On the occurrence and motion of decametre-scale irregularities in the sub-auroral, auroral, and polar cap ionosphere

M. L. Parkinson¹(✉), J. C. Devlin², H. Ye², C. J. Waters³, P. L. Dyson¹, A. M. Breed⁴,* and R. J. Morris⁴

¹Department of Physics, La Trobe University, Victoria 3086, Australia
²Department of Electronic Engineering, La Trobe University, Victoria 3086, Australia
³Department of Physics, University of Newcastle, New South Wales 2038, Australia
⁴Atmospheric and Space Physics, Australian Antarctic Division, Kingston, Tasmania 7050, Australia

*Deceased, 5th September, 2002

E-mail: m.parkinson@latrobe.edu.au
Fax: 61-3-94791552
Ph: 61-3-94791433
Abstract. The statistical occurrence of decametre-scale ionospheric irregularities, average line-of-sight (LOS) Doppler velocity, and Doppler spectral width in the sub-auroral, auroral, and polar cap ionosphere (–57°Λ to –88°Λ) has been investigated using echoes recorded with the Tasman International Geospace Environment Radar (TIGER), a SuperDARN radar located on Bruny Island, Tasmania (147.2°E, 43.4°S geographic; –54.6°Λ). Results are shown for routine soundings made on the magnetic meridian beam 4 and the near zonal beam 15 during the sunspot maximum interval December 1999 to November, 2000. Most echoes were observed in the nightside ionosphere, typically via 1.5-hop propagation near dusk and then via 0.5-hop propagation during pre-midnight to dawn. Peak occurrence rates on beam 4 were often >60% near magnetic midnight and ~ –70°Λ. They increased and shifted equatorward and pre-midnight with increasing $K_p$ ($B_z$ southward) due to activation of the cross-polar cap jet and substorm activity. The occurrence rates remained very high for $K_p$ >4, despite enhanced $D$-region absorption due to particle precipitation. Average occurrence rates on beam 4 exhibited a relatively weak seasonal variation, consistent with known longitudinal variations in auroral zone magnetic activity (Basu, 1975). The average echo power was greatest between 23 and 07 MLT, confirming the predicted dependency of $E \times B$ instability growth rate on slip velocity (Tsunoda, 1988). Two populations of echoes were identified on both beams, those with low spectral width and a mode value of ~9 m s$^{-1}$ (bin size of 2 m s$^{-1}$) concentrated in the auroral and sub-auroral ionosphere (population A), and those with high spectral width and a mode value of ~70 m s$^{-1}$ concentrated in the polar cap ionosphere (population B). The subset of the population A echoes observed near dusk had characteristics reminiscent of “dusk scatter” (Ruohoniemi et al., 1988), but they maximised post-midnight because of TIGER’s lower latitude. There was a dusk “bite out” of large spectral widths between ~15 and 21 MLT and poleward of –67°Λ, and a pre-dawn enhancement of large spectral widths between ~03 and 07 MLT centred on ~ –61°Λ. The average LOS Doppler velocities revealed frequent westward jets of plasma flow occurred equatorward of, but overlapping, the diffuse auroral oval in the pre-midnight sector.

Key words: 2407 Auroral ionosphere, 2411 Electric fields and currents, 2439 Ionospheric irregularities
1 Introduction

It is well known the transfer of solar-wind energy and momentum to the coupled magnetosphere-ionosphere-thermosphere system is constantly changing due to fluctuations in magnetic reconnection, turbulent boundary layer processes, and dynamic pressure in the solar wind (Kivelson and Russell, 1995). Variations in ionospheric conductivity and thermospheric winds also regulate the flow of energy throughout the system. Some authors have found evidence suggesting these processes, including the magnetospheric boundaries formed by them, produce reasonably distinct signatures in the amplitude and motion of ionospheric irregularities (e.g. Lester et al., 2001; Pinnock et al., 1993). However, there are still outstanding issues such as identifying the best theoretical description of magnetospheric substorms (Lui, 2001), a phenomenon well known to produce brilliant auroral displays and dramatic changes in the distribution of ionospheric irregularities (e.g. Lewis et al., 1997; Yeoman et al., 1999).

The Super Dual Auroral Radar Network (SuperDARN) is a ground-based network of high frequency (HF) backscatter radars providing global scale coverage of the occurrence, amplitude, and motion of ~10-m scale ionospheric irregularities in response to dynamic high-latitude processes (Greenwald et al., 1985, 1995). HF backscatter radars obtain coherent echoes when the obliquely propagating radio waves achieve normal incidence with magnetic field aligned irregularities of sufficient amplitude. The fluid $\mathbf{E} \times \mathbf{B}$ (gradient drift) instability (see Tsunoda, 1988; Kelley, 1989) is the mechanism most often cited as the cause of the 10-m scale irregularities observed at HF. However, the 10-m scale irregularities are thought to be secondary instabilities driven by primary gradient drift instabilities acting at 100-m to 1-km scales (e.g. Jayachandran et al., 2000). The current convective and two-stream instabilities have also been implicated as the cause of irregularities observed at HF (Fejer and Kelly, 1980).

The Tasman International Geospace Environment Radar (TIGER) (Dyson and Devlin, 2000) is a SuperDARN radar located on Bruny Island, Tasmania (147.2°E, 43.4°S geographic; −54.6°Λ geomagnetic). Echo occurrence and motion-related statistics have been compiled for other radars in the SuperDARN network (Ruohoniemi et al., 1988; Leonard et al., 1995; Ruohoniemi and Greenwald, 1997; Nishitani et al., 1997; Milan et al., 1997b; Fukumoto et al.,
1999; Hosokawa et al., 2000; Villain et al., 2002). However, TIGER is the most equatorward of the SuperDARN radars, both geographically and geomagnetically, extending the network coverage to include the midnight sub-auroral and auroral ionosphere for moderate levels of geomagnetic activity. Hence TIGER is favourably located to study ionospheric substorms, and the accompanying narrow channels of large westward drift known as sub-auroral ion drifts (SAIDs) (Galperin et al., 1973; Anderson et al., 1991). Thus we expect the TIGER statistics to differ from those obtained with other SuperDARN radars.

In this paper we report the occurrence statistics and average motions of ionospheric irregularities observed using TIGER during the first year of operation, the sunspot maximum interval December 1999 to November, 2000. The majority of echoes observed using TIGER were “sea echoes” from the Southern Ocean (~62%), but these have been excluded in this study. The results have been sorted according to universal time (UT), magnetic local time (MLT), season, the geomagnetic activity index, $K_p$, and the interplanetary magnetic field (IMF) vector separated into the four basic quadrants of the $B_y$–$B_z$ plane. Wherever possible, the behaviour of the parameters have been related to familiar magnetospheric boundaries and regions, and the behaviour predicted by others.

We report the average LOS Doppler velocities along the magnetic meridian (providing a direct measure of zonal electric fields) and Doppler velocity spread, or “spectral widths.” The latter are a measure of the spread of irregularity motion within the sampling volume corresponding to individual range cells, and are thought to be enhanced by Pc 1–2 hydromagnetic wave activity (André et al., 1999; André et al., 2000). Broad band bursts of ULF wave activity measured by an induction coil magnetometer located at Macquarie Island (159.0°E, 54.5°S; –65°Λ) are associated with large spectral widths appearing at the same magnetic latitude in the field of view (FOV) of the TIGER radar (Parkinson et al., 2003c).

The occurrence and motion of 10-m scale irregularities observed with HF backscatter radars are determined by the product of various instrumental and geophysical factors (Ruohoniemi and Greenwald 1997):
1. The design and operation of the radar including the chosen pulse set and beam sequence, antenna pattern, the transfer function of all hardware elements, and any other factors affecting the radar gain versus frequency and direction all affect the detection of echoes. The logic incorporated in the signal-processing methods used to recognise and characterise the echoes, and the subsequent procedures used to compile the statistics also influence the results.

2. The morphology of the ionospheric layers and the propagation modes they support (Milan et al., 1997b) determine whether the conditions for coherent backscatter are met. Spatial and temporal (diurnal, seasonal, and sunspot cycle) variations in non-deviative absorption (Davies, 1990), and focussing and defocusing of HF rays by the ionosphere are also very important considerations, but they are difficult to quantify without detailed ray tracing.

3. The generation of decameter-scale irregularities by different ionospheric instabilities and their subsequent dissipation is highly variable. Gradients in electron density associated with insolation, large-scale convection, particle precipitation, and atmospheric gravity waves must regulate the growth of $E \times B$ instabilities (Fejer and Kelley, 1980). Enhanced $E$-region conductivity increases dissipation of the irregularities via enhanced cross-field diffusion (Vickrey and Kelley, 1982).

Because of reasons 1. and 2., echo occurrence rates are usually lower limits to the actual irregularity occurrence rates.
2 Observations and analysis

Figure 1 shows the FOV of the TIGER radar mapped in geographic (left) and geomagnetic (right) co-ordinates. The bore sight of TIGER (beams 7/8) points geographic south, whereas beam 4 is closely aligned with the magnetic meridian (226°E). Beam 15 is the most easterly and nearly zonal beam in magnetic co-ordinates. In the fast (normal) common mode of operation, TIGER performs one sequential 16-beam scan from east (beam 15) to west (beam 0), integrating for 3 s (7 s) on each beam. Hence a full scan takes 48 s (112 s), with successive scans synchronised to the start of 1-min (2-min) boundaries. Individual beams in the scan are separated by 3.24°, and the full scan spans 52° of azimuth.

Figure 1 illustrates the large difference between the geographic and magnetic FOVs—some of the underlying dynamics will be characteristic of a high mid-latitude station (e.g. radio propagation, insolation, and \( D \)-region absorption), yet others will be characteristic of the sub-auroral, auroral, and polar cap ionosphere. Figure 1 also illustrates the presence of two separate populations of ionospheric echoes, “A” and “B,” with low and high spectral widths, respectively, (to be defined). Model auroral oval boundaries given by Starkov (1994b) have been superimposed with beam 4 located at midnight MLT. The auroral electrojet index \( AL = -172 \) corresponding to \( K_p = 3 \) used to drive the model was calculated using the conversion given by Starkov (1994a). The Starkov model has been tested against real data, but other models would give similar results.

If occurrence statistics were compiled for all 16 beams combined, it would be difficult separating geophysical and geometric dependencies. Hence we compiled occurrence statistics for beams 4 and 15 (Fig. 1, bold), thereby revealing the most interesting aspects of data recorded on all beams. For example, beam 4 was chosen because it points down the magnetic meridian, providing an overview of dynamics occurring in the sub-auroral, auroral, and polar cap ionosphere (−57°Λ to −88°Λ). Assuming the \( \mathbf{E} \times \mathbf{B}/B^2 \) drift of \( F \)-region irregularities, the corresponding LOS Doppler velocities are also a direct measure of zonal electric fields occurring along the meridian.

In contrast, beam 15 (bold) was chosen because its range window extends from latitude −57°Λ to −72°Λ, providing a detailed view of the nightside sub-auroral and auroral ionosphere. Beam 15 becomes a zonal, eastward-looking beam
at furthest ranges, reaching a maximum latitude of –71.8°Λ (range cell 68) before folding back toward the equator beyond this range. Thus beams 4 and 15 are the two most independent, nearly orthogonal beams in the FOV. Finally, beam 15 is located adjacent to Macquarie Island (–65°Λ), a key sub-antarctic station supporting many ground-based instruments.

Table I

In this study we compiled statistics using all available, common mode data recorded during the sunspot maximum interval, December, 1999 to November, 2000. The actual dates of the measurements are shown in Table 1, subdivided into four seasons redefined to encompass ~90-day intervals centred on the equinoxes and solstices. This sorting emphasises the component of seasonal variability controlled by the solar-zenith angle, though other controls may dominate (Basu, 1975). The radar control programs used to make the normal and fast mode soundings were “normal_scan_nodata” and “normal_scan3,” respectively. We excluded most of the data recorded with other experimental programs to prevent introduction of statistical biases.

The default transmission frequency bands for normal_scan3 were 14.35 to 14.99 MHz during the “day” (21 to 07 UT), and 11.65 to 12.05 MHz during the “night” (07 to 21 UT). A clear frequency search was always performed within these individual frequency bands. However, normal_scan_nodata invoked a frequency search algorithm whenever fewer than 20 range bins contained ionospheric echoes. The program then spent two minutes integrating on beam numbers 2, 6, 10, and 14 at one frequency in each of five different licensed bands spread between 10.1 and 15.6 MHz. The frequency band with the largest number of ionospheric echoes was then adopted in subsequent scans until echoes were detected in fewer than 20 range bins again. The program used the same default bands as normal_scan3 whenever fewer than 5 echoes were detected during a frequency search.

Figure 2

Figure 3

Figure 2 is a histogram showing the roughly trimodal distribution of radar frequencies used throughout the entire study interval. The scale size of
ionospheric irregularities corresponding to each one of the dominant frequency bands were 14.4, 12.3, and 10.3 m, respectively. If it were not for the effects of prohibited frequency bands (shaded), combined with the effects of narrow band interference, the histogram might approximate a bell-shaped or log-normal curve centred somewhere between 10 to 12 MHz. The latter is the known frequency of maximum radar gain.

Figure 3 shows the diurnal variation of the transmitter frequency averaged over 30-min intervals, with scatter bars superimposed. The daytime frequency tends to be >1 MHz larger, simply to compensate for greater refraction associated with higher day-time electron densities, and thereby increase the probability of recording useful echoes at greater ranges. Note the discontinuities near 08 and 19 MLT. Figures 2 and 3 are shown because they represent important biases in our results.

In the common mode of operation, SuperDARN radars calculate the autocorrelation functions (ACFs) of echoes (Hanuise et al., 1993) digitised at 75 range gates starting at 180 km and separated by 45 km (i.e. 180 to 3555 km). The 45-km interval corresponds to the 300-µs width of transmitter pulses. The “FITACF” algorithm (Baker et al., 1995) processes the ACFs to estimate the echo power in logarithmic units of signal-to-noise ratio (i.e. dB), LOS Doppler velocity (m s⁻¹), and the Doppler spectral width (m s⁻¹), for all ranges on every beam. Our version of FITACF rejected echoes with SNR <3 dB, flagging the remainder as sea echoes if the Doppler speeds and spectral widths were less than 50 m s⁻¹ and 20 m s⁻¹ respectively, and determined with small errors. In this study, ionospheric echoes were those defined as such by the FITACF algorithm. This identification is reliable in the vast majority of cases, but some ionospheric echoes are mistaken for ground echoes, and vice versa.

Results shown in the next section are presented in the form of contour plots of echo occurrence and average FITACF parameter versus time and range. Beam 4 results are shown in a standard clock dial format using altitude adjusted corrected geomagnetic co-ordinates (AACGM) (Baker and Wing, 1989). The range gates were mapped to AACGM latitude using the standard analysis procedure. This assumes a virtual reflection height of 300 km, but with tapering to E-region heights at ranges <600 km. The difference between MLT and UT for beam 4 was
about 10 hours 46 min, but this difference changes rapidly near the geomagnetic pole where the beam direction veers away from the magnetic meridian.

A total of 1,666,429 (1,357,310) ionospheric echoes were identified on 149,377 (151,310) separate beam 4 (beam 15) soundings, so the major features shown here are statistically significant. Occurrence rates were calculated by counting the total number of echoes during 15-min intervals of time at each of the 75 ranges, then dividing by the total number of soundings made for a particular category of season, $K_p$, or the IMF. Thus 96 times × 75 ranges = 7200 occurrence rates were calculated for each map showing an average diurnal variation. The total number of echoes in each category was always divided by the actual number of soundings made. Hence the occurrence rates are “self-normalising” with respect to the chosen category.

The $K_p$ index is determined using a network of mid-latitude magnetometers, and is a measure of planetary geomagnetic activity. Ideally, measurements made using TIGER, a nightside auroral oval radar, should be sorted according to the $AL$ index (Davis and Sugiura, 1966). Unfortunately, reliable $AL$ indices were not available for this study.

Finally, the IMF data used in this study were 4-min averages measured on board the Atmospheric Composition Explorer (ACE) spacecraft which orbits the L1 libration point located ~235 Earth radii upstream of the Earth in the solar wind. The orthogonal IMF components $B_x$ and $B_z$ were expressed in the geocentric solar magnetospheric (GSM) co-ordinate system. The IMF components were advected from ACE to the Earth using the geocentric solar ecliptic $x$-location of the spacecraft and an average solar-wind speed of 370 km s$^{-1}$. Although this method of advecting the solar-wind conditions is approximate, the same, basic statistical results would be obtained when using more refined procedures.

**Figure 4**
3 Results

3.1 Beam 4 occurrence rates

3.1.1 Seasonal dependence

Figure 4 shows the occurrence of beam 4 ionospheric echoes sorted according to season for all $K_p$ values. The colour key means the colour for an occurrence rate of say, 49% (red), corresponds to occurrence rates in the range 47.5 to 50.5%. Model auroral oval boundaries (Starkov, 1994b) have been superimposed in each panel using $AL = -108$ nT (summer) (a), $-107$ nT (autumn) (b), $-131$ nT (winter) (c), and $-120$ nT (spring) (d). These values correspond to the average $K_p$ values and standard error bars occurring when ionospheric soundings were made, namely $2.28 \pm 0.01$, $2.27 \pm 0.01$, $2.56 \pm 0.01$, and $2.43 \pm 0.01$ in each season respectively. Note the poleward edge of the discrete auroral oval (dashed curve) delineates a fixed polar cap boundary, but the radar statistics encompass a broad range of geomagnetic activity. Hence we expect the observed echo distributions to be smeared in latitude with respect to the model boundaries.

Similar patterns of echo occurrence were recorded during all seasons, but there were some intriguing differences. For example, the dominant band of echoes observed between $-65^\circ \Lambda$ and $-76^\circ \Lambda$ during the night was confined between $\sim 20$ and $07$ MLT during the summer (a), but extended between $\sim 16$ and $08$ MLT during the winter (c). The azimuthal extent of this enhanced echo occurrence was intermediate during the autumn (b) and spring (d). The regions of peak echo occurrence ($>58\%$; brown) were concentrated after midnight during summer and autumn, before midnight during winter, and nearly symmetric about midnight during spring. However, overall more echoes were observed post-midnight than pre-midnight.

A lesser patch of mostly polar cap echoes was observed between $-70^\circ \Lambda$ and $-82^\circ \Lambda$ on the dusk side, confined between $\sim 16$ and $21$ MLT during the winter. The azimuthal extent of this feature contracted toward midnight during autumn and especially spring, and may have completely merged into the dominant band of nightside auroral echoes during summer. This feature was more distinct in beam 15 observations which showed its azimuthal extent contracted to $\sim 20$ and $23$ MLT.
during summer. Corresponding peak occurrence rates were found most equatorward during the summer, but were largest and most poleward during the autumn.

Relatively few ionospheric echoes were detected in the “dayside ionosphere” (06 to 18 MLT), with occurrence rates mostly <20%. The minimum occurrence rates were centred on ~13 MLT during summer and winter, though closer to noon during autumn and spring. Maximum dayside occurrence rates were observed during winter, and to a lesser extent during autumn, as a consequence of the before-mentioned polar cap echoes extending into the late afternoon. However, the peak occurrence rate was ~46% for an isolated patch of echoes ~1 hour wide centred near 0840 MLT and –78°Λ during the winter. A similar feature was located near –80°Λ during autumn, but the peak occurrence rate dropped to ~34%. The occurrence rates were lowest of all for this feature during summer. When considering all seasons combined, very few ionospheric echoes were detected in the polar cap ionosphere poleward of –80°Λ, but especially during 01 to 16 MLT.

Bands of occurrence rates generally <16% were found between midnight and noon equatorward of –61.8°Λ (i.e. range ≤630 km), whereas the occurrence rates were generally <7% between noon and midnight at similar ranges. The peak occurrence rate was ~20% near 0430 MLT during the summer, and ~40% near 0640 MLT during the winter. When the near-range occurrence rates were averaged for all seasons combined, they were roughly centred near 06 MLT.

The occurrence rates found at close ranges exhibit the characteristics of echoes from meteor trails (Hall et al., 1997), but echoes from E-region plasma instabilities associated with aurora and sporadic E must also contribute. In the following analysis we separate echoes into two groups, the echoes at close ranges ≤630 km and the echoes at far ranges >630 km. The latter are thought to correspond to upper E- and F-region irregularities drifting at the ion convection velocity (Villain et al., 1985).

**Table II**

Table II shows the total number of echoes observed in each season, the total number of beam 4 soundings in each season at ranges >630 km, the average occurrence rates, their standard errors, and the peak occurrence rates. Variability in the total number of soundings reflects upon equipment failures (computer
crashes, power failures, etc.). There are 64 range bins at ranges >630 km. Hence the average occurrence rate (%) is the average of the 96 times × 64 ranges = 6144 occurrence rates calculated for each season. This average does not equal the total number of echoes divided by the total number of beam soundings because there were a different number of soundings in each of the 15-min intervals and 64 ranges. The standard errors (%) were calculated by dividing the standard deviations of the occurrence rates by \(\sqrt{6144}\). The peak occurrence rate is simply the maximum occurrence rate of the 6144 occurrence rates.

Table II shows the largest number of echoes was recorded during winter (cf. Fig. 4c), then spring, summer, and least of all during autumn. However, because of the different number of beam soundings made per season, the average occurrence rate was largest for autumn, next largest for winter, then spring, and least of all for summer. On the other hand, peak occurrence rates were largest in autumn, then summer, and then the same during spring and winter. The standard errors for the averages show the seasonal changes were statistically significant, but systematic biases not related to the occurrence of ionospheric irregularities may be present.

### Table III

Table III compiles the same information as Table II, except it shows the statistics for echoes at ranges \(\leq 630\) km. There are 11 range bins at ranges \(\leq 630\) km, so an average occurrence rate is the average of 96 times \(\times 11\) ranges = 1056 occurrence rates. The occurrence rates were largest (~6.6%) and equal within error limits during summer and winter, and ~2% lower and comparable during autumn and spring. The peak occurrence rates were largest during winter and least during spring, and similar during summer and autumn. The peak occurrence of 38% occurred at ~07 MLT during winter (cf. Fig. 4c).

Lastly, the transmitter pulse set was designed to minimise the detrimental effects of range aliasing. However, the narrow, circular striations in all panels of Fig. 4 (e.g. the prominent ring at \(\sim -67^\circ\Lambda\)) correspond to bad ranges in the ACFs derived using the chosen pulse sequence.
3.1.2 Geomagnetic activity dependence

Figure 5 shows the occurrence rates of ionospheric echoes for all seasons combined and sorted according to the geomagnetic activity index $K_p$. As in Fig. 4, peak occurrence rates were usually observed in the nightside auroral and polar cap ionosphere between $-65^\circ \Lambda$ and $-76^\circ \Lambda$. However, for quiet conditions, $K_p = 0$ to 1 (part a), the patch of mostly polar cap echoes found between 18 and 01 MLT and $-73^\circ \Lambda$ and $-82^\circ \Lambda$ contained a comparable number of echoes to the band found further equatorward between 22 and 05 MLT, and $-70^\circ \Lambda$ and $-76^\circ \Lambda$. For $K_p > 1$ to 2 (b) the polar cap feature still contained many echoes, but fewer than the main band of auroral and polar cap echoes. The latter expanded to between 2030 to 0500 MLT and $-66^\circ \Lambda$ and $-76^\circ \Lambda$. For $K_p > 2$ to 3 (c) and more disturbed conditions (d, e, f) the polar cap feature became indistinguishable as the main band of auroral echoes expanded in longitude and latitude, even extending into the dayside ionosphere.

Overall, peak occurrence rates tended to shift equatorward with $K_p$, as did the equatorward boundary of the model auroral oval. However, the peak occurrence rates were partly “trapped” in the latitude range $-63^\circ \Lambda$ to $-76^\circ \Lambda$, until very disturbed conditions, $K_p > 4$ to 5 (e), when an arc of echoes almost completely encircled the polar cap. For the most disturbed conditions of all, $K_p > 5$ to 6 (f), there was a lot of $E$- and $F$-region scatter at close ranges, and scatter from both close and far ranges became very patchy, but locally intense.

### Table IV

Table IV is in the same format as Table II, except it shows the changes in average and peak occurrence rate with the $K_p$ index. The average occurrence rate was smallest during the quietest conditions (Fig. 5a), it grew to a maximum for $K_p > 4$ to 5 (cf. Fig. 5e), and thereafter (Fig. 5f) fluctuated with increasing $K_p$. For example, the average occurrence rate was 20.2% for $K_p > 5$ to 6, then 12.8% for $K_p > 6$ to 7, etc. During the most disturbed intervals (Fig. 5f) the auroral oval began to expand equatorward of the 0.5-hop range window. Auroral $E$ echoes must have begun masking meteor echoes at close ranges, as well as $F$-region scatter at greater ranges.

Although not apparent in Table IV, the peak occurrence rates trended from 56% for the quietest intervals to 100% during more disturbed intervals (not
This is because the occurrence rates were calculated using a smaller and smaller number of intervals encompassing larger and larger geomagnetic storms. Hence the patchy distribution of echoes in Fig. 5f. Statistics for echoes at close ranges $\leq 630$ km are not shown because there was no significant dependency on geomagnetic activity until $K_p > 5$.

**Figure 6**

### 3.2 Beam 4 average FITACF parameters

#### 3.2.1 Power and elevation angles

Figure 6a shows a map of the average power returned by the FITACF algorithm for ionospheric echoes with SNR $> 3$ dB, and for all seasons and levels of geomagnetic activity combined. When sorted according to season and $K_p$, some variations similar to those for the occurrence rates were found. Average IMF components for the entire data base were $(B_x, B_y, B_z) = (0.0, 0.6, -0.1$ nT). These values were used to drive the DMSP satellite-based Ionospheric Convection Model (DICM) (Papitashvili and Rich, 2002) which outputs high-latitude electric potentials. The results have been superimposed as equipotential contours representing streamlines of ionospheric flow velocity. In Fig. 6, the flow direction is clockwise in the dusk cell and anticlockwise in the dawn cell, resulting in nearly antisunward flow across the central polar cap.

Figure 6a shows the main band of echo power $> 18$ dB occurred between 19 and 08 MLT and $-62^\circ \Lambda$ and $-72^\circ \Lambda$. Larger echo power $> 20$ dB occurred between 23 and 07 MLT and equatorward of $-70^\circ \Lambda$. The maximum in the distribution was centred near 0245 MLT. The exception was winter when the maximum powers were centred on midnight. The echo power rapidly increased at the equatorward edge of the main band ($\sim -62^\circ \Lambda$), maximised at $\sim -64^\circ \Lambda$, and thereafter gradually decreased toward the geomagnetic pole. Minimum average power of 9 dB occurred in the dayside ionosphere between 11 and 16 MLT, diametrically opposite the region of maximum power. Overall, the distribution of power was rotated further dawnward and $-3^\circ \Lambda$ equatorward of the main echo occurrence shown in Fig. 4.
Figure 6b shows the corresponding average elevation angles calculated by measuring the time delay between the arrival of the same echoes received on the main 16 element antenna array and the 4 element interferometer subarray. Milan et al. (1997a) discussed the interferometer technique and associated problems. Our analysis of the TIGER elevation angles suggest their absolute values are systematically too large, but their relative variations are usually consistent with ray-tracing results, and can be used to help identify different propagation modes.

Figure 6b shows the average elevation angles were typically ~23 to 28° in regions corresponding to maximum occurrence rate (Figs. 4, 5) and power (Fig. 6a). However, the elevation angles were highly variable, ranging from a minimum of 18° at dawn to a local maximum of 30° near 2245 MLT and −76°Λ. A patch of enhanced elevation angles (24° to 30°) occurred between ~19 and 03 MLT and −70°Λ and −87°Λ. This feature corresponds to the patch of mostly polar cap echoes (Figs. 4, 5) with moderate SNR ~11 to 18 dB (Fig. 6b), and suggests it sometimes extended just past magnetic midnight.

Figure 7

3.2.2 LOS Doppler velocities

Figure 7 shows the average LOS Doppler velocities sorted into four categories of the IMF vector in the $B_y$–$B_z$ plane, namely $B_y$ negative, $B_z$ positive (a), $B_y$ positive, $B_z$ positive (b), $B_y$ negative, $B_z$ negative (c), and $B_y$ positive, $B_z$ negative (d). By positive and negative we mean the IMF components were $>0.5$ nT and $<-0.5$ nT, respectively. The corresponding average IMF components ($B_x$, $B_y$, $B_z$) were (1.9, −4.0, 3.5 nT) (a), (−1.8, 4.6, 3.6 nT) (b), (1.9, −4.0, −3.6 nT) (c), and (−1.7, 4.5, −3.6 nT) (d), respectively. These values were used to drive the DICM and obtain the equipotentials superimposed in all parts. The flow direction is clockwise in the weak afternoon cell in part (a), and anticlockwise in the weak morning cell in part (b). Dayside sunward flows are known to occur more often under $B_z$ northward conditions.

Figure 7 basically shows the familiar cross polar jet was most developed for $B_z$ negative conditions (c, d). Note the dayside region of large poleward velocities (brown; $\sim < –240$ m s$^{-1}$) was most extensive for $B_y$ positive conditions (d). These velocities correspond to flows entering the convection throat during 08 to 14 MLT
at ~ −78°Λ. The nightside region of large equatorward velocities (purple; ~210 m s\(^{-1}\)) was most extensive for \(B_z\) negative conditions (c). These velocities correspond to flows exiting the polar cap during 20 to 01 MLT. They subsequently veered zonally and produced the extensive regions of moderate, equatorward LOS velocity (blue; ~120 m s\(^{-1}\)) during 19 to 02 MLT poleward of ~ −68°Λ. The maps of average LOS Doppler velocity show variations similar to those in Fig. 7 when sorted according to season. However, the region of large poleward velocities centred in the pre-noon sector were clearly more extensive during summer, then spring, winter, and least of all during autumn.

**Figure 8**

### 3.2.3 Doppler spectral widths

Figure 8 shows the average Doppler spectral widths for all seasons and levels of geomagnetic activity combined. The tendency for the small and large spectral widths to alternate in bands separated by ~3°Λ wide was caused by bad ranges in the ACF analysis. Ideally, these artefacts should be quantified by modelling the pulse set behaviour and then deconvolved from the observations. However, all the major features to be described were geophysical and reproducible using subsets of the entire data set.

The largest spectral widths, >350 m s\(^{-1}\) (brown), were concentrated in the pre-noon polar cap ionosphere at ~ −80°Λ. However, an arc of large spectral widths >300 m s\(^{-1}\) (orange) extended into the nightside ionosphere between 23 and 06 MLT. The spectral widths declined quickly equatorward of ~73°Λ near noon (and ~70°Λ near dawn), whereupon they were <160 m s\(^{-1}\) (blue) across much of the remaining dayside ionosphere. Similarly, the nightside spectral widths declined quickly near midnight, decreasing from ~260 m s\(^{-1}\) at ~70°Λ to ~100 m s\(^{-1}\) equatorward of ~67°Λ. There was a significant “bite out” in spectral widths to values <220 m s\(^{-1}\) centred on dusk, but extending from 15 to 21 MLT poleward of 67°Λ.

There was an ~2 to 3°Λ wide trough in spectral width (<160 m s\(^{-1}\)) centred on ~ −66°Λ and encircling the entire 24 h of MLT. This feature persisted when the data were sorted according to season. The spectral widths again increased to values >160 m s\(^{-1}\) equatorward of ~63°Λ, especially between 1600 and 0130
MLT. A thin band of large spectral widths >200 m s\(^{-1}\) was centred pre-dawn, between 0230 to 0730 MLT and \(-60^\circ\) and \(-63^\circ\).

The results shown in Fig. 8 were sorted according to season (not shown). All the relative variations shown in Fig. 8 were apparent. However, there was a significant change in the extent of the pre-noon region with large spectral widths, from most extensive during spring, then summer, winter, and least of all during autumn. During spring the region of average spectral width >200 m s\(^{-1}\) extended in longitude to encompass the entire high-latitude ionosphere poleward of \(-70^\circ\), except of course from ~17 to 21 MLT.

The spectral widths were also sorted according to \(K_p\) (not shown). The spectral widths behaved similar to the echo occurrences (Fig. 5), namely there was a tendency for the nightside regions of large spectral width to be trapped at preferred ranges until the onset of large geomagnetic activity. The relative variations in spectral width were most like the Fig. 8 variations for moderately disturbed conditions, \(K_p = 2+\) to 3. For \(K_p = 0\) to 1, the region of large spectral widths >300 m s\(^{-1}\) was concentrated in the sector 23 to 07 MLT at \(-74^\circ\). As \(K_p\) increased the regions of large spectral width expanded into the pre-noon polar cap ionosphere, as well as equatorward. For the most disturbed conditions there was a strong tendency for the regions of large spectral width to further expand, until there was an almost symmetric distribution about the AACGM pole. However, there was still evidence for the dusk bite out.

When sorted according to the IMF (not shown), the high-latitude regions of large spectral widths were least extensive for \(B_y\) positive, \(B_z\) positive, and most extensive for \(B_y\) negative, \(B_z\) negative. The dusk bite out in spectral width was also more prevalent for \(B_z\) positive.

Finally, Fig. 8 is annotated with the approximate locations of some important magnetospheric boundaries and regions. These annotations will be discussed in section 4.3.

**Figure 9**

### 3.3 Beam 15 occurrence rates

Figure 1 shows how beam 15 provided a detailed view of the nightside sub-auroral and auroral ionosphere, becoming an eastward-looking beam very
sensitive to zonal flows at furthest ranges. Occurrence statistics for beam 15 observations were presented by Parkinson et al. (2002a). Here we further analyse beam 15 observations in the context of beam 4 observations to investigate the behaviour of ionospheric scatter with very low spectral width.

First consider Fig. 9 which shows histograms of echo occurrence versus Doppler spectral width recorded on beam 15 (solid curve) and beam 4 (dotted curve) for all seasons and levels of geomagnetic activity combined. More echoes were observed on beam 4 than beam 15 (660,646 versus 624,051). For each beam there were two distinct populations of ionospheric echoes, “A” and “B.” Population A consisted of echoes with low spectral width $<$38 m s$^{-1}$ and had a mode value of $\sim$9 m s$^{-1}$ (bin size of 2 m s$^{-1}$). They constituted 16.7% and 9.8% of the echoes observed using beam 15 and beam 4, respectively. Population B consisted of echoes with moderate to very large spectral width $\geq$38 m s$^{-1}$, and had a mode value of only $\sim$70 m s$^{-1}$. More echoes with spectral width $<$38 m s$^{-1}$ were recorded on beam 15, and more echoes with spectral width $>$38 m s$^{-1}$ were recorded on beam 4. Although the distribution functions for the two populations must overlap, the population with mode value 9 m s$^{-1}$ was completely dominant beneath the critical value 38 m s$^{-1}$.

Figure 10 compiles the occurrence of population A echoes observed on beam 15 versus UT and group range, with corresponding magnetic latitudes superimposed. It makes less sense compiling beam 15 results in the polar plot form of beam 4 because beam 15 traverses 68º of longitude (~4.5 h of MLT). However, nominal values of MLT in the ionosphere above Macquarie Island, located just to the east of beam 15, are shown at top. Similar to Fig. 4, model auroral oval boundaries are also superimposed in each panel using $AL = -109$ nT (a), $-108$ nT (b), $-131$ nT (c), and $-120$ nT (d). These values correspond to the average $K_p$ values occurring when beam 15 soundings were made, namely $2.30 \pm 0.01$ (a), $2.28 \pm 0.01$ (b), $2.56 \pm 0.01$ (c), and $2.43 \pm 0.01$ (d).

Figure 10 shows the occurrence of population A echoes observed on beam 15 was similar to the occurrence of echoes with any spectral width on beam 4 (Fig. 4). However, the peak occurrence rates were displaced further toward dawn and the equator than in Fig. 4. Specifically, the main band of echoes observed on
beam 15 (>8%; karki) was concentrated between 23 and 07 MLT and –63°Λ and –67°Λ. Hence these echoes were mainly concentrated in the post-Harang diffuse auroral oval, but also in the discrete auroral oval and sub-auroral ionosphere. Very few of these echoes were found in the polar cap ionosphere.

Like the occurrence of echoes recorded on beam 4 (Fig. 4), the azimuthal extent of the dominant band of echoes observed on beam 15 was least during summer, greatest during winter, and intermediate during autumn and spring. A lesser patch of mostly auroral oval echoes was observed between –65°Λ and –72°Λ on the dusk side, confined between ~15 and 21 MLT during the winter. The azimuthal extent of this feature contracted toward midnight during autumn and spring, and most of all during summer.

The bands of echoes observed with occurrence rate mostly <6% equatorward of –60°Λ correspond to backscatter from meteor trails, as well as E- and F- region plasma instabilities associated with aurora and sporadic E.

**Table V**

Table V shows the total number of population A echoes (spectral width <38 m s\(^{-1}\)) observed at ranges >630 km in each season, the total number of beam 15 soundings in each season, the average occurrence rates, their standard errors, and the peak occurrence rates. Because we are only considering echoes with spectral width <38 m s\(^{-1}\), the occurrence rates are much lower than those given for beam 4 (Table II). The average occurrence rates were largest for beam 15 during autumn, then winter, summer, and least of all for spring. On the other hand, peak occurrence rates were largest in autumn, then summer, spring, and winter. Variations in the averages are more meaningful than variations in the peak values.

**Figure 11**

3.4 Beam 15 average LOS Doppler velocity

Figure 11 shows the average LOS Doppler velocities for beam 15 ionospheric echoes with any spectral width and \(K_p\) value. The results have been sorted according to season, and the same model auroral oval boundaries used in Fig. 10 have been superimposed. The dominant feature in all seasons is the transition from large approaching (blue) to large receding (brown) Doppler velocities.
centred near 22 MLT at −70°Λ, but occurring later at closer ranges (lower latitude). This feature corresponds to the transition from westward to eastward return flows at the low-latitude limit of two-cell convection patterns, and is closely related to the Harang discontinuity, a feature normally identified using magnetometer data.

The colour coding used in Fig. 11 suggests large average westward flows were more extensive than large eastward flows. Indeed, some very large westward flows (>300 m s⁻¹) overlapped the diffuse auroral oval, and extended equatorward into the sub-auroral ionosphere before magnetic midnight. For example, during summer there was an “island” of large westward flow centred near 21 MLT and −62.5°Λ. Similar sub-auroral flows persisted during autumn and especially spring, but were concentrated at higher latitude during winter.

When sorted according to geomagnetic activity, the strong westward flows were absent at sub-auroral latitudes for $K_p = 0$ to 1. The auroral flows intensified with increasing $K_p$, becoming prevalent at sub-auroral latitudes for $K_p > 3$ to 4 (and similarly for $B_z$ strongly negative). When only the echoes with spectral width <38 m s⁻¹ were considered, the region of large westward flow before midnight shifted equatorward into the sub-auroral ionosphere.

4 Discussion

4.1 Beam 4 diurnal and $K_p$ variations

From the auroral oval boundaries (Starkov, 1994b) superimposed in Fig. 4, we infer that most of the ionospheric echoes observed at ranges >630 km on beam 4 were from decametre-scale irregularities drifting in the nightside discrete auroral and polar cap ionosphere. However, many echoes were from irregularities in the nightside diffuse aurora and sub-auroral ionosphere. Fig. 5 showed the location of the main band of nightside echoes tended to expand in longitude and equatorward with increasing levels of geomagnetic activity. For the quietest conditions, $K_p = 0$ to 1 (Fig. 5a), most of the echoes were associated with the polar cap ionosphere, but for $K_p > 2$ to 3 (Fig. 5c), and higher levels of activity, the majority of the echoes were associated with the expanded discrete auroral oval.
Figures 4 and 5 show there was a tendency for more echoes to be observed post midnight in the main band of auroral and polar cap echoes. However, when the occurrence rates were sorted according to $K_p$ (Fig. 5), there was a tendency for large occurrence rates to shift pre-midnight for more disturbed conditions, $K_p > 3$ (parts d, e, and f). The average backscatter power (Fig. 6a) clearly maximised post-midnight, between 23 and 07 MLT, and was aligned with the leading edge of the main band of peak occurrence rate ($\sim -65^\circ$). Overall, more echoes were recorded with higher SNR post-midnight.

The concentration of echoes with large SNR post-midnight was partly due to decreasing $D$-region absorption of the backscattering radio waves, and partly due to the formation of more intense irregularities. It is difficult quantifying the relative contributions of these two effects without detailed modelling of radio-wave propagation and irregularity formation and dissipation. However, the $f_{min}$ variations in ionograms recorded at high mid-latitude stations show that absorption tends to decrease rapidly at sunset, and not near midnight.

The linear growth rate for the $E \times B$ instability (Linson and Workman, 1970) is $\gamma = \omega / L$ for $\omega \ll v_{in}$ where $V_0$ is the “slip” velocity, or the magnitude of the plasma velocity minus the neutral wind velocity. $L$ is the gradient scale length of plasma density, $\omega = \omega + j \gamma_0$ is the wave frequency, and $v_{in}$ is the ion-neutral collision frequency. Here we have in mind gradient drift waves growing on plasma density gradients in the roughly horizontal, cross field direction at high latitudes. Tsunoda (1988) explains how these waves will grow in proportion to the slip velocity, since if $V_0 = 0$, no Pedersen currents can flow to provide the polarisation fields which destabilise the plasma density.

Moreover, Tsunoda (1988) argued that larger slip velocities, and thus more intense irregularities, should occur post-midnight. Note the large slip velocities required for irregularity production will tend to occur whenever ionospheric electric fields or neutral winds change rapidly, since it takes some time for an equilibrium to be achieved between the ion and neutral gas motions. More energetic electron precipitation (Gussenhoven et al., 1983) and thermospheric gravity-wave perturbations (Conde and Innis, 2001) occur post midnight. This also implies larger slip velocities and thus irregularity production post-midnight.

Parkinson et al. (2002b) presented a case study (see their Fig. 3) which showed sudden increases in backscatter power in association with convection flow
bursts occurring past the Harang discontinuity. Figures 4, 5, and 6 provide statistical evidence for more intense irregularity production in the ~23 to 07 MLT sector. Because of the short life time of decametre irregularities, Fig. 4 also suggests the most active source region for the irregularities observed using TIGER was the nightside ionosphere overlapping the poleward edge of the auroral oval, and extending into the discrete auroral oval. Figure 5 suggests this source region tended to shift equatorward and pre-midnight into the discrete auroral oval during more disturbed intervals. We speculate this is because more slip-velocity transients developed pre-midnight in the discrete oval during ionospheric substorms.

Although the average occurrence rates (Table II) for the largest $K_p$ values were only representative of a small number of storms, they clearly showed that localised “hot spots” of echo occurrence were often observed, even during major storms when there was intense particle precipitation. It seems that ionospheric absorption due to particle precipitation reduces echo occurrence in transient, spatially localised episodes. However, overall the echo occurrence remains very high during major storms, probably because of strong and frequent slip-velocity transients.

All of the preceding argues against the diurnal variation in $D$-region absorption being the only cause of the post-midnight enhancement of echoes with large SNR.

Figure 4 showed the enhanced echo occurrence actually consisted of two separate regions, a main one found between $\sim -65^\circ \Lambda$ and $-76^\circ \Lambda$ persisting beyond magnetic midnight, and a lesser patch of mostly polar cap echoes observed between $\sim -70^\circ \Lambda$ and $-82^\circ \Lambda$ near dusk. The familiar equatorward expansion of the auroral oval with MLT (for the same level of geomagnetic activity) can only partly explain these two echo regions. This is because one of them clearly lay well into the polar cap.

Recall that variability in the refraction of the radio waves influences the detection of ionospheric scatter. The ionospheric electron density encountered along the ray path determines the preferred range windows at which the radio waves achieve normal incidence with magnetically field-aligned irregularities (Villain et al., 1985). To produce observable echoes, these preferred range windows must also correspond to ionospheric regions associated with intense
irregularity production. However, to some extent ionospheric irregularities will create the conditions required to observe them, since they will enhance radio-wave refraction, and thus increase the probability of the radio waves achieving normal incidence.

The lesser patch of mostly polar cap echoes observed at higher latitude on the dusk side corresponds to a preferred range window due to 1.5-hop propagation, and the main band of echoes observed at lower latitude and later MLT corresponds to a preferred range window due to 0.5-hop propagation. In a statistical sense, these two preferred range windows overlap. However, the lesser region of mostly polar cap echoes was mostly observed during quiet conditions because the main auroral oval expanded equatorward into the preferred range window due to 0.5-hop propagation during more disturbed conditions. Presumably, echoes were usually not observed at dusk via 0.5-hop propagation during quiet conditions because of weak irregularity production in the sub-auroral ionosphere where insolation was more direct.

The preceding interpretation was confirmed by (i) the sudden decrease in operating frequency at 19 MLT (Fig. 3) which will tend to favour detection of echoes via 0.5-hop propagation, (ii) the elevation angle data (Fig. 6b) which suggest the two regions corresponded to separate propagation modes, and (iii) examination of the behaviour of 1.5-hop ionospheric echo traces with respect to 1.0-hop sea echo traces in range-time plots for individual days.

The behaviour of the latter was consistent with the behaviour of the ionospheric parameters $h_m F_2$ and $f_0 F_2$ in ionograms recorded nearby TIGER at Hobart (147.3°E, 42.9°S geographic). Past sunset, $h_m F_2$ became large and $f_0 F_2$ small, and 1.0-hop sea echo traces gradually receded to great ranges until they were lost. Ionospheric echoes in the preferred range window due to 1.5-hop propagation were observed until this happened. Then nightside auroral $E$ and $F$ layers began to support the detection of scatter via 0.5-hop propagation. The contraction of the lesser region of mostly polar cap echoes from dusk in winter toward later MLT in summer is consistent with the well-known seasonal variation in $F$-region sunset time.

Some of the echoes observed using TIGER were associated with the pre-noon greater cusp consisting of the true cusp, cleft, and mantle (Newell and Meng, 1992). For example, there was a peak occurrence rate of ~46% near 0840 MLT.
and \(-78^\circ\) during winter (Fig. 4b). This feature was centred poleward of the poleward edge of the auroral oval, so many of the corresponding irregularities may have been concentrated in the mantle rather than the cusp proper. Why were so few dayside echoes observed, especially when the cusp is known to be such an intense source of irregularity production?

The true ranges of the auroral and polar cap ionosphere are greater during the daytime. Except during very disturbed conditions, dayside echoes will be observed using TIGER via 1.5- and 2.5-hop propagation, resulting in greater divergent power losses. D-region absorption of the backscattering radio-waves will also be greater during the daytime (cf. Fig. 6a). Radio-wave absorption was probably least during the morning in winter when the Sun was lower on the horizon, and greatest just past noon (~13 MLT) in summer when the Sun was high in the sky. Lastly, the amplitude of ionospheric irregularities will tend to be weaker when the ionosphere is directly illuminated by the Sun.

### 4.2 Beam 4 results: seasonal variations

Table II showed the average occurrence rate of ionospheric echoes at ranges >630 km was greatest during autumn (18.7%), then winter (15.6%), spring (15.0 %), and least of all during summer (13.7%). The variation of beam 15 echoes was similar. These relatively small variations were statistically significant and similar to the familiar, but unexplained, seasonal variation in auroral activity with peak activity near the March (autumn) equinox. We note that if reliable AL indices were available for our study period, they might have shown peak auroral activity, and thus irregularity production, near autumn equinox.

Scintillation of VHF signals traversing the ionosphere and received with ground-based antennas are caused by ionospheric irregularities of scale size ~250 m to 1 km. Typical power spectra of ionospheric irregularities show a cascade of irregularities from these scale sizes down to the decametre-scale size observed using HF backscatter radar (Tsunoda, 1988). Hence we expect there to be a correspondence between the occurrence of ionospheric irregularities implied by the two measurement techniques.

Indeed, the diurnal and seasonal variation of scintillation index observed at Narssarssuaq, Greenland (+63°\(\Lambda\)) (Aarons, 1982), (see Fig. 19 therein) resembled
the variation of occurrence rate shown in Table II. The Narssarssuaq scintillation index maximised in the months of March and April, and then slowly declined throughout the remainder of the year, reaching a minimum during November and December. A similar but weaker seasonal behaviour was observed using TIGER, even though the stations reside in different longitude sectors, and opposite hemispheres. The diurnal maxima also had similar character. However, the diurnal scintillation maxima were centred pre-midnight (~23 MLT) at Narssarssuaq, whereas the diurnal maxima of TIGER echoes tended to occur post-midnight, as predicted by gradient drift theory.

Basu (1975) investigated the UT seasonal variations of auroral zone activity by compiling average $AL$ indices. Basu’s analysis revealed variations in auroral activity which were attributed to variations in the plane of symmetry of the plasma sheet with respect to the solar magnetospheric equatorial plane. The seasonal variations in $AL$ were consistent with the seasonal variation in Narssarssuaq scintillations. The seasonal variations were strongest for auroral stations in the geographic meridian containing, or opposite to, the geomagnetic pole. It is likely $AL$ is also a measure of decametre irregularity production, as well as scintillation activity. Consulting Fig. 2 of Basu (1975), there should be a relatively weak seasonal variation in echo occurrence observed at a station where magnetic midnight occurs at ~14 UT. This is consistent with the relatively weak seasonal variation of TIGER echoes.

It is well known that changes in the dipole tilt angle regulate the transfer of solar-wind energy into the coupled magnetosphere-ionosphere-thermosphere system (Russel and McPherron, 1973). However, the system is very complex and many factors must be considered to explain the peak irregularity production near autumn equinox. These factors include variations in conditions satisfying the anti-parallel merging hypothesis (Crooker, 1979), and variations in the ionospheric conductivity due to changes in the elevation angle of the Sun and particle precipitation. The conductivity of the conjugate ionosphere will also affect the closure of field-aligned currents. Aurora, intense electric fields, and thus irregularity production concentrate in regions of low ionospheric conductivity (Newell et al., 2001).

The presence of a conducting $E$ region reduces the lifetime of irregularities in the $F$ region by allowing the cross-field plasma diffusion to proceed at the faster
ion rate, rather than the slower electron rate (Vickrey and Kelley, 1982; Kelley et al., 1982). Hence for the same slip velocity, irregularities “dissolve” faster in the presence of a conducting $E$ region.

The preceding ideas need to be incorporated into a sophisticated model from which ionospheric irregularity occurrence can be inferred.

### 4.3 Beam 4 LOS Doppler velocities and spectral widths

Figure 7 showed the average LOS Doppler velocities sorted according to the IMF vector, with DICM equipotentials superimposed to help show how the direct radar observations were consistent with a basic two-cell convection pattern with a cross polar cap jet most developed under $B_z$ negative conditions. Further detail can be compared; for example, Fig. 7c shows a region of near zero LOS velocity (karki) centred near ~04 MLT and –75°A. This implies the location of the centre of the dawn convection cell, in better agreement with the results of the DICM model than the DMSP-calibrated IZMEM model (Papitashvili and Rich, 2002; see their Figs. 2 and 7). However, such comparisons are best made using SuperDARN convection potentials derived using LOS Doppler velocities measured by all the SuperDARN radars combined (Shepherd and Ruohoniemi et al., 2000).

When average Doppler parameters were sorted according to season (not shown) they revealed the region of large poleward velocities and spectral widths centred in the pre-noon ionosphere were more extensive during summer, then spring, winter, and least of all during autumn. This is nearly opposite to the seasonal variation in echo occurrence rates in the pre-noon ionosphere, namely a maximum during winter, then autumn, spring, and least of all during summer. To first order, one might expect the echo occurrence rates (and average spectral widths) to increase with convection velocity. However, a deeper analysis of the conditions affecting the growth and decay of irregularities is required. This includes determining the slip velocities, and allowing for enhanced conductivity due to direct insolation. The latter probably quickly dissipates ionospheric irregularities forming during summer.

Figure 8 showed the average Doppler velocity spectral widths for all seasons and $K_p$ values combined. Variations in the spectral widths may represent genuine variations in the hydromagnetic wave activity (André et al., 1999; André et al.,
2000) or small- to medium-scale convective turbulence. The region of large spectral widths extended into the pre-noon ionosphere and intensified with increasing $K_p$ (or $B_z$ southward) conditions (not shown). This suggests dayside reconnection may drive the hydromagnetic wave activity or turbulence responsible for the large spectral widths. These variations will also reflect upon corresponding changes in magnetospheric regions.

Well-known ionospheric locations mapping to the greater cusp, polar cap (PC), and convection reversal boundary (CRB) are superimposed in Fig. 8. When the spectral widths are plotted versus group range and time for TIGER beam 4, a persistent latitudinal decrease in nightside spectral width is often observed (Parkinson et al., 2002b). The spectral width boundary is usually very sharp, occurring within two range gates or ~90 km, and its location expands equatorward or contracts poleward depending on geomagnetic activity. Hence the nightside spectral widths decrease gradually in Fig. 8 because they are averages over a non-stationary boundary location. Nevertheless, the gradual statistical boundary still expanded equatorward with $K_p$.

Because the spectral width boundary is so sharp in case study data, it is well defined using any spectral width threshold between ~50 and 200 m s$^{-1}$. However, Fig. 9 suggests the use of a lower (higher) threshold will more reliably select population A (B) echoes only.

Parkinson et al. (2002b) also argued that (i) the spectral width boundary mapped to the open-closed magnetic field line boundary (OCB) in the evening and midnight sector, (ii) the scatter with low spectral width just equatorward of the spectral width boundary mapped to the auroral oval, and (iii) the equatorward limit of this scatter mapped to the poleward wall of the main ionospheric trough. Hence we have inferred nominal locations of the OCB, plasma sheet boundary layer (PSBL), central plasma sheet (CPS), and plasmapause in Fig. 8.

Large spectral widths were observed encircling the dawn sector but not the dusk sector. This suggests there may be more hydromagnetic wave activity or turbulence in the dawn sector. The bite out in large spectral widths centred on dusk may be related to the dusk bulge of the plasmapause which disappears during geomagnetic storms, or large $K_p$, as was observed. Lastly, we speculate the thin band of large spectral widths >200 m s$^{-1}$ found between 0230 to 0730 MLT.
and $-60^\circ \Lambda$ and $-63^\circ \Lambda$ may be associated with $F$-region irregularities forming high in the pre-sunrise trough when electron densities plummet.

### 4.4 Beam 15 results

Figure 9 revealed two separate populations of ionospheric echoes, “A” and “B,” having low and moderate to very large spectral widths, respectively. Parkinson et al. (2002b) showed that population A (B) tended to occur equatorward (poleward) of the OCB in the pre-midnight sector. However, the morphology is complicated. For example, echoes with large spectral width occurred equatorward of the OCB, and vice versa, and no doubt subsidiary populations exist. Nevertheless, the existence of two populations, one mapping to closed field lines and the other to open field lines, must be indicative of the magnetospheric processes driving the small-scale velocity fluctuations causing the large spectral widths.

The peak occurrence rate occurred at the mode value $\sim 9$ m s$^{-1}$ for beam 15, but at the mode value $\sim 70$ m s$^{-1}$ for beam 4. This is largely due to a simple geometrical effect: beam 15 samples many more ranges in the sub-auroral and auroral ionosphere where the low spectral widths are concentrated. Moreover, beam 15 becomes a magnetic zonal beam, and thus is more sensitive to intense irregularities growing in the direction of the primary $\mathbf{E} \times \mathbf{B}$ waves drifting zonally at lower latitudes.

On the other hand, irrespective of spectral width and range, more echoes were observed on beam 4, than beam 15 (1,666,429 versus 1,357,305). This is because beam 4 is a meridional beam which traverses a greater range of latitudes, thereby increasing the probability of encountering conditions favouring the production of irregularities. Beam 4 is also more sensitive to the intense, primary $\mathbf{E} \times \mathbf{B}$ waves drifting in the direction of the cross-polar cap jet.

Figure 10 showed the peak occurrence rates of population A echoes on beam 15 were displaced further toward dawn and equatorward than for beam 4. This is because strong equatorward flows in the cross-polar jet tend to occur pre-midnight, and favour production of population B echoes, whereas strong eastward return flows tend to occur post-midnight, favouring production of population A echoes. The strong westward flows tending to occur pre-midnight are less important because of the smaller slip velocities (Tsunoda, 1988).
Population A echoes observed using the TIGER radar are reminiscent of the “dusk scatter” first reported by Ruohoniemi et al. (1988) using observations made with the Goose Bay radar (60.45°W, 53.3°N geographic; +61.9°A). The occurrence of dusk scatter maximises in the main ionospheric trough near the solar terminator during the winter (Hosokawa et al., 2002). TIGER beam 15 observations during the winter revealed the lesser patch of mostly auroral oval echoes detected via 1.5-hop propagation (Fig. 10 c). Similar to dusk scatter, these echoes had peak occurrence rates in the diffuse auroral oval at ~18 MLT. However, for TIGER, the dusk scatter did not stand out as a separate or dominant feature in the sub-auroral ionosphere. Rather, the dominant feature for this kind of scatter was centred in the post-midnight diffuse auroral oval.

During the winter TIGER detects population A echoes at dusk via 1.5-hop propagation between ~15 and 22 MLT and −65°A and −72°A. Because the Goose Bay radar is located at higher latitude (+61.9°A vs. −54.6°A), it will observe the same kind of irregularities via 0.5-hop propagation. However, it will become more difficult for the Goose Bay radar to observe population A echoes at later MLT when the diffuse auroral oval expands equatorward. On the other hand, the TIGER radar will observe the diffuse auroral oval via 0.5-hop propagation, even at magnetic midnight. This does not preclude the possibility of “hot spots” in the occurrence of population A echoes measured by other radars, such as where the solar terminator crosses the main ionospheric trough, or in the aftermath of SAIDs (Parkinson et al., 2002c).

Furthermore, because of the tilt of the geomagnetic dipole toward Australia, the TIGER radar is only 7.3° magnetically equatorward of the Goose Bay radar, yet 9.9° geographically equatorward. During the winter the sunset terminator crosses the Goose Bay field of view (FOV) at a significantly earlier MLT than the TIGER FOV. This may explain why dusk scatter is not detected via 0.5-hop propagation using the TIGER radar, since direct insolation of the corresponding preferred range window will cause the dissipation of ionospheric irregularities. Annual variations in the location of the sunset terminator are also consistent with seasonal variations in beam 15 observations.

Finally, beam 15 is very sensitive to SAIDs which occur pre-midnight in regions of low ionospheric conductivity such as the main ionospheric trough (Anderson et al., 1991). The observed seasonal variation in large westward flows,
Fig. 11, must be related to the insolation and thus conductivity of the radar FOV and its conjugate location, as well as the occurrence of substorms leading to the formation of SAIDs. The $K_p$ and spectral width dependency of the westward flows also supports an association between substorms, SAIDs, and the formation of the main ionospheric trough (Parkinson et al., 2002c).

5 Summary

In this paper we compiled occurrence statistics for ionospheric echoes observed using the TIGER radar (∼54.6°Λ) on the magnetic meridian or “polar cap” beam 4, and the magnetic zonal or “auroral” beam 15. These two beams are nearly orthogonal and summarise most of the important aspects of ionospheric echoes observed using the radar:

1. Two populations of ionospheric echoes were identified. Population A echoes had low spectral width and a mode value of ∼9 m s⁻¹ (bin size of 2 m s⁻¹), and were concentrated in the nightside auroral ionosphere. Population B echoes had high spectral width and a mode value of ∼70 m s⁻¹, and were concentrated in the polar cap ionosphere. More population A echoes were observed using beam 15 with peak occurrence rates overlapping the average location of the nightside diffuse auroral oval. On the other hand, more population B echoes were observed on beam 4 with peak occurrence rates overlapping the average location of the discrete auroral oval and polar cap ionosphere.

2. Populations A and B must exist because of distinct dynamical regions in the coupled magnetosphere-ionosphere system. For example, population A echoes were concentrated on closed field lines between dusk and just past midnight, whereas population B echoes were concentrated on open field lines (Parkinson et al., 2002b). The larger spectral widths of population B may be caused by enhanced hydromagnetic wave activity transmitted to the polar cap ionosphere (e.g. some nightside variant of the André et al., 1999 hypothesis), or more turbulent convection occurring in the polar cap ionosphere.
3. There was a dusk “bite out” of large spectral widths between ~15 and 21 MLT and poleward of −67°Λ. This feature may be related to the dusk bulge of the plasmapause, and is consistent with an enhancement of population A echoes in the dusk sector. Other poorly understood features include the pre-dawn enhancement of large spectral width located between ~03 and 07 MLT, and centred on ~ −61°Λ. Because this feature maps to near the expected location of the main ionospheric trough (L ~ 4 to 5), it may be caused by patches of field-aligned irregularities sometimes observed near the pre-sunrise trough (Parkinson et al., 1996).

4. The main source region for the nightside irregularities observed by TIGER included the discrete auroral oval and polar cap ionosphere just poleward of the OCB. Peak occurrence rates of beam 4 echoes were often >60% just after magnetic midnight and ~ −70°Λ. They tended to shift pre-midnight and equatorward with increasing $K_p$ ($B_z$ southward) due to expansion of the auroral oval and substorm activity. Overall, more echoes with high SNR were observed post-midnight, probably because of larger slip velocities there, confirming a basic prediction of $E \times B$ instability theory (Tsunoda, 1988).

5. Peak occurrence rates remained high even for $K_p > 4$, despite enhanced D-region absorption due to particle precipitation. This suggests the more poleward SuperDARN radars lose echoes during storms, mostly because the ionospheric irregularities expand equatorward of their FOVs. However, the radio-wave paths for TIGER may refract into the F region without traversing regions of strong absorption, whereas this is less likely to occur for the more poleward radars located under the auroral oval.

6. Nightside echoes were typically observed first via 1.5-hop propagation near dusk and then via 0.5-hop propagation during pre-midnight to dawn. Variations in the transition time between the two modes was earliest during winter (~20 MLT), and latest during summer (~23 MLT), consistent with the familiar seasonal variation in the F-region terminator. The subset of population A echoes observed on beam 15 near dusk had
characteristics reminiscent of dusk scatter (Ruohoniemi et al., 1988), but population A echoes were not a distinct feature confined to the sub-auroral ionosphere, and their occurrence maximised post-midnight because of TIGER’s lower latitude.

7. The seasonal variation in echo occurrence was relatively weak, but showed a familiar peak in auroral activity near the March (autumn) equinox. This relatively weak variation was consistent with the known longitudinal variations in auroral zone magnetic activity (Basu, 1975).

8. Figure 11, the average LOS Doppler velocities on the zonal beam 15, suggest that SAID-like phenomena occurred frequently in the sub-auroral and auroral ionosphere, especially in the pre-midnight sector.

We conclude the TIGER radar can be used to study nightside ionospheric irregularities during all seasons and under a broad range of geomagnetic conditions. Knowledge of these occurrence statistics will facilitate the design of numerous experiments, and the subsequent interpretation of results, and thus improve our understanding of some of the features shown here.

Acknowledgments. This work was supported by the Australian Research Council, the Australian Antarctic Science Advisory Council, and the Ian Potter Foundation. We thank N. F. Ness of the Bartol Research Institute for making ACE magnetic field data available over the internet, and Vladimir Papitashvilli for providing us with the source code for the DICM convection model. We also thank the numerous people who contributed to the construction, development, and maintenance of TIGER.
References

Aarons, J.: Global morphology of ionospheric scintillations, Proc. IEEE, 70, 359–378, 1982.

Anderson, P. C., Heelis, R. A., and Hanson, W. B.: The ionospheric signatures of rapid subauroral ion drifts, J. Geophys. Res., 96, 5785–5792, 1991.

André, R., Pinnock, M., and Rodger, A. S.: On the SuperDARN autocorrelation function observed in the ionospheric cusp, Geophys. Res. Lett., 26, 3353–3356, 1999.

André, R., Pinnock, M., and Rodger, A. S.: Identification of the low-altitude cusp by Super Dual Auroral Radar Network radars: A physical explanation for the empirically derived signature, J. Geophys. Res., 105, 27081–27093, 2000.

Baker, K. B. and Wing, S.: A new magnetic coordinate system for conjugate studies of high latitudes, J. Geophys. Res., 94, 9139–9143, 1989.

Baker, K. B., Dudeney, J. R., Greenwald, R. A., et. al.: HF radar signatures of the cusp and low-latitude boundary layer, J. Geophys. Res., 100, 7671–7695, 1995.

Basu, S.: Universal time seasonal variation of auroral zone magnetic activity and VHF scintillation, J. Geophys. Res., 80, 4725, 1975.

Conde, M., and Innis, J.: Thermospheric vertical wind activity mapped by the Dynamics Explorer-2 satellite, The Cedar Post, 43, 12, September, 2001.

Crooker, N. U.: Dayside merging and cusp geometry, J. Geophys. Res., 84, 951–959, 1979.

Davies, K.: Ionospheric Radio, IEE Electromagnetic Waves Series 31, London, UK: Peter Peregrinus Ltd., 1990.

Davies, T. N., and Sugiura, M.: Auroral electrojet activity index $AE$ and its universal time variations, J. Geophys. Res., 71, 785, 1966.

Dyson, P. L., and Devlin, J. C.: The Tasman International Geospace Environment Radar, The Physicist (The Australian Institute of Physics), 37, 48–53, March/April, 2000.

Fejer, B. G., and Kelley, M. C.: Ionospheric irregularities. Rev. Geophys. Space Phys., 18, 401–454, 1980.

Fukumoto, M., Nishitani, N., Ogawa, T., Sato, N., Yamagishi, H., Yukimatu, A. S.: Statistical analysis of echo power, Doppler velocity and spectral width obtained with the Syowa south HF radar, Adv. Polar Upper Atmos. Res., 13, 37–47, 1999.
Galperin, Y. I., Ponomarev, V. N., and Zosimova, A. G.: Direct measurements of ion drift velocity in the upper ionosphere during a magnetic storm, 2. Results of measurements during the November 3, 1967, magnetic storm, Cosmic Res (Russian), 11, 283–292, 1973.

Greenwald, R. A., Baker, K. B., Hutchins, R. A., and Hanuise, C.: An HF phased-array radar for studying small-scale structure in the high-latitude ionosphere, Radio Sci., 20, 63–79, 1985.

Greenwald, R. A., Baker, K. B., Dudeney, J. R., et. al.: DARN/SuperDARN: A global view of the dynamics of high-latitude convection, Space Sci. Rev., 71, 761–796, 1995.

Gussenhoven, M. S., Hardy, D. A., and Heinemann, N.: Systematics of the equatorward diffuse auroral boundary, J. Geophys. Res., 88, 5692–5708, 1983.

Hall, G. E., MacDougall, J. W., Moorcroft, D. R., St.-Maurice, J.-P., Manson, A. H., and Meek, C. E.: Super Dual Auroral Radar Network observations of meteor echoes, J. Geophys. Res., 102, 14,603–14,614, 1997.

Hanuise, C., Villain, J. P., Gresillon, D., Cabrit, B., Greenwald, R. A., and Baker, K. B.: Interpretation of HF radar ionospheric Doppler spectra by collective wave scattering theory, Ann. Geophysicae, 11, 29–39, 1993.

Hosokawa, K., Iyemori, T., Yukimatu, A. S., and Sato, N.: Spatial distribution of irregularity occurrence rate in the subauroral F region as observed by the SuperDARN radars, Proc. SuperDARN 2000 Workshop, Beechworth, Australia., 2000.

Hosokawa, K., Sugino, M., Lester, M., Sato, N., Yukimatu, A. S., and Iyemori, T.: Simultaneous measurement of duskside subauroral irregularities from the CUTLASS Finland radar and EISCAT UHF system, Submitted to J. Geophys. Res., 2002.

Jayachandran, P. T., St.-Maurice, J.-P., MacDougall, J. W., and Moorcroft, D. R.: HF Detection of slow long-lived E region plasma structures, J. Geophys. Res., 105, 2425–2442, 2000.

Kelley, M. C., Vickrey, J. F., Carlson, C. W., and Torbert, R.: On the origin and spatial extent of high-latitude F region irregularities, J. Geophys. Res., 87, 4469–4475, 1982.

Kelley, M. C.: The Earth’s ionosphere – Plasma physics and electrodynamics, Academic Press, San Diego, California, 1989.

Kivelson, M. G. and Russell, C. T. (Eds.): Introduction to space physics, Cambridge Univ. Press, Cambridge, U.K., 1995.

Leonard, J. M., Pinnock, M., Rodger, A. S., Dudeney, J. R., Greenwald, R. A., and Baker, K. B.: Ionospheric plasma convection in the southern hemisphere, J. Atmos. Solar-Terr. Phys., 57, 889–897, 1995.

Lester, M., Milan, S. E., Besser, V., and Smith, R.: A case study of HF radar spectra and 630.0 nm auroral emission in the pre-midnight sector, Ann. Geophysicae, 19, 327–339, 2001.
Lewis, R. V., Freeman, M. P., Rodger, A. S., Reeves, G. D., and Milling, D. K.: The electric field response to the growth phase and expansion phase onset of a small isolated substorm, Ann. Geophysicae, 15, 289–299, 1997.

Linson, L. M., and Workman, J. B.: Formation of striations in ionospheric plasma clouds, J. Geophys. Res., 75, 3211, 1970.

Lui, A. T. Y.: Current controversies in magnetospheric physics, Reviews Geophys., 39, 535–563, 2001.

Milan, S. E., Jones, T. B., Robinson, T. R., Thomas, E. C., and Yeoman, T. K.: Interferometric evidence for the observation of ground backscatter originating behind the CUTLASS coherent HF radars, Ann. Geophysicae, 15, 29–39, 1997a.

Milan, S. E., Yeoman, T. K., Lester, M., Thomas, E. C., and Jones, T. B.: Initial backscatter occurrence statistics from the CUTLASS HF radars, Ann. Geophysicae, 15, 703–718, 1997b.

Newell, P. T. and Meng, C.-I.: Mapping the dayside ionosphere to the magnetosphere according to particle precipitation characteristics, Geophys. Res. Lett., 19, 609-612, 1992.

Newell, P. T., Greenwald, R. A., and Ruohoniemi, J. M.: The role of the ionosphere in aurora and space weather, Rev. Geophys., 39, 137–149, 2001.

Nishitani, N., Ogawa, T., Sato, N., Yamagishi, H., Yukimatu, A. S., and Watanabe, M.: Averaged pattern of ionospheric echo region and convection: initial results from the Syowa station HF radar, Proc. NIPR Symp. Upper Atmos. Phys., 10, 42–49, 1997.

Papitashvili, V. O. and Rich, F. J.: High-latitude ionospheric convection models derived from Defense Meteorological Satellite Program ion drift observations and parameterized by the interplanetary magnetic field strength and direction, J. Geophys. Res., 107, In Press, 2002.

Parkinson, M. L., Dyson, P. L., and Quach, A. T. D.: Arrival of ionospheric troughs and oblique spread-F in the wake of large-scale travelling ionospheric disturbances during the intense auroral storms of August 22 and 23, 1990, J. Geomag. and Geoelect., 48, 1381–1405, 1996.

Parkinson, M. L., Devlin, J. C., Dyson, P. L., Pinnock, M., Ye, H., Morris, R. J., and Waters, C. L.: Diurnal, seasonal, and geomagnetic activity variations in the occurrence of decametre-scale irregularities in the auroral and subauroral ionosphere, Proceedings of the Workshop on the Applications of Radio Science, Refereed Paper G9, Leura, New South Wales, 20–22 February, 2002a.

Parkinson, M. L., Dyson, P. L., Pinnock, M., Devlin, J. C., Hairston, M. R., Yizengaw, E., and Wilkinson, P. J.: Signatures of the midnight open-closed magnetic field-line boundary during balanced dayside and nightside reconnection, Ann. Geophysicae, In Press, 2002b.
Parkinson, M. L., Pinnock, M., Dyson, P. L., Ye, H., Devlin, J. C., and Hairston, M. R.: On the lifetime and extent of an auroral westward flow channel observed during a magnetospheric substorm, Submitted to Ann. Geophysicae, 2002c.

Pinnock, M., Rodger, A. S., Dudeney, J. R., Baker, K. B., Newell, P. T., Greenwald, R. A., and Greenspan, M. E.: Observations of an enhanced convection channel in the cusp ionosphere, J. Geophys. Res., 98, 3767–3776, 1993.

Ruohoniemi, J. M., Greenwald, R. A., Villain, J.-P., Baker, K. B., Newell, P. T., and Meng, C.-I.: Coherent HF radar backscatter from small-scale irregularities in the dusk sector of the subauroral ionosphere, J. Geophys. Res., 93, 12871–12882, 1988.

Ruohoniemi, J. M., and Greenwald, R. A.: Rates of scattering occurrence in routine HF radar observations during solar cycle maximum, Radio Sci., 32, 1051–1070, 1997.

Russel, C. T. and McPherron, R. L.: Semiannual variation of geomagnetic activity, J. Geophys. Res., 78, 92–108, 1973.

Shepherd, S. G. and Ruohoniemi, J. M.: Electrostatic potential patterns in the high latitude ionosphere constrained by SuperDARN measurements, J. Geophys. Res., 105, 23005-23014, 2000.

Starkov, G. V.: Statistical dependencies between the magnetic activity indices, Geomag. Aeronomy, 34, 101–103, 1994a.

Starkov, G. V.: Mathematical model of the auroral boundaries, Geomag. Aeronomy, 34, 331–336, 1994b.

Tsunoda, R. T.: High-latitude F region irregularities: a review and synthesis, Rev. Geophys., 26 (4), 719–760, 1988.

Vickrey, J. F. and Kelley, M. C.: The effects of a conducting E layer on classical F region cross-field plasma diffusion, J. Geophys. Res., 87, 4461–4468, 1982.

Villain, J. P., Caudal, G., and Hanuise, C.: A SAFARI-EISCAT comparison between the velocity of F region small-scale irregularities and ion drift, J. Geophys. Res., 90, 8433–8444, 1985.

Villain, J. P., André, R., Pinnock, M., Greenwald, R. A., and Hanuise, C.: A statistical study of the Doppler spectral width of high latitude ionospheric F region recorded with SuperDARN coherent HF radars, Ann. Geophysicae, In Press, 2002.

Yeoman, T. K., Lewis, R. V., Milan, S. E., and Watanabe, M.: An interhemispheric study of the ground magnetic and ionospheric electric fields during the substorm growth phase and expansion phase onset, J. Geophys. Res., 104, 14867–14877, 1999.
**Figure Captions**

**Fig. 1.** The field of view (FOV) of the TIGER radar mapped to geographic (left) and geomagnetic co-ordinates (right), both drawn on the same grid to emphasise differences. The magnetic meridian pointing beam 4 and the eastern beam 15 are shown in bold. Shaded pixels represent ionospheric echoes with spectral widths \(<200 \text{ m s}^{-1}\) (light) and \(>200 \text{ m s}^{-1}\) (dark) recorded during the full scan commencing 1716 UT on 5 September, 2000. The location of auroral oval boundaries given by the Starkov (1994b) model for $AL = -172 \text{ nT \ (K_p = 3)}$ are superimposed: poleward boundary of the discrete aurora (dashed curve), equatorward boundary of the discrete aurora (solid curve), and equatorward boundary of the diffuse aurora (dotted curve).

**Fig. 2.** Histogram showing the probability of the radar selecting a particular transmitter frequency during the study period, December 1999 to November 2000. The radar electronics can operate anywhere between 8 and 20 MHz, but shaded regions correspond to frequency bands we never use under the conditions of our RF license.

**Fig. 3.** The diurnal variation of transmitter frequency averaged over 30-min intervals of MLT during the study period, December 1999 to November 2000. The scatter bars correspond to ± one standard deviation. The discontinuities in transmitter frequency at 0746 and 1946 MLT (2100 and 0900 UT) correspond to the transitions between default day and night frequency bands, respectively.

**Fig. 4.** The occurrence rate of beam 4 ionospheric echoes for all $K_p$ values detected during (a) summer (days 313 to 035), (b) autumn (days 036 to 126), (c) winter (days 127 to 221), and (d) spring (days 222 to 312). The results are shown versus MLT and magnetic latitude, with noon (12 MLT) at top, and dusk (06 MLT) at right, and the equatorward boundary at $-57^\circ \Lambda$. Magnetic latitudes $-60^\circ$, $-70^\circ$, and $-80^\circ \Lambda$ have been superimposed. No data were acquired poleward of $-88^\circ \Lambda$. Model auroral oval boundaries have been superimposed (see text).

**Fig. 5.** The occurrence rate of beam 4 ionospheric echoes detected during all seasons, and sorted according to geomagnetic activity. (a) $K_p = 0$ to 1, (b) $K_p >1$ to 2, (c) $K_p >2$ to 3, (d) $K_p >3$ to 4, (e) $K_p >4$ to 5, and (f) $K_p >5$ to 6. Model auroral oval boundaries for (a) $AL = -21 \text{ nT \ (K_p = 1-)}$, (b) $AL = -64 \text{ nT \ (K_p = 2-)}$, (c) $AL = -141 \text{ nT \ (K_p = 3-)}$, (d) $AL = -240 \text{ nT \ (K_p = 4-)}$, (e) $AL = -350 \text{ nT \ (K_p = 5-)}$, and (f) $AL = -458 \text{ nT \ (K_p = 6-)}$ have been superimposed.
Fig. 6. (a) Average power of ionospheric echoes with SNR >3 dB recorded on beam 4 for all seasons and levels of geomagnetic activity combined, and (b) the corresponding average elevation angles measured using the interferometer subarray. Average FITACF parameters are not shown in this and subsequent plots if fewer than 2 valid FITACF results were obtained per range-time bin. Thus many of the short-scale fluctuations are a measure of statistical uncertainty. Equipotential contours calculated using the DICM model (see text) have been superimposed. The minimum electric potential in the dusk cell is –23.4 kV, the maximum potential in the dawn cell is 11.3 kV, and contours are separated by 2.5 kV.

Fig. 7. (a) Average LOS Doppler velocities recorded on beam 4 and sorted into four sectors in the $B_y$–$B_z$ plane: (a) $B_y$ negative, $B_z$ positive, (b) $B_y$ positive, $B_z$ positive, (c) $B_y$ negative, $B_z$ negative, and (d) $B_y$ positive, $B_z$ negative. Equipotential contours calculated using the DICM model have been superimposed. Minimum and maximum potentials occur in the patterns are as follows: (a) –24.2 kV in the weak afternoon cell, (b) 9.5 kV in the weak morning cell, (c) –52.8 kV in the dusk cell and 26.8 kV in the dawn cell, and (d) –38.0 kV in the dusk cell and 31.2 kV in the dawn cell. Contours are separated by 5 kV.

Fig. 8. Average Doppler spectral widths recorded on beam 4 for all seasons and $K_p$ values combined. Magnetic $L$ shells of 4, 5, 6, 7, and 8 have been superimposed, as well as the same equipotential contours superimposed in Fig. 6.

Fig. 9. Histograms of the number of ionospheric echoes versus Doppler spectral width recorded on beam 15 (solid curve) and beam 4 (dotted curve) during all seasons and $K_p$ values combined. A bin size of 2 m s$^{-1}$ was used.

Fig. 10. The occurrence rate of population A echoes recorded on beam 15 during (a) summer, (b) autumn, (c) winter, and (d) spring for all $K_p$ values. The results are shown versus UT and group range, with magnetic latitudes –60°, –65°, and –70°A superimposed. Nominal values of MLT in the ionosphere above Macquarie Island are given at top. Similar to Fig. 4, model auroral oval boundaries for (a) $AL = -109$ nT ($K_p = 2.30$), (b) $AL = -108$ nT ($K_p = 2.28$), (c) $AL = -131$ nT ($K_p = 2.56$), and (d) $AL = -120$ nT ($K_p = 2.43$) have also been superimposed.

Fig. 11. Average LOS Doppler velocities for beam 15 ionospheric echoes with any spectral width and $K_p$ value recorded during (a) summer, (b) autumn, (c) winter, and (d) spring. The same model auroral oval boundaries used in Fig. 10 have been superimposed.
Table I. TIGER normal scan data analysed in this study

| Summer, 1999 & 2000 | Autumn, 2000 | Winter, 2000 | Spring, 2000 |
|----------------------|--------------|--------------|--------------|
| December 02–09, 19–31| February 14–18, 27–29 | May 07–18, 24–31 | August 14–18, 23–24, 25–28 |
| January 01–03, 13–13, 18–31 | March 01–04, 29–31 | June 01–04, 05–15, 21–26 | September 01–21 |
| February 01–02 | April 05–06, 11–12, 14–23 | July 01–04, 05–06, 12–20 | October 03–17, 20–26 |
| November 09–14, 20–30 | May 01–02 | | November 05–07 |
Table II. Seasonal changes in beam 4 occurrence rates, range >630 km

|                      | Summer | Autumn | Winter | Spring |
|----------------------|--------|--------|--------|--------|
| Total no. echoes     | 384,257| 303,488| 457,373| 419,371|
| Total no. beam soundings | 40,702 | 24,164 | 44,311 | 40,200 |
| Average occurrence rate (%) | 13.70  | 18.68  | 15.60  | 15.01  |
| Standard error (%)   | 0.19   | 0.21   | 0.18   | 0.18   |
| Peak occur. Rate (%) | 71     | 77     | 65     | 65     |
Table III. Seasonal changes in beam 4 occurrence rates, range ≤630 km

|                         | Summer | Autumn | Winter | Spring |
|-------------------------|--------|--------|--------|--------|
| Total no. echoes        | 31,794 | 14,293 | 33,673 | 22,180 |
| Total no. beam soundings| 40,702 | 24,164 | 44,311 | 40,200 |
| Average occurrence rate (%) | 6.57  | 4.92  | 6.60  | 4.44  |
| Standard error (%)      | 0.16   | 0.14   | 0.20   | 0.10   |
| Peak occur. Rate (%)    | 23     | 25     | 38     | 14     |
| $K_p$ | 0–1  | >1–2 | >2–3 | >3–4 | >4–5 | >5–6 |
|-------|------|------|------|------|------|------|
| Total no. echoes | 272,966 | 417,971 | 440,474 | 257,342 | 117,522 | 30,387 |
| Total no. beam soundings | 30,901 | 40,447 | 39,682 | 22,412 | 10,018 | 3,462 |
| Average occurrence rate (%) | 11.71 | 15.43 | 17.01 | 17.22 | 17.56 | 12.34 |
| Standard error (%) | 0.16 | 0.20 | 0.22 | 0.23 | 0.23 | 0.20 |
| Peak occur. Rate (%) | 56 | 74 | 80 | 85 | 74 | 82 |
Table V. Seasonal changes in beam 15 occurrence rates, range >630 km

|                           | Summer | Autumn | Winter | Spring |
|---------------------------|--------|--------|--------|--------|
| Total no. echoes          | 76,880 | 68,038 | 96,532 | 67,443 |
| Total no. beam soundings  | 40,231 | 26,214 | 44,384 | 40,481 |
| Average occurrence rate (%) | 2.44   | 3.58   | 2.93   | 2.07   |
| Standard error (%)        | 0.05   | 0.06   | 0.05   | 0.04   |
| Peak occur. Rate (%)      | 27     | 36     | 21     | 23     |
Fig. 1. The field of view (FOV) of the TIGER radar mapped to geographic (left) and geomagnetic co-ordinates (right), both drawn on the same grid to emphasise differences. The magnetic meridian pointing beam 4 and the eastern beam 15 are shown in bold. Shaded pixels represent ionospheric echoes with spectral widths <200 m s$^{-1}$ (light) and >200 m s$^{-1}$ (dark) recorded during the full scan commencing 1716 UT on 5 September, 2000. The location of auroral oval boundaries given by the Starkov (1994b) model for $AL = -172$ nT ($K_p = 3$) are superimposed: poleward boundary of the discrete aurora (dashed curve), equatorward boundary of the discrete aurora (solid curve), and equatorward boundary of the diffuse aurora (dotted curve).
Fig. 2. Histogram showing the probability of the radar selecting a particular transmitter frequency during the study period, December 1999 to November 2000. The radar electronics can operate anywhere between 8 and 20 MHz, but shaded regions correspond to frequency bands we never use under the conditions of our RF license.
Fig. 3. The diurnal variation of transmitter frequency averaged over 30-min intervals of MLT during the study period, December 1999 to November 2000. The scatter bars correspond to ± one standard deviation. The discontinuities in transmitter frequency at 0746 and 1946 MLT (2100 and 0900 UT) correspond to the transitions between default day and night frequency bands, respectively.
Fig. 4. The occurrence rate of beam 4 ionospheric echoes for all $K_p$ values detected during (a) summer (days 313 to 035), (b) autumn (days 036 to 126), (c) winter (days 127 to 221), and (d) spring (days 222 to 312). The results are shown versus MLT and magnetic latitude, with noon (12 MLT) at top, and dusk (06 MLT) at right, and the equatorward boundary at $-57^\circ$A. Magnetic latitudes $-60^\circ$, $-70^\circ$, and $-80^\circ$A have been superimposed. No data were acquired poleward of $-88^\circ$A. Model auroral oval boundaries have been superimposed (see text).
Fig. 5. The occurrence rate of beam 4 ionospheric echoes detected during all seasons, and sorted according to geomagnetic activity. (a) $K_p = 0$ to 1, (b) $K_p > 1$ to 2, (c) $K_p > 2$ to 3, (d) $K_p > 3$ to 4, (e) $K_p > 4$ to 5, and (f) $K_p > 5$ to 6. Model auroral oval boundaries for (a) $AL = -21$ nT ($K_p ≈ 1$), (b) $AL = -64$ nT ($K_p = 2$), (c) $AL = -141$ nT ($K_p = 3$), (d) $AL = -240$ nT ($K_p = 4$), (e) $AL = -350$ nT ($K_p = 5$), and (f) $AL = -458$ nT ($K_p = 6$) have been superimposed.
Fig. 6. (a) Average power of ionospheric echoes with SNR > 3 dB recorded on beam 4 for all seasons and levels of geomagnetic activity combined, and (b) the corresponding average elevation angles measured using the interferometer subarray. Average FITACF parameters are not shown in this and subsequent plots if fewer than 2 valid FITACF results were obtained per range-time bin. Thus many of the short-scale fluctuations are a measure of statistical uncertainty. Equipotential contours calculated using the DICM model (see text) have been superimposed. The minimum electric potential in the dusk cell is –23.4 kV, the maximum potential in the dawn cell is 11.3 kV, and contours are separated by 2.5 kV.
Fig. 7. (a) Average LOS Doppler velocities recorded on beam 4 and sorted into four sectors in the $B_y$–$B_z$ plane: (a) $B_y$ negative, $B_z$ positive, (b) $B_y$ positive, $B_z$ positive, (c) $B_y$ negative, $B_z$ negative, and (d) $B_y$ positive, $B_z$ negative. Equipotential contours calculated using the DICM model have been superimposed. Minimum and maximum potentials occur in the patterns are as follows: (a) –24.2 kV in the weak afternoon cell, (b) 9.5 kV in the weak morning cell, (c) –52.8 kV in the dusk cell and 26.8 kV in the dawn cell, and (d) –38.0 kV in the dusk cell and 31.2 kV in the dawn cell. Contours are separated by 5 kV.
Fig. 8. Average Doppler spectral widths recorded on beam 4 for all seasons and $K_p$ values combined. Magnetic $L$ shells of 4, 5, 6, 7, and 8 have been superimposed, as well as the same equipotential contours superimposed in Fig. 6.
Fig. 9. Histograms of the number of ionospheric echoes versus Doppler spectral width recorded on beam 15 (solid curve) and beam 4 (dotted curve) during all seasons and $K_p$ values combined. A bin size of 2 m s$^{-1}$ was used.
Fig. 10. The occurrence rate of population A echoes recorded on beam 15 during (a) summer, (b) autumn, (c) winter, and (d) spring for all $K_p$ values. The results are shown versus UT and group range, with magnetic latitudes $-60^\circ$, $-65^\circ$, and $-70^\circ$ shown. Nominal values of MLT in the ionosphere above Macquarie Island are given at top. Similar to Fig. 4, model auroral oval boundaries for (a) $AL = -109$ nT ($K_p = 2.30$), (b) $AL = -108$ nT ($K_p = 2.28$), (c) $AL = -131$ nT ($K_p = 2.56$), and (d) $AL = -120$ nT ($K_p = 2.43$) have also been superimposed.
Fig. 11. Average LOS Doppler velocities for beam 15 ionospheric echoes with any spectral width and $K_p$ value recorded during (a) summer, (b) autumn, (c) winter, and (d) spring. The same model auroral oval boundaries used in Fig. 10 have been superimposed.