assumed that this coincided with the southward border of the auroral oval. Several traces are evident in Figure 5, where the scattering function distributions have been plotted as a function of the geomagnetic colatitude of the northern wall of the trough. Trace 1 corresponds to the great circle mode.

Figure 4. Scattering function correlation with Kp for the Uppsala–Leicester path, 6.95 MHz, 1 December 2001 to 13 January 2002. Note: data within 3° of the great circle azimuth have been excluded from the analysis in order to highlight off-great circle features.

Trace 2 has a fixed azimuth deviation of about 20° to the north of the great circle and probably corresponds to scattering from auroral irregularities. Trace 3 exhibits a very pronounced trend and can be associated with refraction from the northern wall of the trough. The distribution of delay as a function of auroral oval position is given in the lower frame of Figure 5, with the various traces marked by the same numbers as in the

azimuth case. Several features can be distinguished. The delay is enhanced from geomagnetic colatitudes of about 24° where refraction (Trace 3) is predominant, i.e., the increased delay is accompanied by a strong northward deviation in azimuth. This behavior follows the changes in the position of the auroral oval and midlatitude trough north wall. The weak trace 2, which is flat in azimuth, exhibits a small increasing trend in delay. This is more

Figure 5. Azimuth and delay distribution correlation with auroral oval position for the Uppsala–Leicester path, 6.95 MHz.

evident when off great circle propagation due to refraction is not supported.

[12] As was noted above, frequencies in the range 4.5–18 MHz were employed for these measurements. Very similar structures of off-great circle effects were observed at frequencies in the 7–14 MHz range. At the lower end of the frequency band (4.6 MHz), the propagation was largely within a few degrees of the great circle direction, whilst at the upper frequency (18.1 MHz) off-great circle

modes were occasionally observed, but not often enough to obtain reliable statistics.

3.2. Kirkenes to Kiruna Path, 6.78 MHz

[13] The Kirkenes to Kiruna path (450 km, great circle bearing at the receiver 63°) is, for the most part, located under the expected position of the auroral oval. For this path, it is interesting to note that, unlike the Uppsala to Leicester path, the general signal behavior does not exhibit regular day-to-day behavior.

Figure 6. Diurnal dependence of the scattering function for the Kirkenes-Kiruna path, 6.78 MHz, 11 December 2004 to 17 January 2005.

[14] Presented in Figure 6 are the occurrence statistics of azimuth, elevation angles and delay of the individual modes from approximately five weeks of measurements plotted as a function of time of day. The signal tends to arrive from the great circle direction ($\sim 63^\circ$) and at a delay of 2 ms except for a few hours around local noon (1000 UT). This may be contrasted to the Uppsala–Leicester path where off great circle path propagation was observed at night. No signals were received in the interval just before sunrise (0500–0700 UT) since it is

likely that the operating frequency exceeded the MUF at this time. In the top frame, off great circle modes with azimuth deviations of about 40° to the south and up to 50° to the north are evident between 0800 and 1200 UT. These modes are accompanied by delays of about 3–4 ms (middle frame) and elevation angles of 40° – 60° (bottom frame).

[15] Since the position of southern border of the auroral oval depends on the level of geomagnetic activity, then it is reasonable to expect correlation of the

Figure 7. Scattering function correlation with Kp index for the Kirkenes-Kiruna path, 6.78 MHz, 11 December 2004 to 17 January 2005.

scattering function distributions with Kp. In Figure 7, the azimuth, delay and elevation angle distributions have been plotted as a function of Kp. The distinctive off great circle modes northward and southward are apparent only for Kp just under ~ 1 , when presumably the southward border of the auroral oval crosses the propagation path.

[16] Azimuth, delay and elevation angle scattering function distributions have been plotted versus the magnetic colatitude of the southern border of the auroral oval in Figure 8. A southward trace (i.e., azimuths larger than

the great circle direction) with maximum azimuth deviation from great circle of about 60° is apparent at colatitudes of between 18° and 19° while a northward trace is evident between 18.5° and 20° (top frame). The southward trace may be a result of the signal being refracted in the steep gradients of the southern wall of the dayside high-latitude trough [e.g., see Pryse *et al.*, 2005], while the northward trace is consistent with the signal scattering from irregularities in the auroral zone or refraction from the poleward wall of the dayside trough.

Figure 8. Scattering function correlation with auroral oval position for the Kirkenes-Kiruna path, 6.78 MHz, 11 December 2004 to 17 January 2005.

Significantly larger delays up to around 3.5 ms (middle frame), and higher elevation angles of about 50° (bottom frame) are associated with the off-great circle modes. There is a seasonal dependence on the time of day at which the off-great circle propagation is observed – during the day in winter and at night during spring. Unfortunately in the spring, the range of K_p values that occurred when HF observations were available was not large enough to determine whether the off-great circle propagation had a K_p dependence at that time.

[17] The structure of HF signals propagated in the auroral region depends to a large extent on auroral activity and hence on space weather conditions. The effects of the interplanetary magnetic field components and various solar wind particle fluxes on the HF measurements presented here have been investigated. With the exception of an intriguing effect found with different levels of proton density in the solar wind measured by the ACE satellite (observations were obtained from <http://omniweb.gsfc.nasa.gov>) and presented in Figure 9, no

Figure 9. Scattering function correlation with auroral oval position for two levels of the proton density: 0–5 protons/cm³ (left) and 5–30 protons/cm³ (right).

other correlations were found. In Figure 9, the azimuth, elevation and delay scattering function distributions have been plotted for two bands of the proton density of 0–5/cm³ and 5–30/cm³. While both northward and southward traces of azimuth deviation are observed, the northward deviations in azimuth are weak when the proton density is less than 5/cm³, but the southward trace is well pronounced. By contrast, when the proton density is higher (between 5–30/cm³) the azimuth is only deviated northward and then only as the auroral oval comes further south. This behavior may be related to changes in the morphology of the trough and auroral

oval, since as proton density increases the intensity of the irregularities may also increase, particularly to the north of the path. As a consequence, the limited dynamic range of our experimental system means signals deviated to the south are sufficiently weak compared to those from the north that they are no longer detected.

4. Concluding Remarks

[18] Observations of azimuth and delay have been presented for HF signals propagating over two paths:

one in the region of the night time midlatitude trough (Uppsala–Leicester) and the other in the auroral zone (Kirkenes–Kiruna). In both cases, measurements were taken over periods in excess of one year, although only observations from an interval of about six weeks centred roughly on the winter solstice have been presented in this paper.

[19] There is a strong diurnal variation in the scattering functions parameters for both paths. In the Uppsala–Leicester case, signals arrive from azimuths significantly off-great circle at night, while in the Kirkenes–Kiruna case, off great circle propagation is only observed during the day at times close to local noon. Previous work [Siddle *et al.*, 2004a, 2004b] concluded that the off great circle propagation observed on the Uppsala–Leicester path results from the signals reflected or scattered from the electron density gradients or irregularities in the poleward wall of the trough. Since it is well known that the latitude of the poleward wall of the midlatitude trough tends to move to lower latitudes as Kp increases, the dependence of the azimuth deviation on Kp presented in this paper strongly supports the previous conclusions.

[20] Although observations presented for the Kirkenes–Kiruna path do not exhibit a strong relationship of the azimuth and delay with Kp, a more pronounced correlation with position of the equatorward boundary of auroral oval was found – particularly for the delay. It is likely that this behavior arises from the presence of the daytime high-latitude trough which will lie across or slightly to the north of the path midpoint for low Kp, across or to the south for moderate Kp and well to the south for high Kp. The observed behavior also depends on the level of particle precipitation, with only northward deviated signals being detected when the proton density is higher than 5 cm^{-3} . It may be that the occurrence of on great circle propagation for these conditions masks the presence of the weaker southward deviated signal.

[21] The authors aim to develop improved techniques for the prediction of HF signal characteristics for signals propagating via the northerly regions of the ionosphere. Many geophysical processes influence this region of the ionosphere in a complex manner, and insight into how the signal characteristics vary, as a function of geophysical parameters is an important step towards this goal.

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