*Ann. Geophysicae* Paper, 6th February, 2002

# Multiple time delays between IMF-driven convection changes at cross polar locations in the high-latitude ionosphere

M. L. PARKINSON[1](✉ ), M. PINNOCK[2], P. L. DYSON[1], J. C. DEVLIN[3], C. L. WATERS[4], P. R. SMITH[3], AND A. M. BREED[5]

[1]*Department of Physics, La Trobe University, Victoria 3086, Australia*

[2]*British Antarctic Survey, Natural Environment Research Council, Cambridge CB3 0ET, UK*

[3]*Department of Electronic Engineering, La Trobe University, Victoria 3086, Australia*

[4]*Department of Physics, University of Newcastle, New South Wales 2038, Australia*

[5]*Atmospheric and Space Physics, Australian Antarctic Division, Kingston, Tasmania 7050, Australia*

E-mail: m.parkinson@latrobe.edu.au

Fax: 61-3-94791552

Ph: 61-3-94791433

**Abstract.** Two SuperDARN radars were used to measure time delays between the arrival of interplanetary magnetic field (IMF)-driven convection changes at various locations in the high-latitude ionosphere situated diametrically across the geomagnetic pole from each other (i.e., separated by ~12 h of magnetic local time). The recently commisioned Tasman International Geospace Environment Radar (TIGER) and the Halley SuperDARN radars were operated in a special mode to give normal full-scan soundings interlaced with high time resolution observations (~6 sec) along the magnetic meridian. The results for three case studies are presented here. The first occurred at ~0601 UT on 12 February, 2000 when the $B_z$ component of the IMF swung from ~+11 nT to –16 nT during 25 min, and the convection change in the morning ionosphere ~(0322 MLT, 70°S AACGM latitude) started ≥7 min after it first appeared in the late afternoon ionosphere ~(1627 MLT, 72°S). ). There was also evidence for a very rapid (<2 min) response of the afternoon sector during a brief interval of $B_y$-dominated, $B_z$-northward merging preceeding the impact of the southward transition. The second case occurred at ~1525 UT on 01 April, 2000, when the $B_z$ component swung from +7 nT to –5 nT during 4 min. The Halley radar recorded the immediate arrival of the convection change just past magnetic noon ~(1240 MLT, 83°S), but possible responses observed by the TIGER radar in the morning ionosphere ~(0224 MLT, 73°S) did not occur until ~8–11 and ~33 min later, with a substorm onset signature definitely occurring ~85 min later. The last case occurred at ~1826 UT on 24 September, 2000 when the $B_z$ and $B_y$ components swung from +3 nT to –5 nT, and –9 nT to +3 nT, respectively, the former during 4 min. A substantial decrease of solar-wind dynamic pressure of 4.8 nPa also occurred in <7 min. Nearly simultaneous ionospheric responses, probably associated with the pressure decrease, were observed by both radars: in the afternoon sector by Halley ~(1540 MLT, 75°S) and in the morning sector by TIGER ~(0451 MLT, 70°S). The observations suggests that the IMF-driven convection change occurred ~0–3 min later in the morning ionosphere. Overall, these initial observations are consistent with the main impact of IMF-driven convection propagating throughout the high-latitude ionosphere at phase speeds on the order of 10 km $s^{-1}$. However, the observations do not negate the possibility of very rapid but weak responses extending into the nightside ionosphere, and possibly communicated by fast-mode waves propagating through the magnetospheric cavity, the *F*-region ionosphere, or the Earth-ionosphere wave-guide.

***Key words:*** *electric fields and currents, ionosphere-magnetosphere interactions, plasma convection*

# 1 Introduction

It is well accepted that the convection of plasma in the high-latitude ionosphere poleward of the main ionospheric trough (~65° magnetic latitude) is strongly influenced by the interplanetary magnetic field (IMF) and solar-wind velocity (Kelley, 1989; Kivelson and Russell, 1995). The area of the polar cap ionosphere, or the region where geomagnetic flux is open to the IMF, inflates when dayside reconnection (i.e., merging) dominates, but then deflates when reconnection in the tail dominates (Siscoe and Huang, 1985). Inflation will prevail when $B_z$ (the northward component of the IMF) is strongly negative, but reconnection in the tail will become important after some threshold of magnetic tension has been reached in the tail lobes. However, deflation must dominate when $B_z$ subsequently swings strongly positive and energy in the tail is released at a faster rate than it accumulates. Hence high-latitude convection is usually driven by a balance between flows generated by merging of the IMF at the dayside magnetopause and the subsequent reconnection of geomagnetic flux tubes in the current sheet separating the tail lobes.

Cowley and Lockwood (1992) (CL92 hereafter) elucidated a dynamic process by which magnetosphere-ionosphere coupling can be driven by “balanced” and “unbalanced” reconnection. When dayside merging dominates, newly created open flux in the cusp excites high-latitude convection until a new equilibrium open-closed field line boundary is established at all magnetic local times (MLTs). Importantly, the authors suggested a time delay on the order of 15 min for newly created flux in the dayside ionosphere to cause complete reconfiguration of the nightside boundary (and hence the entire high-latitude convection). The time delay consists of two parts, the first corresponding to magnetic flux tubes being swept back into the near-Earth tail lobes at magnetosheath velocities of ~100–200 km $s^{-1}$, and so is on the order of 10 min. The second part corresponds to the effects of the boundary layer perturbation propagating hydromagnetically to the ionosphere, and is on the order of 5 min. At ionosphere altitudes, these two delays combine to communicate the initial perturbation of open flux around the open-closed boundary at ~5–10 km $s^{-1}$.

Numerous studies have found results consistent with a finite time delay for the apparent propagation of IMF-driven convection changes throughout the high-latitude dayside ionosphere (Lockwood et al., 1986; Etemadi et al., 1988; Todd et al., 1988; and Saunders et al., 1992). Khan and Cowley (1999) extended this work to include a comprehensive statistical analysis of nightside responses. They performed both a cross-correlation study and a large set of case studies using 300 h of data with north to south changes in $B_z$ and field-perpendicular *F*-region ionospheric drifts measured with the EISCAT UHF radar at 66.3° magnetic latitude. As with earlier studies, their results suggest the most rapid ionospheric responses occur near 14 hours MLT, with the subsequent nightside responses delayed, on average, by about 6 min. However, their results showed a lot of variability, being scattered between less than zero minutes on the dayside to greater than 30 min near magnetic midnight. Other studies have found some very long time delays of ~10–40 min for the midnight auroral ionosphere to respond to the arrival of IMF changes at the dayside magnetopause (Lester et al., 1993; Taylor et al., 1994). 7

Jayachandran and McDougall (2000) found a two-step response of the polar cap ionosphere consisting of an initial weak response about 10 min after the arrival of the IMF change in the ionosphere followed by a slowly propagating but stronger enhancement of the convection speed. Clearly, more high-time resolution observations of the central polar cap need to be analysed.

Although numerous observations of the ionosphere have been interpreted in the context of the CL92 picture of solar wind-magnetosphere interactions, some recent observations and analyses suggest the initial convection response to changes in $B_z$ and $B_y$ (the dawn-to-dusk component of the IMF) can occur nearly simultaneously across the entire high-latitude ionosphere:

1. Ridley et al. (1997, 1998) studied the evolution of residual convection patterns obtained by subtracting a base convection pattern prior to a sharp transition in the IMF. They concluded that large-scale convection changes are "broadcast from the cusp region to the rest of the ionosphere in a matter of seconds." However, the interpretation of their results was challenged (Lockwood and Cowley, 1999) and then defended (Ridley et al., 1999). Ruoheniemi et al. (2002) noted that the assimilative technique used by Ridley et al. will tend to globalise local responses.

2. Dudeney et al. (1998) reported an unusually rapid $B_y$ response of the ionospheric signature of what they took to be the boundary between the classical central plasma sheet and boundary plasma sheet. Their observations were of the dawn and dusk ionospheres which might be expected to change simultaneously in response to the IMF because of their equal distance from noon.

3. Ruoheniemi and Greenwald (1998) presented concurrent observations made by four Super Dual Auroral Radar Network (SuperDARN) radars in the Northern Hemisphere. For a single event, they concluded that the convection pattern in the "entire high-latitude zone reconfigured practically simultaneously" in response to a sudden negative turning of $B_z$ (~12 nT in 2.5 min), yet they also noted the presence of time delays of 2 to 4 min. There were significant fluctuations in $B_y$ immediately before the step-like decrease in $B_z$, and their stack plots of Doppler velocity recorded at 1835 and 2050 MLT did not show a rapid response at latitudes beneath ~75°N in the nightside ionosphere.

4. Shepherd et al. (1999) also used SuperDARN data to identify another nearly simultaneous response of the dayside high-latitude ionosphere extending from ~75° to 85°N magnetic latitude and from ~9 to 16 MLT. They suggested draping of the IMF over a large portion of the dayside magnetopause may have explained the rapid response.

5. Watanabe et al. (2000) performed a detailed analysis of a single, complex event in which $B_z$ swung south-to-north one hour after a prolonged period of $B_z$ northward conditions. They concluded that a nearly simultaneous global response

was observed within 2 to 3 min of the northward turning because the magnetosphere retained a memory of the earlier $B_z$ northward conditions.

6. Murr and Hughes (2001) found very clear simultaneous magnetometer responses at 12, 15, 18, and 21 MLT in the high-latitude ionosphere poleward of 65° magnetic. Their case studies were selected on the basis of very sharp $B_z$ southward turnings.

7. Finally, Nishitani et al. (2001) studied the high-latitude response to a single large and sudden $B_z$ southward turning accompanied by a significant change in solar-wind density. They speculated their observations were consistent with a two-level response, namely an instantaneous global response communicated by magnetosonic waves, and a slower expansion of the dusk polar cap boundary (as per CL92).

The interpretation of some of the previous results might be disputed, but overall they suggest that sometimes the signatures of large-scale IMF-driven convection changes are rapidly broadcast across the entire high-latitude ionosphere. How often and under what conditions this occurs remains to be answered.

Also of relevance here are the observations showing that geomagnetic sudden commencement and some IMF-related signatures can occur nearly simultaneously near the dayside dip equator (e.g., Matsushita, 1962; Nishida, 1968; Araki, 1977). Kikuchi et al. (1996) recently studied quasi-periodic *DP* 2 magnetic fluctuations and found the time delay for associated magnetometer perturbations to penetrate to dayside equatorial latitudes was less than 25 s. They invoked a variant of the Araki (1994) model to explain their observations: fast-mode compressional waves propagating from the magnetopause toward the Earth encounter gradients in magnetospheric plasma density. There they couple to Alfvén-modes which communicate field-aligned currents to the high-latitude ionosphere. The associated electric fields subsequently propagate to the dip equator at nearly the speed of light via the "parallel plane transmission line" composed of the Earth and the highly conducting dayside ionosphere.

Perhaps the slower IMF-driven convection changes can be explained by the CL92 picture, whereas the more rapid changes can be explained by fast-mode hydromagnetic disturbances propagating directly through the magnetospheric cavity or the *F*-region ionosphere, or electrically through the Earth-ionosphere wave guide formed by a boundary layer of enhanced ionospheric conductivity. The recent work of Kikuchi et al. (1996) suggests the rapid responses might be confined to regions of enhanced *E*-region conductivity usually occurring in the dayside ionosphere. This also suggests an important role for auroral and thin *E*-region layers in the high-latitude nightside ionosphere.

There are still pertinent questions that require experimental investigation. Do large-scale convection changes manifest in the nightside ionosphere on the order of 10 min after an initial dayside response, or do they manifest nearly instantaneously (≤ 2 min) across the entire high-latitude ionosphere? Are large-scale convection changes communicated throughout the high-latitude ionosphere via several mechanisms, and if so, how frequently and under what conditions? Does the magnetospheric convection always drive the ionospheric convection, or can the ionospheric convection drive the magnetospheric convection? Finally, when nightside reconnection is activated, do convection changes appear in the dayside ionosphere?

# 2 Experimental design

## 2.1 Solar-wind data

Because of their continuity, solar-wind speed, pressure, and IMF data measured on board the Advanced Composition Explorer (ACE) located about 235 *Re* upstream of the Earth were the primary solar-wind parameters used in this study. We reproduce the IMF data in the geocentric solar magnetospheric (GSM) co-ordinate system with 16-s time resolution, but note that fluctuations on time scales <10 min may not be representative of the actual conditions impacting the Earth's magnetosphere. However, similar data recorded on board Wind, the Interplanetary Monitoring Platform-8 (IMP8), and Geotail spacecraft were used to help fix the actual arrival times of solar-wind conditions in the noon-sector ionosphere to an accuracy of several minutes.

Accurate estimates of the noon-sector arrival times were not critical in this study, but reasonably accurate procedures were adopted. The IMF advection times from IMP8 to the magnetopause (nominally located at 10 *Re*) were estimated using propagation along the geocentric solar ecliptic $x$-direction, GSE($x$), at an average solar-wind speed representative of each event. The reduced solar-wind speed in the magnetosheath was allowed for by taking one eighth of the solar-wind speed over the final 3 *Re*. We then advected the IMF data a further 2 to 3 min (as required to round-off to the nearest minute) to allow for the Alfvénic communication of electric fields from the magnetopause to the ionosphere.

## 2.2 HF radar data

The primary aim of this study was to measure time delays between the initial manifestation of IMF-driven convection changes in the field of views (FOVs) of two SuperDARN radars located roughly diametrically opposite the altitude adjusted corrected geomagnetic pole (AACGM) (Baker and Wing, 1989). The two radars used in this study were the Southern Hemisphere Auroral Radar Experiment (SHARE) located at Halley Base (76°S, 26°W, geographic), Antarctica, and the Tasman International Geospace Environment Radar (TIGER) located in Tasmania (43°S, 147°E), Australia. SuperDARN radars are oblique-looking HF backscatter radars performing sequential 16-beam scans covering over 52° in azimuth and measuring backscatter power (dB), line-of-sight (LOS) Doppler velocity (m $s^{-1}$), and the Doppler spectral width (m $s^{-1}$) at 45-km range intervals out to 3555 km, as described in detail by Greenwald et al. (1985, 1995). Echo parameters are derived from analysis of the auto-correlation functions of backscattered signals (Baker et al., 1995).

**Figure 1**

Figure 1 illustrates the relative locations of the radar FOVs in magnetic co-ordinates during the three case studies analysed in this paper. Two-dimensional velocities for a representative two-cell convection pattern given by the IZMIRAN electrodynamic model (IZMEM) for ($B_x$, $B_y$, $B_z$) = (0, −5, −5) nT have been superimposed to help the reader make sense of the radar LOS observations shown in the results sections.

The Halley radar is located at a higher latitude favouring the detection of cusp scatter, whereas TIGER is located at a lower latitude favouring the detection of scatter associated with the nightside auroral oval, though both radars are capable of measuring the initial manifestation of convection changes at any MLT. If IMF-driven convection changes first manifest in the noon sector, and then propagate around the open-closed field-line boundary (OCB), we might expect the shortest time delays when the radars are aligned near the dawn-dusk meridian, and the longest time delays to be observed when they are aligned near the noon-midnight meridian.

Halley beam 8 and TIGER beam 4 are the beams most closely aligned with the magnetic meridian (bold black in Fig. 1). Hence the radar scans used in this study consisted of 3-s integrations on each beam within the Halley beam sequence 0, 8, 1, 8, 2, 8, …, 15, 8, 0, 8, etc. These integrations were synchronised with the TIGER beam sequence 15, 4, 14, 4, 13, 4, …, 0, 4, 15, 4, etc., without any delays between successive scans. Thus full beam scans were repeated every 96 s with 6-s time resolution measurements interleaved on the two magnetic meridian pointing beams.

In subsequent sections we present range-time plots of LOS Doppler velocities measured with 6-s time resolution and 2-dimensional velocities estimated from full-scan measurements with 2-min resolution. The 6-s resolution measurements were taken to achieve a sampling period much shorter than the minimum observed time delays (~1–3 min), otherwise the convection changes might have been confused with instrumental noise or unrelated geophysical transients. For example, when using 2-min resolution data alone, the uncertainty in the time delays must be $\pm\sqrt{2}$ min, and this is a reasonable estimate of the maximum errors in the arrival times reported here.

Our estimates of the arrival time of convection changes were based upon the assessment of a number of factors combined, such as distinct, persistent changes in range-time plots of LOS Doppler velocity, equatorward expansions of backscatter boundaries, and the redistribution of LOS Doppler velocity in full-scan plots, the last confirmed by a beam-swinging analysis of 2-dimensional flow vectors.

Ionospheric convection is a complex, non-stationary process with almost continuous fluctuations in ion motion, the causes of which are only partly understood. Hence we endeavoured to associate the IMF transitions with large-scale convection changes indicative of the establishment of the dayside two-cell convection pattern (or the *DP* 2 current system). We required the amplitude of the signatures indicating the arrival of the convection changes to be significantly greater than the normal background of continuous fluctuations in the HF radar data. This is the principle McPherron (1970) originally used to define the growth phase of a magnetospheric substorm.

The full-scan observations were of two extensive high-latitude regions, but the high-time resolution observations were only along two magnetic meridians at different MLTs. This meant we had limited knowledge of the behaviour of the global convection pattern, so we could not reliably measure the time scales for the convection patterns to reconfigure subject to the initial impact of the IMF transition in the noon-sector ionosphere. Nor could we necessarily measure the initial ionospheric impact in the noon sector. However, because of their proximity to magnetic noon, it was possible to infer this time using magnetometer data in the 12 February case, and Halley radar data in the 1 April case.

The preceding difficulties were not a serious problem because the aim of the study was to measure the time delays between the initial manifestation of convection changes at locations diametrically opposite the AACGM pole. The design philosophy was to make use of direct and very sensitive radar measurements whenever possible. Although we cannot model the global convection patterns (as per Ridley et al., 1998), we emphasise the advantage of not having to invoke any models, such as required for ionospheric conductivity, when interpreting our direct observations of ionospheric plasma drift made using two instruments separated by ~12 h of MLT.

The nominal time equation used for Halley beam 8 was MLT=UT−0246. Similarly, for TIGER beam 4, MLT=UT+1046, but both these corrections were invalid for the range gates close to the AACGM pole where the differences between MLT and UT changed rapidly with latitude. AACGM co-ordinates at an altitude of 300 km have been used throughout this paper.

### 2.3 Magnetometer data

The arrival times of the convection changes measured by the HF radars were also compared with those implied by magnetometer measurements made at the Australian stations Davis (68.6°S, 78.0°E, 74.6°S magnetic), Casey (66.3°S, 110.5°E, 80.8°S), and Macquarie Island (54.5°S, 158.9°E, 64.8°S). Because we were primarily interested in detecting the small, initial responses, we only show the perturbations in the magnetic field *X* (North), *Y* (East), and *Z* (down) components, corrected by subtracting a baseline defined by their diurnal average values.

**Figure 2**

## 3 Observations and analysis

### 3.1 Case study 1: ~06 h UT, 12 February, 2000

Figure 1 shows the relative locations of the two radar FOVs and magnetometer stations during this event (red). Figure 2a shows the $B_y$ (blue) and $B_z$ (red) components of the IMF measured on board the ACE spacecraft. $B_y$ was strongly negative (< −10 nT) throughout the period of the main convection change, whereas $B_z$ was as much as 11-nT northward during the 90-min period preceding 0538 UT, but by 0603 UT had swung to –16 nT. That is, $B_z$ decreased by 27 nT during 27 min, or –1.08 nT min$^{-1}$. This was a large decrease in $B_z$, but not an especially sudden transition. However, as will be seen in the radar data, a reasonably step-like change of the high-latitude convection occurred. We might also expect some enhanced velocities during the $B_y$-dominated, $B_z$-weakly northward interval immediately preceding the $B_z$ transition because of the low-latitude merging known to occur for IMF clock angles approaching ±90° (Freeman et al., 1993).

During this event the ACE, Wind, and IMP8 spacecraft were located at approximate GSE($x, y, z$) co-ordinates of (242, −10, 24), (133, −2, 9), and (23, 22, 7) *Re*, respectively. The same basic IMF behaviour was preserved during the advection of the solar wind past the three spacecraft. IMP8 was located upstream and relatively close to the dusk flank of the Earth's bowshock, permitting a fairly accurate estimate of when the IMF change reached the ionosphere. The ACE data plotted in Fig. 2a were first advanced in time to match key features in the IMP8 records, and then advanced a further 8 min to allow for both the propagation of the solar wind from IMP8 through the magnetosheath to the magnetopause (~6 min), and the subsequent Alfvénic communication of solar wind potential to the ionosphere (nominally, ~2 min). We use the same method to advect the ACE data to noon-sector response times in the other two case studies.

Examination of Wind and IMP8 solar-wind data revealed no significant dynamic pressure change simultaneous with the $B_z$ southward transition. Examination of Halley magnetometer data (~0322 MLT) and LANL spacecraft data also revealed no evidence for the occurrence of a magnetospheric substorm until ~160 min after the southward turning.

The first vertical line in Fig. 2 is located at 0542 UT and represents a reasonable estimate of when $|B_z| < |B_y|$, probably triggering low-latitude merging at a low rate. The vertical line at 0601 UT intercepts $B_z$ at −5 nT, and represents the latest possible arrival time of the $B_z$ southward transition in the noon-sector ionosphere. It also immediately proceeds a further sharp $B_z$ southward turning, but recall that variability on time scales <10 min may have been different when the IMF reached the magnetopause. The final vertical line at 0608 UT represents an unambiguous identification of the start of the step-like arrival of the $B_z$ southward change in the Halley radar data (0323 MLT).

Figures 2b and c show range-time plots of LOS Doppler velocity measured on the high-time resolution beams 4 and 8 of the TIGER and Halley radars, respectively. Superimposed in these panels are lines of constant AACGM latitude and nominal values of MLT in smaller typeface just above the UT base. The TIGER radar was detecting scatter from the return flow of the dusk convection cell between ~65° and 80°S (magnetic latitudes hereafter) during the late afternoon (~16 to 17 MLT). Simultaneously, the Halley radar was detecting backscatter from the nightside auroral oval between ~64° and 80°S during the early morning hours (~3 to 4 MLT).

It can be difficult quantifying magnitudes using the colour keys used in Figs. 2b and c. Hence line plots of LOS Doppler velocity for the high-time resolution beams are shown in Fig. 2d. These curves show velocities averaged over ranges 1600 to 2200 km for TIGER beam 4 (red), ranges 1300 to 3555 km for TIGER beam 0 (black), and ranges 750 to 1600 km for Halley beam 8 (blue). These limits were chosen to encompass the relevant ionospheric scatter and important ionospheric convection changes.

Figure 2 show the start of the convection change associated with vigorous $B_z$ southward reconnection commenced in the TIGER FOV by 0601 UT at the latest. The vertical line at 0601 UT marks the start of a rapid equatorward expansion of the backscatter boundary (part b), and the start of a poleward flow burst to $< -700$ m $s^{-1}$ (part d). Because this was shortly after the initial detection of continuous backscatter, there may have been large convection velocities present earlier, probably associated with the $B_y$-dominated, $B_z$-weakly northward conditions. Indeed, large velocities were observed on the most westerly beams (towards noon). For example, the LOS Doppler velocities for beam 0 are shown in Fig. 2d. These large velocities were seen to gradually expand easterly towards the high beam numbers.

During the interval of $B_z$ strongly northward conditions preceding 0542 UT, the Halley radar detected a sequence of quasi-periodic (~10 min), equatorward flow busts (>700 m $s^{-1}$) associated with equatorward-propagating patches of decametre-scale irregularities, presumably in proximity to the exit of the polar cap flow. These flow bursts were probably driven by magnetotail reconnection because they occurred in the nightside ionosphere under $B_z$ northward conditions.

Figure 2c shows the Halley radar observed a final equatorward flow burst commencing shortly after 0542 UT. This flow burst had a slightly different character, appearing to expand equatorward from the central polar cap. If this flow burst was not driven by magnetotail reconnection, it may represent a nightside response to the brief interval of $B_y$-dominated, $B_z$-weakly northward merging. Importantly, it may also represent a rapid dayside response extending into the central polar cap, but with a progressively longer delay at lower latitudes in the morning sector.

A persistent, unambiguous change in the character of the Halley beam 8 velocities was seen later at 0608 UT when the equatorward and bursty flows were terminated and replaced by a flow with weakly poleward or zero meridional component. We associate this change with the transition to a convection pattern controlled by the $B_z$ strongly southward condition. This is at least 7 min after dayside merging started to dominate the high-latitude flow, commencing by 0601 UT at the very latest (Fig. 2b,d).

It was tempting to identify the start of decreasing LOS velocity observed on Halley beam 8 at 0601 UT (Fig. 2d) as an instantaneous response to the $B_z$ southward turning. However, this perturbation was no greater than any number that occurred during the preceding interval of $B_z$ northward conditions, and is not statistically significant. Similarly, it was tempting to identify the large flow burst on TIGER beam 4 commencing at 0607 UT as an instantaneous response to the $B_z$ southward turning, but again, this feature does not represent a persistent change in the overall character of the scatter, and it occurred at least 6 min after the IMP8-implied arrival time of the $B_z$ southward turning anyway.

An estimate of the arrival time for a large-scale convection change should not be based solely upon an analysis of LOS Doppler-velocities measured along a single radar beam because the results are not always representative of the changes occurring throughout the entire FOV. Hence an independent method was used to estimate the time difference between the arrival of the convection change in the two radar FOVs. The equatorward edges of *F*-region backscatter shown in Figs. 2b, c expanded equatorward in response to $B_z$ turning southward, and then contracted back toward the pole when $B_z$ swung northward. These equatorward boundary changes are well known to be controlled by inflation and deflation of the polar cap ionosphere as field lines open and close to the IMF, respectively (Pinnock et al., 1993; Lewis et al., 1998). By drawing freehand curves along the equatorward edges of backscatter in Figs. 2b, c the boundaries were seen to reach their most equatorward limits of 68°S at ~0628 in TIGER beam 4, and 64°S at ~0634 in Halley beam 8. This suggests an ~6 min delay between the arrival of the convection change in the afternoon and morning sectors.

## Figure 3

The full-scan plots were also examined in detail when analysing our observations, but to be concise, we only show a subset of them for the first case study. The full-scan plots shown in Fig. 3a–f were chosen for reproduction because of the continuity of scatter within their FOVs, and to further substantiate our estimates of the arrival times. The plots show colour-coded LOS Doppler velocity measured by the TIGER radar (top foot prints) and Halley radar (bottom foot prints). Red and yellow colours developing in the TIGER full-scans suggest the afternoon convection change was more gradual than apparent from the single beam analysis, probably arriving in the afternoon sector well before 055954 (part c), and definitely by 060500 UT (part d). Scatter with large poleward velocities expanded westward from beam 0 at finite speed before reaching beam 4, and then expanded equatorward. Changes in the distribution of irregularity occurrence are also thought to indicate convection changes (Ruohoniemi et al., 2002), probably because the convection velocity is an important term in the gradient drift instability (Kelley, 1989). However, in this particular case, we can only be certain the convection change commenced in the TIGER FOV by 0601 UT at the very latest. The transition from blue to green colours in the Halley full-scans was more sudden, revealing the arrival of the change in the morning sector between 060840 and 061300 (parts e and f).

To further validate our estimates of the ionospheric response times, we analysed the full-scan Doppler velocities using the beam-swinging algorithm to produce plasma flow vectors, as described by Ruohoniemi et al (1989). Note that the beam-swinging technique will only determine accurate velocities in the case of fairly simple, uniform flows, as modelled by Freeman et al. (1991). In this study the technique was used primarily to determine, on a scale comparable to the whole backscatter region, changes in flow magnitude, and the quadrant of the flow direction; no demanding inferences on magnitude or direction were made. Thus the detailed fluctuations shown in some of the subsequent plots should not be regarded as significant.

## Figure 4

Figure 4 shows 2-dimensional flow vectors derived using TIGER reference beam 4 and 2-min time resolution, the reliable resolution facilitated by full-scan observations. The afternoon convection velocities were directed poleward and westward, consistent with a flow about to enter the cross polar jet on the dayside edge of a dusk convection cell. From about 0604 UT onward the flows intensified toward ~2 km $s^{-1}$, and expanded equatorward as more open flux accumulated in the polar cap. Beyond about 0632 UT the flows poleward of 71°S developed a strong eastward component. They may represent a delayed response to a significant dynamic pressure pulse arriving at 0625 UT, or more likely the furthest range cells began to sample the central polar cap flow, just poleward of the convection reversal boundary (CRB) in an expanded dusk cell.

Figure 4b shows the highly variable flows estimated along beam 8 of the Halley radar during the early morning hours. Preceding about 0608 UT the zonal flow components fluctuated between east and west, but the meridional components were nearly always equatorward, as would be expected for the flows convecting out of the nightside polar cap, through the influence of magnetotail reconnection, and into the nightside auroral oval. Beyond about 0608 UT the flows became predominantly zonal, consisting of a band of strong westward flows (~1 km $s^{-1}$) poleward of a band of strong eastward flows. The sharp boundary between the two bands probably delineates the CRB of a dawn convection cell which expanded equatorward when $B_z$ turned southward.

**Figure 5**

Figure 5 shows corresponding perturbations in the magnetic field *X*, *Y*, and *Z* components measured at Davis (08 MLT, 74.6ºS), Casey (12 MLT, 80.8ºS), and Macquarie Is. (18 MLT, 64.8ºS). The relative locations of these stations were shown in Fig. 1 (purple). Note that applying the right-hand rule in the southern hemisphere, a positive (negative) deflection of the *X* component corresponds to a westward (eastward) *F*-region drift, and a positive (negative) deflection of the *Y* component corresponds to an equatorward (poleward) *F*-region drift.

Figure 5b shows the equivalent current vectors implied by the Casey magnetometer (12 MLT) responded rapidly to the immediate IMF conditions. The *X* component began to rapidly increase at 0544 UT, consistent with enhanced dawnward flows, as expected to occur at the start of $B_y$-dominated, $B_z$-weakly northward reconnection. A similar but weaker signature in the Davis *X*-component occurred three minutes later at ~0547 UT (08 MLT). The Macquarie Is. *X* component (18 MLT) also began to turn positive at 0544 UT, probably because of enhanced westward flows which prevail in this sector at 65ºS. Note that scatter appeared in the TIGER FOV equatorward of 69ºS at the same time (Fig. 2b), and showed the effects of Pc 5 wave activity on closed field lines. Hence the Macquarie Is. *X*-component may not have trended positive until ~0550 UT. Nevertheless, taken together the data provide possible evidence for a very rapid response of the afternoon sector (~12 to 18 MLT) extending from ~65ºS into the central polar cap (recall Fig. 2e).

Figure 5b also shows the Casey *Y* component swung negative at 0552 UT, consistent with the start of antisunward flows associated with the $B_z$ southward transition. This also suggests the radar estimate of ~7 min was the minimum delay for the convection change to arrive in the morning ionosphere. The *Y* component subsequently remained negative throughout the $B_z$ southward period. Starting at 0630 UT, the *Y* component subsequently swung positive, consistent with the start of sunward flows associated with $B_z$ northward conditions (cf., Fig. 2a).

However, the large number of transients seen in the Davis and Macquarie Is. magnetograms prevented unambiguous detection of when the IMF transition occurred. A classic bipolar signature was centred near 0608 UT in the *X* component measured at Macquarie Is., but an analysis of ULF wave activity is beyond the scope of this study.

In summary, the results shown in Figs. 2 to 4 suggest there may have been a very rapid response in the afternoon sector to the onset of $B_y$-dominated, $B_z$-weakly northward merging, but the response showed an increasing delay further equatorward in the morning sector. The main $B_z$ southward convection change appeared in the late afternoon ionosphere ~(1627 MLT, 72°S) at least 7 min before the arrival of the same change in the early morning ionosphere ~(0322 MLT, 70°S ). This is the minimum time difference because the data suggests the convection change probably arrived earlier in the late afternoon ionosphere, but almost certainly by 0608 UT in the early morning ionosphere.

## Figure 6

### 3.2 Case study 2: ~15 h UT, 01 April, 2000

Figure 1 shows the relative locations of the two radar FOVs during this event (green). Figure 6a shows the $B_y$ and $B_z$ components of the IMF measured on board the ACE spacecraft. $B_z$ was up to 7-nT northward for nearly two hours preceding 1524 UT, but swung sharply southward toward –5 nT at 1525 UT, and then more gradually trended southward for 2 hours, reaching nearly –11 nT by 1725 UT. Again $B_y$ was negative, but only about –4 nT. As in the previous case study, IMP8 IMF and solar-wind data were used to shift the ACE IMF components to noon-sector response times. Neither ACE, Wind, nor IMP8 spacecraft data suggested a dynamic pressure pulse arrived at the same time as the initial southward turning of $B_z$.

This second example illustrates large-scale responses to a convection change driven by a $B_z$ southward transition. As the Halley radar data showed, the convection change arrived in the noon-sector ionosphere close to when expected, but the TIGER data showed the dominant response of the early morning ionosphere was sluggish, perhaps occurring 33 min later at 1558 UT during the growth phase of a substorm with an onset at 1650 UT. The Macquarie Is. magnetometer also detected an onset signature near 1650 UT, and a dispersionless particle injection was also observed by the geosynchronous (6.6 *Re*) LANL 1994-084 spacecraft located close to midnight at 1650 UT, confirming the onset of the magnetospheric substorm (Henderson et al., 1996). Provisional values of the AE index reached 800 nT during the main phase of the substorm.

Figure 6b shows range-time plots of the LOS Doppler velocities measured on the high-time resolution beam 8 of the Halley radar. During the arrival of the $B_z$ southward transition the Halley radar was detecting cusp-like backscatter distinguished by large spectral widths >220 m $s^{-1}$ (not shown) (Baker et al., 1995; Milan et al., 1998; and Moen et al., 2001) located between ~79° and 85°S during ~12 to 13 MLT. The greater cusp consisting of the true cusp, cleft, and mantle should be located further poleward under $B_z$ northward conditions (Parkinson et al., 1999).

Substantial equatorward velocities (>200 m $s^{-1}$) measured on Halley beam 8 suggest that some strong sunward flows were present in the dayside polar cap up until 1525 UT. Beyond 1525 UT the beam 8 measurements were dominated by large poleward velocities (<–200 m $s^{-1}$), and suggest the start of strong antisunward flows (i.e., the arrival of the $B_z$ southward transition). From this time onward a band of backscatter expanded poleward until about 1610 UT. At the same time, another band of backscatter, initially very weak, emerged and expanded equatorward as $B_z$ southward conditions were consolidated. This bifurcation of the scatter resembles the radar and auroral imager signatures presented by Milan et al. (2000) for a similar $B_z$ southward transition.

The preceding interpretation was confirmed by a detailed examination of Halley full-scan data. Prior to 1525 UT, equatorward Doppler velocities were present on Halley beams 6 to 13, and moderate poleward velocities were present on the lowest and highest beam numbers. This suggests the plasma flowed sunward between two convection cells. After 1525 UT, large poleward velocities appeared on all beam numbers. This is consistent with lobe-cell reconnection driven by a northward-pointing $B_z$ (Crooker and Rich, 1993), giving way to dayside magnetopause reconnection driven by a southward-pointing $B_z$.

**Figure 7**

Two-dimensional flow vectors estimated along Halley beam 8 using 2-min resolution are shown in Fig. 7a. The moderate flows of <400 m s$^{-1}$ towards the east prior to 1525 UT do not accurately represent the flow because the algorithm was confused by the complicated distribution of LOS velocity under $B_z$ northward conditions. Beyond 1525 UT the flows intensified to >600 m s$^{-1}$ toward the west and poleward (i.e., antisunward), and thereafter remained in essentially the same direction, eventually strengthening to nearly 2 km s$^{-1}$ beyond 1700 UT (not shown). This was in concert with the equatorward expansion of the dayside cusp as the $B_z$ southward conditions were consolidated (cf., Fig. 6b).

Now we consider the LOS Doppler velocities measured on the high-time resolution beam 4 of the TIGER radar, Fig. 6c. TIGER was detecting backscatter from the nightside auroral oval between ~64° and 80°S during the early morning hours, ~01 to 04 MLT. The Doppler shifts recorded on beam 4 (the western part of the FOV) were predominantly toward the radar (>100 m s$^{-1}$), but the Doppler shifts recorded on the easterly beams were predominantly away from the radar. This means the flows were persistently towards the east.

Figures 6c shows no clear, unambiguous signature of a convection change arriving immediately following the initial dayside response at 1525 UT. This includes no clear changes in the velocities and backscatter boundaries. Nor does the line plot of average LOS Doppler velocity (Fig. 6d; blue) reveal the start of a significant perturbation until about 1639 UT. Perhaps the LOS velocities were burstier (>300 m s$^{-1}$) prior to 1525 UT, possibly because of active magnetotail reconnection under $B_z$ northward conditions. However, overall the nightside ionosphere appeared insensitive to the dayside response.

Figure 7b shows 2-dimensional flow vectors estimated along TIGER beam 4, with flow magnitudes >300 m s$^{-1}$ drawn in bold to emphasise the high velocity regime on open field lines. Throughout most of the interval the nightside velocities poleward of 67°S were about 500 m s$^{-1}$ toward the east and often weakly equatorward. This is consistent with antisunward motion of plasma exiting the polar cap and veering toward the east equatorward of the CRB. An exception occurred between 1504 and 1510 UT when there were some strong sunward flows under $B_z$ northward conditions.

The TIGER data exhibited some features strongly reminiscent of the substorm growth-phase signatures reported by Lewis et al. (1998) and Voronkov et al. (1999). The gross behaviour of the equatorward boundary of the scatter shown in Fig. 6c suggests that it tended to migrate poleward from 65° to 69°S up until 1536 UT. Thereafter it rapidly expanded equatorward until about 1545 UT, followed by a more gradual expansion, though with intervals of poleward contraction. The poleward and equatorward expansions of backscatter starting at 1535 and 1536 UT, respectively (Fig. 6c), and the brief transient in the spectral width boundary at 1533 UT (not shown), may represent very early signatures of a growth phase associated with the $B_z$ southward turning. Figure 7b also suggests the equatorward boundary of the beam-swung vectors with magnitudes >300 m s$^{-1}$ tended to gradually expand equatorward beyond about 1540 UT. Combined, this constitutes evidence for a weak nightside response about 8–11 min after the initial dayside response.

There was also evidence for a nightside response occurring near to 1558 UT: the TIGER radar began to detect a persistent equatorward expansion of the poleward region of equatorward velocity >200 m $s^{-1}$ (Fig. 6c), and especially spectral widths (not shown). A perturbation in the beam-swung velocities also occurred at this time (Fig. 7b).

During this event there were persistent fluctuations in backscatter boundaries and LOS Doppler velocities (Fig. 6c), and the beam-swung vectors were fairly uniform (Fig. 7b). Hence the nightside responses identified at 1536 and 1558 UT have an uncertainty of a few minutes. The only distinct nightside response in the radar data was the growth-phase signature starting at 1634 UT (Fig. 6d). This signature preceded the substorm onset at 1650 UT marked by the loss of backscatter, probably due to enhanced *D*-region radio-wave absorption. An analysis of the interesting dayside velocity transients appearing near and beyond the substorm onset (Figs. 6b, 7b) is beyond the scope of this paper.

Corresponding perturbations in the magnetic field *X*, *Y*, and *Z* components measured at Davis (17 MLT), Casey (21 MLT), and Macquarie Is. (03 MLT) were examined, but are not shown. All components measured at all stations exhibited growth-phase signatures, with a zero-level response possibly commencing as early as 1525 UT. Initially, the signatures were very weak, but grew slowly in time until they were clearly recognisable by 1536 UT (~10 nT at Davis and <3 nT at Casey and Macquarie Is.). These initial magnetometer responses may have been driven by changes in ionospheric conductivity or field-aligned currents, as well as changes in convection electric fields.

In summary, the Halley radar recorded clear evidence for the arrival of the $B_z$ southward transition at 1525 UT in the early afternoon ionosphere ~(1240 MLT, 83°S). Prior to 1525 UT there were sunward flows, probably associated with lobe-cell merging under $B_z$ northward conditions. After 1525 UT there were strong antisunward flows measured on all beams, as would be expected for a standard two-cell convection pattern forming under $B_z$ southward conditions (Heppner and Maynard, 1987). The TIGER radar did not record clear evidence for the immediate arrival of the same convection change in the early morning ionosphere ~(0150 MLT, 73°S), but it may have recorded a weak nightside response about 8–11 min later near 1536 UT. There was also evidence for a nightside response 33 min later near to 1558 UT, namely an equatorward expansion of the poleward region of equatorward velocities and enhanced spectral widths. Certainly the $B_z$ southward conditions had a dramatic affect on the nightside ionosphere by 1650 UT, the expansion phase onset of a substantial substorm.

**Figure 8**

## 3.3 Case study 3: ~18 h UT, 24 September, 2000

Figure 1 shows the relative locations of the two radar FOVs during this event (blue). Figure 8a shows the $B_y$ and $B_z$ components of the IMF measured on board the ACE spacecraft during 1730 to 2000 UT, 24 September, 2000. IMP8 measurements showing important changes in the solar-wind dynamic pressure have been superimposed. The IMP8 spacecraft was located upstream and relatively close to the bowshock at GSE(*x, y, z*) co-ordinates of ~(33, –16, –7) *Re*. Good quality IMF data were not recorded by IMP8 during this interval, but the ionospheric arrival times of solar-wind discontinuities were ultimately fixed using data recorded by Geotail located in the magnetosheath on the dawn flank near ~(2, –13, 2) *Re*.

A major ionospheric convection change commenced near 1822 UT when $B_z$ swung from ~2.5 nT to –5.2 nT during a 4-min interval. This sharp southward turning was coincident with a slower $B_y$ transition from –9 to +3 nT. As shown by the IMP8 measurements, it was also accompanied by a decrease in dynamic pressure of about 4.8 nPa in <7 min (1-min resolution data). This transition followed 3 min later, but may have arrived in the ionosphere at the same time or earlier because of the faster magnetopause to ionosphere communication time thought to occur for dynamic pressure pulses.

The solar-terrestrial interactions were complex in this case, yet they afford us an opportunity to begin investigating whether changes in dynamic pressure sometimes mediate the convection changes associated with IMF transitions. Dynamic pressure pulses often accompany IMF transitions, producing ionospheric transients including convection vortices. The ultimate objective of analysing the effects of ideal, simple solar-wind discontinuities is to understand more complex dynamics like those occurring in this example.

Figure 8b shows the LOS Doppler velocities measured on the high-time resolution beam 8 of the Halley radar. Initially, the Halley radar detected backscatter distinguished by large spectral widths >200 m $s^{-1}$ (not shown) located between ~75° and 82°S during the magnetic afternoon (~15 MLT). The equatorward boundary of this backscatter gradually expanded equatorward under the influence of a weak $B_z$ southward condition (~ –2 nT), but temporarily contracted poleward when $B_z$ briefly swung northward during 1758 to 1820 UT. The subsequent, brief outage of scatter did not occur on all beam numbers, as shown by the continuity of velocity observed on beam 10 (part d). Thereafter, $B_z$ underwent the aforementioned major southward turning at ~1822 UT. The equatorward expansion of the backscatter accelerated by 1834, though possibly as early as 1825 UT. The initial dayside ionospheric response was very rapid, ~2–3 min after the expected noon-sector response.

**Figure 9**

Fig. 8a showed a $B_y$ negative swing accompanied by a substantial decrease in dynamic pressure arriving near to 1749 UT. The distribution of LOS Doppler velocities in the full-scan commencing 17:49:18 UT was complex, suggesting the formation of vortical flows in the afternoon ionosphere. The Halley beam-swung flow vectors, Fig. 9a, were also perturbed at this time. We associate this (and other) transients with the effects of the dynamic pressure decrease occurring at this time. That is, we effectively invoke a mechanism similar to the Araki (1994) model.

The next transition affecting the Halley radar data occurred when $B_z$ swung weakly northward at 1800 UT. Figure 9a shows this transition was clearly distinguished by a strong reversal in the flow direction from eastward and poleward to westward and poleward in the full scan commencing 18:01:12 UT. The flow direction before the convection change was consistent with that found on the poleward side of the dusk cell in a $B_z$ southward two-cell pattern. The subsequent flow direction suggested the imposition of a new flow regime consistent with $B_y$-dominated, $B_z$-weakly northward merging. That is, $B_y$ was strongly negative (−9 nT) by this time; hence subdued, low-latitude merging continued (Freeman et al., 1993).

Figure 8b also suggests that ~300 m s$^{-1}$ flows with a substantial sunward component subsequently developed in the polar cap ionosphere between 1812 and 1834 UT, and poleward of 84°S. This suggests there was simultaneous lobe-cell merging associated with $B_z$ turning northward, similar to the conditions reported by Oieroset et al. (1997). The polar cap flows persisted beyond the arrival of the major solar-wind discontinuity at 1822 UT, suggesting a considerable delay (8−10 min) for the new IMF condition to reorganise the polar cap flows. This is in agreement with the example shown in Fig. 1 of Jayachandran and MacDougall (2000).

The initial impact of the major solar-wind discontinuity arriving at ~1822 UT was clearly distinguished in the Halley full scan commencing at 18:26:40 UT. It showed the sudden onset of a complicated pattern of LOS Doppler velocity, possibly indicative of a transient convection vortex driven by the fast arrival of pressure pulse effects. However, by 18:31:45 UT, or 5 min later, the complicated pattern of LOS Doppler velocity had settled into a simpler pattern consistent with stronger westward and poleward motion controlled by the $B_z$ southward transition. Figure 9a shows these motions remained fairly uniform, intensifying to values >1 km s$^{-1}$ as the afternoon scatter expanded equatorward. They were probably driven by enhanced $B_z$-southward dominated reconnection taking over the weaker $B_y$-dominated low-latitude merging existing prior to 1825 UT.

Now we consider the LOS Doppler velocities measured on the high-time resolution beam 4 of the TIGER radar, Fig. 8c. TIGER was detecting backscatter from the nightside auroral oval between ~64° and 77°S during the predawn hours, ~04 to 06 MLT. The LOS Doppler velocities were mostly moderate and poleward, as would be expected for a meridional beam traversing the predawn sector of a standard two-cell convection pattern. Figure 9b shows the beam-swung flow vectors were mostly eastward and slightly poleward, and <600 m s$^{-1}$ throughout the event.

Recall the Halley full-scan data revealed a transient commencing at 17:49:18 UT that we associated with a dynamic pressure decrease (and $B_y$ negative transition). The TIGER data revealed no clear evidence for the arrival of this event, although it is possible a vortex traversed the radar FOV faster than could be resolved by the full-scan data (96-s resolution). It is also true that the difference between positive and negative $B_y$ convection patterns would be difficult to resolve in the pre-dawn sector.

Recall the Halley full-scan data also revealed the arrival of a $B_y$-dominated, $B_z$-weakly northward transition at 1801 UT. We speculate this event was revealed in the TIGER data by the gradual onset of weaker eastward velocities commencing at 1818 UT, some 17 min after the change arrived in the afternoon ionosphere. The weaker velocities persisted until the sudden affects of the major solar-wind discontinuity arriving shortly after.

Figure 8c summarises the basic response of the nightside ionosphere to the solar-wind discontinuity arriving at 1822 UT in the noon sector. Large poleward Doppler velocities <−300 m s$^{-1}$ (red) appeared at latitude 70°S at 1825 UT, and then expanded poleward with time. Large spectral widths (>200 m s$^{-1}$; not shown) were also activated at 1825 UT. The equatorward boundary of the poleward region of large Doppler shift (<–300 m $s^{-1}$) and spectral width subsequently trended equatorward beyond 1840 UT, reaching ~68°S by 1904 UT. The complicated response starting at 1825 UT may have been caused by a convection vortex driven by the dynamic pressure decrease, and the subsequent equatorward expansion of a $B_z$-southward two-cell convection pattern.

The first TIGER full scan showing convincing evidence for the arrival of the dynamic pressure decrease started at 18:26:30 UT, and strong poleward velocities arrived shortly after (Fig. 9b). These poleward velocities first arrived on the most easterly beams at latitudes >70°S, but also quickly appeared on beam 4. They ceased at the same time as the sunward-drifting scatter detected in the dayside polar cap (84°S) by the Halley radar (Fig. 8b). They were replaced by strong eastward flows across the full-scan data commencing at 1834 UT, ~3 min later than consolidation of $B_z$ southward flows in the dayside ionosphere. The eastward flows subsequently intensified and expanded equatorward as $B_z$ remained about –7 nT. Thus the sequence of events beyond 1834 UT was probably caused by a strengthening of the *DP* 2 current system in the nightside ionosphere.

Corresponding perturbations in the magnetic field *X*, *Y*, and *Z* components measured at Davis (20 MLT), Casey (00 MLT), and Macquarie Is. (06 MLT) were also examined. The large number of magnetometer transients prevented the unambiguous detection of ionospheric currents associated with the start of $B_y$-dominated, $B_z$-northward low-latitude reconnection near to 1800 UT. However, there was evidence for the rapid arrival of the major solar-wind discontinuity at ~1825 UT in the *Y* components measured at Casey, and especially Davis.

In summary, the Halley radar recorded clear evidence for the arrival of the $B_y$-dominated, $B_z$-northward transition at 1801 UT in the afternoon ionosphere ~(1515 MLT, 75°S). Figure 9a showed the flow vectors reversed from eastward to westward. Evidence for the same transition recorded by TIGER was difficult to identify, possibly consisting of the gradual decay of velocity some 17 min later in the early morning ionosphere ~(0443 MLT, 70°S).

The Halley radar measurements also showed clear evidence for the arrival of the $B_z$ southward transition in the afternoon ionosphere at ~(1540 MLT, 75°S), probably at about 1831 UT, or ~6 min after the initial response to the dynamic pressure decrease at 1825 UT. The equatorward boundary of scatter also moved equatorward after 1832 UT. The TIGER radar also showed clear evidence for the arrival of the $B_z$ southward transition in the morning ionosphere ~(0451 MLT, 70°S), probably at about 1834 UT, or ~9 min after the nearly simultaneous effects of the dynamic pressure decrease. The initial appearance of strong poleward flows due to the dynamic pressure decrease gave way to strong eastward flows associated with an intensification of the *DP* 2 current system. Because it is not possible to completely separate the effects of the dynamic pressure decrease and the IMF transition with our limited observations, they suggest a ~0–3-min delay between the arrival of the large-scale convection change in the two radar FOVs.

# 4. Discussion

For a study of this kind it might be argued that ideally $B_z$ should have been positive for a prolonged period (thereby exhausting reconnection in the tail) before a step-like transition of $B_z$ toward the south, where it should have remained steady for the duration of the convection change. $B_x$, $B_y$, and the solar-wind dynamic pressure should also have remained steady for the duration of each event. However, large step-like transitions in $B_z$ are unrepresentative of the vast majority of convection changes occurring on a day-to-day basis, and it may be false to assume the response times measured under such conditions are generally applicable. It might have taken years to record a single such "ideal event," so we simply chose the first three events in which large-scale IMF-driven convection changes could be identified in mostly continuous backscatter recorded by both radars.

It might also be argued that all the IMF transition should have occurred faster than the expected ionospheric response times. However, even for gradual southward turnings of $B_z$, there is probably some threshold beyond which enhanced dayside reconnection occurs (Ridley et al., 1997). Moreover, if the inter-ionospheric communication time is finite, there must always be measurable time delays between the appearance of gradual convection changes in the day and night ionospheres. As was seen in our radar observations, there were step-like convection changes anyway. Hence within the limit that we tended to select events associated with strong southward turnings of $B_z$, our three case studies were representative of the solar-wind discontinuities occurring on a day-to-day basis.

Because of the large magnetic field in the ionosphere, the ionospheric plasma flow is incompressible. This implies the only convection change fronts which can exist and move at measurable velocities are aligned with flow lines (i.e., boundaries across which the change in velocity is purely shear). Stated another way, at any instant of time the ionospheric flow lines must always close upon themselves. The flows within these patterns can speed up or slow down, or the pattern boundaries can expand or contract in size, but convection change fronts cannot propagate with a component in the flow direction. This is why our estimates of the arrival time of convection changes were based upon the assessment of a number of factors combined including persistent changes in the distribution of LOS Doppler velocity in full-scan plots, equatorward expansions of backscatter boundaries, and changes in spectral width signatures.

**Table 1**

Table 1 summarises the solar-wind discontinuities, the location of the ionospheric measurements, and the time delays determined for the three sets of HF radar data analysed in this paper. The last two discontinuities are treated as belonging to the same overall event. The variations in the time delays are roughly consistent with those expected if the effects of convection changes propagate away from noon around the dawn and dusk OCBs toward midnight. The minimum delay should be observed when the two radars are aligned near to dawn and dusk (as in case study 3), and the maximum delay when the two radars are aligned near to noon and midnight (as in case study 2). An intermediate delay should be observed for intermediate locations (as per case study 1). However, we will consider other possible explanations for these results.

The Earth-ionosphere wave guide might rapidly communicate convection changes from their first observation in the noon-sector ionosphere (Kikuchi et al., 1996). In this model it is important to consider how much the radar FOVs were directly illuminated because the spatial distribution of conductivity may affect the apparent propagation speed. The effects of a potential difference applied to an uniform ionosphere should reach a steady state on a time scale $\propto 1/(4\pi\Sigma_p)$ where $\Sigma_p$ is the height-integrated Pederson conductivity (Cole, 1960). If so, the most rapid ionospheric responses will occur in the dayside ionosphere illuminated by sunlight. The day- and night-side auroral ovals might also mediate rapid ionospheric responses.

The 12 February case was a late summer event, and the 01 April and 24 September cases were near to the austral autumn and spring equinoxes, respectively. During the 12 February case, TIGER (43°S geographic) was observing the afternoon ionosphere and the Halley radar (76°S geographic) was observing the early morning (predawn) ionosphere. The solar zenith angles at this time were such that the TIGER FOV was strongly illuminated by the Sun whereas the Halley radar FOV was weakly illuminated. Nevertheless, the *E*-region conductivity must have been relatively high throughout much of the two FOVs. This contrasts with the 01 April event when the Halley FOV was directly illuminated whereas the TIGER FOV was dark. Hence the conductivity of the latter FOV was due to the presence of *F*-region plasma and particle precipitation. Finally, during the 24 September event the *E*-region conductivity must have been relatively high throughout the Halley FOV whereas the terminator crossed the TIGER FOV. This means that we can only be sure the easternmost beams of TIGER had a strongly conducting *E*-region.

Clearly, the importance of ionospheric conductivity needs to be quantified using observations and theory. However, our qualitative assessment suggests the 12 February event, and probably the more complex 24 September event, should have the fastest response times, whereas the 01 April event should have the slowest response time. This is in agreement with our results, but a comparison based upon three events is statistically insignificant, and the ionospheric delays for many more events need to be measured to judge the importance of ionospheric conductivity in the rapid manifestation of high-latitude convection changes.

Now we consider a second hypothesis, namely the communication of convection changes by magnetosonic waves propagating in the topside ionosphere. Neudegg et al. (1995) presented observations showing that fast-mode waves propagating horizonatally in the *F*-region were severely attenuated (~10 dB 100 km$^{-1}$). Perhaps this means that rapid nightside responses are more likely to be observed for major disturbances generating large amplitude hydromagnetic waves. Otherwise the observation of rapid responses would favour the mechanism proposed by Kikuchi et al. (1996). This in turn suggests that the ionospheric conductivity is a critical factor, in line with our limited observations.

In the Table 1 columns headed "Dayside Response" and "Nightside Response" we include entries like "Clarity excellent." These entries refer to the clarity of the convection changes identified in the HF radar data, and are a subjective measure of our confidence in the transition times. The clarity of the dayside response was always satisfactory, whereas the corresponding nightside responses varied from very good to poor, even when continuous radar scatter was recorded. The lack of clarity in the nightside responses, including the long time delays for substorms to occur (e.g., 160 minutes after the $B_z$ southward turning on 12 February, and 85 minutes on 1 April), confirms that nightside dynamics are partly detached from the immediate solar-wind conditions (i.e., long time delays must be involved).

In our three examples the dayside velocities rapidly responded to the prevailing IMF conditions, with the equatorward boundary of the *F*-region scatter expanding equatorward or poleward, as $B_z$ swung southward or northward, respectively (e.g., Fig. 2a, b). This was especially so in proximity to the ionospheric footprint of the cusp. In contrast, the nightside ionospheric velocities and *F*-region scatter behaved largely independent of the immediate IMF conditions. The sluggish response of the 01 April case was an extreme example, with unambiguous nightside signatures not occurring until tens of minutes latter when substorm growth and expansion onsets were clearly identified. A 33 min delay was observed, but not understood. However, it might be reconciled with an ~1 km $s^{-1}$ convection speed if the convection change only had to propagate around the nightside OCB (i.e., from 18 to 24 MLT) because field-line draping caused an instantaneous response of the entire dayside ionosphere (Shepherd et al., 1999).

Observations of quasi-periodic flow bursts in the cusp (e.g., Pinnock et al., 1995; Provan et al., 1998), often interpreted in terms of pulsed reconnection at the dayside magnetopause, are commonly observed with SuperDARN radars. It is interesting to note that so far we have not observed a sequence of nightside flow bursts synchronised with a sequence of dayside flow bursts, both presumably driven by bursty reconnection across the dayside magnetopause (or in the magnetotail). Qualitatively, our observations are consistent with the accepted notions of "driven" and "spontaneous" reconnection in the day- and night-side magnetospheres, respectively.

It seems reasonable to speculate that different solar-wind and IMF histories pre-condition the night-side response of the magnetosphere. In particular, "spontaneous" nightside reconnection might be especially sensitive to initial conditions. To test this idea it would be interesting to identify numerous events with nearly identical solar-wind and IMF histories, and thereby discern the influence of internal atmospheric and magnetospheric conditions on the observed ionospheric convection response. For example, the internal state of the thermosphere-ionosphere-magnetosphere system might sometimes control the nightside convection response, resulting in some unusually long delays.

Evidence for convection changes manifesting with finite delays was found in all our case studies. Perhaps the difficulty in identifying instantaneous response times in the magnetograms may have been due to them responding to changes in ionospheric conductivity and field-aligned currents, as well as electric fields driving the ionospheric Hall currents (e.g., see Parkinson et al., 1999). This contrasts with HF radars which are thought to measure the true drift of *F*-region irregularities (Villain et al., 1985). However, the nearly instantaneous (but infinitesimally small) response implied by the Macquarie Is. magnetogram on 01 April implies the corresponding growth-phase signatures may have been too weak to discern above instrumental noise and geophysical transients affecting the radar data.

The apparent sluggish response observed on 01 April might also be partly explained by the relative insensitivity of a radar looking perpendicular to zonal flows in the post-midnight sector. These zonal flows do not necessarily change dramatically when $B_z$ turns southward and the nightside twin convection cells are replaced by dayside twin convection cells associated with the *DP* 2 current system, as per CL92. That is, the convection patterns associated with both current systems are very similar in this sector. In all of our observations one radar FOV was located in the afternoon sector, and the other in the morning sector. Ideally, to detect any weak, initial response, the radar look direction might need to be parallel to the convection velocity change, as might occur in proximity to the Harang discontinuity during the pre-midnight hours.

A very small time delay was observed during the 24 September event when the two radars were aligned close to dawn and dusk, and the $B_z$ southward turning was coincident with a significant drop in dynamic pressure. Both of these conditions are conducive to the observation of small time delays, the former due to propagation of changes around the OCB (as per CL92), and the latter due to discontinuities in dynamic pressure launching fast-mode waves in the magnetospheric cavity. The effects of pressure pulses and IMF-driven convection changes might be more clearly separated using measurements of three events with similar solar-wind and IMF histories. The first event might include an IMF transition but no pressure pulse, the second event a pressure pulse but no IMF transition, and the third event the same pressure pulse and IMF transition combined. Of course, the measurements should be made using the same instruments in the same season, solar activity level, and MLT-MLAT sectors—a difficult task to achieve.

# 5. Reconciliation

We explore the various ways in which the finite time delays for IMF-driven convection changes apparent in our HF radar observations might be reconciled with the very rapid responses reported by others (e.g., Ruoheniemi and Greenwald, 1998; Shepherd et al., 1999):

1. Except perhaps for the 01 April event, our case studies did not approximate to the ideal of a truly instantaneous decrease in $B_z$ after a prolonged interval of $B_z$ positive conditions. Even for the 01 April event, $B_z$ only decreased at a rate of ~2.8 nT min$^{-1}$, and the nightside scatter displayed bursty velocities preceding the event. Hence when $B_z$ swung southward the dayside merging may have been partly balanced by reconnection in the tail, which masked the effects of the enhanced *DP* 2 current system by suppressing the equatorward expansion of the polar cap boundary.

2. The statistical results of Khan and Cowley (1999) show that, on average, there is a finite time delay for the nightside ionosphere to respond to dayside convection changes. The scatter in their data points suggests there were some very fast response times (or estimates of the propagation time of the IMF from the satellite to the ionosphere were sometimes erroneous). Ridley et al. (1998) suggested the fastest response times are observed for large and sharp IMF changes. The other SuperDARN radar observations of rapid response times also tended to be for sharper (but not larger) $B_z$ southward turnings than reported here; yet those observations showed discernible time delays anyway.

3. The nightside *F*-region scatter observed here was somewhat more equatorward than in previous studies. The difference was >5° in latitude (>556 km) when contrasted with the event reported by Ruohoniemi and Greenwald (1998). Their observations were also in the pre-midnight sector where a more distinct response might be observed in the Harang discontinuity, as argued earlier. Moreover, if the time delay observed by these authors were actually about 2 to 4 min on the dayside, their results would be entirely consistent with ours (see Introduction, point 3), and probably those of CL92 and Khan and Cowley (1999).

4. Shepherd et al. (1999) suggested that draping of the IMF across much of the dayside magnetopause as a possible cause of nearly simultaneous responses in the dayside ionosphere. When the newly opened *X*-lines map to an extended spatial region in the dayside ionosphere, the apparent propagation delays are reduced. There might be considerable variability in this process, resulting in a spread of time delays.

5. Similarly, Chisham et al. (2000) found an interhemispheric time delay between the start of a convection change and suggested this was partly a consequence of the relative distances to the dominant merging region on the magnetopause. Depending on the IMF orientation and dipole tilt angle, the merging region will be much closer to one hemisphere. For example, in our 12 February case study there was possible evidence for a very rapid response in the afternoon sector, yet finite delays in the morning sector. The IMF orientation and dipole tilt angle were such that $B_y$-dominated, $B_z$-weakly northward merging site was probably closest to the afternoon sector in the southern hemisphere. Obviously, there will be considerable variability in the location of reconnection sites satisfying the anti-parallel merging hypothesis, and thus also the associated ionospheric delays.

6. The instantaneous ionospheric responses observed by Murr and Hughes (2001) at 12, 15, 18, and 21 MLT were based upon an analysis of ground-based magnetograms. Magnetometers respond to changes in *E*-region currents, and to a lesser extent, field-aligned and magnetospheric currents. Hence it is not entirely clear how much of the initial magnetometer responses represent sudden changes in ionospheric conductivity, global current systems, or local electric fields. HF radars have the advantage of more directly observing the effects of ionospheric electric fields, whilst potentially having a sensitivity comparable to that of magnetometers. For example, Parkinson et al. (1999) compared digital ionosonde measurements of *F*-region drift with equivalent current vectors, and found the calibration was on the order of 5 m $s^{-1}$ per 1 nT.

7. Finally, our observations and analyses have their limitations. For example, we might have been able to identify smaller time delays if we had the overlapping radar data required to produce accurate 2-dimensional vectors. However, there would still be an element of subjectivity in interpreting the resulting convection patterns, and this naturally leads to significant uncertainties in estimates of the time delays. The radar data also suffers from being patchy at times: changes in ionospheric propagation conditions and the production and loss rates of *F*-region decametre-scale irregularities can mask the true arrival time of convection changes. Nevertheless, irregularity production and hence backscatter power are expected to rapidly intensify in response to enhanced electric fields; hence we do not consider these complicating factors to be a major problem in the present studies.

# 6. Closing remarks

Our initial selection of dual HF radar measurements made at cross-polar locations at various MLTs suggest there is considerable variability in the response time of the ionosphere to IMF-driven convection changes. We have outlined reasons to believe the response times will change depending on the particular thermosphere-ionosphere-magnetosphere coupling involved. Indeed, different response times might act simultaneously. However, we do not claim to have completely reconciled the observation of fast and slow response times, and further work is required to understand the true complexity of the apparent ionospheric delays.

The present observations are consistent with finite time delays ≥7 min for the large-scale nightside convection (~65° to 75°S) to start changing after the initial IMF-driven response of the dayside convection (~70° to 80°S). The magnetic co-ordinates of the TIGER and Halley radar FOVs were converted to geographic co-ordinates to estimate a great circle distance of ~4000 km separating them. Hence a 7-min time delay implies the initial dayside responses were broadcast to the nightside ionosphere at phase speeds on the order of ~10 km $s^{-1}$. This result is consistent with the comprehensive results reported by Khan and Cowley (1999), yet like theirs, it does not mean that much slower or faster convection changes do not occur.

For appropriate IMF and solar-wind discontinuities, rapid ionospheric convection changes might be broadcast on a global scale by fast-mode waves propagating through the magnetospheric cavity, the *F*-region ionosphere, or the Earth-ionosphere waveguide. Indeed, there may be several fundamental phase speeds (and time delays) associated with complimentary processes (Nishitani et al., 2001). Some of the very rapid dayside responses might be explained by the consequences of field-line draping and the anti-parallel merging hypothesis. Finally, we reiterate that our limited observations are consistent with the mechanism whereby convection changes are broadcast to the nightside via perturbations associated with the creation of open flux sweeping around the flanks of the magnetosphere toward the magnetotail, as enunciated by CL92.

*Acknowledgments.* This work was supported by the Australian Research Council, the Australian Antarctic Science Advisory Committee, the UK's Natural Environment Research Council, DSTO Salisbury, the Ian Potter Foundation, IPS Radio and Space Services, RLM Systems Pty. Ltd, and the State Government of Tasmania. We thank the many people who contributed to the construction, maintainence, and operation of the Halley and TIGER radars. Kevin O'Rourke and David Glynn (BAS) are thanked for writing the radar control program used for the experiments. We also thank the many people who made available various spacecraft data available including R. Belian of Los Alamos National Laboratory (LANL) (LANL 1994-084 energetic particles), L. Frank of the University of Iowa (Geotail plasmas), S. Kokubun of STELAB Nagoya University (Geotail magnetic fields), A. Lazarus of the Massachusetts Institute of Technology (IMP8 plasmas), R. Lepping of NASA Goddard Space Flight Center (GSFC) (IMP8 and Wind magnetic fields), K. Ogilvie of GSFC (Wind solar wind), A. Szabo of GSFC (IMP8 magnetic fields), D. J. McComas of LANL (ACE solar wind), and N. F. Ness of Bartol Research Institute (ACE magnetic fields). We thank the referees for their many constructive suggestions.

# References

**Araki, T.,** Global structure of geomagnetic sudden commencements, *Planet. Space Sci.,* **25,** 373–384, 1977.

**Araki, T.,** A physical model of the geomagnetic sudden commencement, in *Solar wind sources of magnetospheric ultra-low-frequency waves, Geopys. Monogr. Ser.,* **81,** 183–200, Edited by M. J. Engebretson, K. Takahashi, and M. Scholer, Washington D.C., 1994.

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

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

**Chisham, G., M. Pinnock, and A. S. Rodger,** Poleward-moving HF radar flow bursts in the cusp: Transient changes in flow speed or direction? *Geophys. Res. Lett.,* **27,** 919–922, 2000.

**Chisham, G., M. Pinnock, A. S. Rodger, and J.-P. Villain,** High-time resolution conjugate SuperDARN radar observations of the dayside convection response to changes in IMF bHigh-time resolution conjugate SuperDARN radar observations of the dayside convection response to changes in IMF $B_y$, *Ann. Geophysicae*, **18,** 191–201, 2000.

**Cole, K. D.**, A dynamo theory of the aurora and magnetic disturbance, *Australian J. Phys.,* **13**, 484-497, 1960.

**Coleman, I. J., M. Pinnock, and A. S. Rodger,** The ionospheric footprint of antiparallel merging regions on the dayside magnetopause, *Ann. Geophysicae*, **18,** 511–516, 2000.

**Cowley, S. W. H., and M. Lockwood,** Excitation and decay of solar wind-driven flows in the magnetosphere-ionosphere system, *Ann. Geophysicae*, **10,** 103–115, 1992.

**Crooker, N. U., and F. J. Rich,** Lobe cell convection as a summer phenomenon, *J. Geophys. Res.,* **98,** 13,403–13,407, 1993.

**Dudeney, J. R., A. S. Rodger, M. P. Freeman, J. Pickett, J. Scudder, G. Sofko, and M. Lester,** The nightside ionospheric response to IMF By changes, *Geophys. Res. Lett.,* **25,** 2601–2604, 1998.

**Etemadi, A., S. W. H. Cowley, M. Lockwood, B. J. I. Bromage, and D. M. Willis,** The dependence of high-latitude dayside ionospheric flows on the north-south component of the IMF: A high time resolution correlation analysis using EISCAT "POLAR" and *AMPTE UKS* and *IRM* data, *Planet. Space Sci.,* **36,** 471–498, 1988.

**Freeman, M. P., J. M. Ruohoniemi, and R. A. Greenwald,** The determination of time-stationary 2-D convection patterns with single station radars, *J. Geophys. Res.,* **96,** 15,735–15,749, 1991.

**Freeman, M. P., C. J. Farrugia, L. F. Burlaga, M. R. Hairston, M. E. Greenspan, J. M. Ruohoniemi, and R. P. Lepping,** The interaction of a magnetic cloud with the Earth: Ionospheric convection in the northern and southern hemispheres for a wide range of quasi-steady interplanetary magnetic field conditions, *J. Geophys. Res.,* **98,** 7633–7655, 1993.

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

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

**Henderson, M. G., G. D. Reeves, R. D. Belian, and J. S. Murphree,** Observations of magnetospheric substorms occurring with no apparent solar wind/IMF trigger, *J. Geophys. Res.,* **101,** 10,773–10,791, 1996.

**Heppner, J. P., and N. C. Maynard,** Empirical high-latitude electric field models, *J. Geophys. Res.,* **92,** 4467–4489, 1987.

**Jayachandran, P. T., and J. W. MacDougall,** Central polar cap convection response to short duration southward interplanetary magnetic field, *Ann. Geophysicae.,* **18,** 887–896, 2000.

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

**Khan, H., and S. W. H. Cowley,** Observations of the response time of high-latitude ionospheric convection to variations in the interplanetary magnetic field using EISCAT and IMP-8 data, *Ann. Geophysicae.,* **17,** 1306–1335, 1999.

**Kikuchi, T., H. Lühr, T. Kitamura, O. Saka, and K. Schlegel,** Direct penetration of the polar electric field to the equator during a *DP 2* event as detected by the auroral and equatorial magnetometer chains and the EISCAT radar, *J. Geophys. Res.,* **101,** 17,161–17,173, 1996.

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

**Lewis, R. V., M. P. Freeman, A. S. Rodger, G. D. Reeves, and D. K. Milling,** The electric field response to the growth phase and expansion phase onset of a small isolated substrom, *Ann. Geophysicae,* **15,** 289–299, 1997.

**Lewis, R. V., M. P. Freeman, and G. D. Reeves,** The relationship of HF radar backscatter to the accumulation of open magnetic flux prior to substorm onset, *J. Geophys. Res.,* **103,** 26,613–26,619, 1998.

**Lester, M., O. de la Beaujardière, J. C. Foster, M. P. Freeman, H. Lühr, J. M. Ruohoniemi, and W. Swider,** The response of the large scale ionospheric convection pattern to changes in the IMF and substorms: results from the SUNDIAL 1987 campaign, *Ann. Geophysicae,* **11,** 556, 1993.

**Lockwood, M., A. P. van Eyken, B. J. I. Bromage, and D. M. Willis,** Eastward propagation of a plasma convection enhancement following a southward turning of the interplanetary magnetic field, *Geophys. Res. Lett.,* **13,** 72–75, 1986.

**Lockwood, M., and S. W. H. Cowley,** Comment on "A statistical study of the ionospheric convection response to changing interplanetary magnetic field conditions using the assimilative mapping of ionospheric electrodynamics technique" by A. J. Ridley et al., *J. Geophys. Res.,* **104,** 4387–4391, 1999.

**McPherron, R. L.,** Growth phase of magnetospheric substorms, *J. Geophys. Res.,* **75,** 5592–5599, 1970.

**Matsushita, S.,** On geomagnetic sudden commencements, sudden impulses, and storm durations, *J. Geophys. Res.,* **67,** 3753–3777, 1962.

**Milan, S. E., T. K. Yeoman, and M. Lester,** The dayside auroral zone as a hard target for coherent HF radars, *Geophys. Res. Lett.,* **25,** 3717, 1998.

**Milan, S., M. Lester, S. W. H. Cowley, and M. Brittnacher,** Convection and auroral response to a southward turning of the IMF: Polar UVI, CUTLASS, and IMAGE signatures of transient magnetic flux transfer at the magnetopause, *J. Geophys. Res.,* **105,** 15,741–15,755, 2000.

**Moen, J., H. C. Carlson, S. E. Milan, N. Shumilov, B. Lybekk, P. E. Sandholt, and M. Lester,** On the collocation between dayside auroral activity and coherent HF radar backscatter, *Ann. Geophysicae,* **18,** 1531–1549, 2001.

**Murr, D. L., and W. J. Hughes,** Reconfiguration timescales of ionospheric convection, *Geophys. Res. Lett.,* **28,** 2145–2148, 2001.

**Neudegg, D. A., B. J. Fraser, F. W. Menk, H. J. Hansen, G. B. Burns, R. J. Morris, and M. J. Underwood,** Sources and velocities of Pc1-2 ULF waves at high-latitudes, *Geophys. Res. Lett.,* **22**, 2965–2968, 1995.

**Nishida, A.,** Coherence of geomagnetic DP2 magnetic fluctuations with interplanetary magnetic variations, *J. Geophys. Res.,* **73,** 5549–5559, 1968.

**Nishitani, N., T. Ogawa, N. Sato, H. Yamagishi, M. Pinnock, J-P Villain, G. Sofko, and O. Troshichev,** A study of the dusk convection cell's response to an IMF southward truning, *J. Geophys. Res.,* In Press, 2001.

**Oieroset M., P. E. Sandholt, W. F. Denig, S. W. H. Cowley,** Northward interplanetary magnetic field cusp aurora and high-latitude magnetopause reconnection, *J. Geophys. Res.,* **102**, 11,349−11,362, 1997.

**Parkinson, M. L., A. M. Breed, P. L. Dyson, and R. J. Morris,** Signatures of the ionospheric cusp in digital ionosonde measurements of plasma drift above Casey, Antarctica, *J. Geophys. Res.,* **104**, 22,487−22,498, 1999.

**Parkinson, M. L., P. R. Smith, P. L. Dyson, and R. J. Morris,** Nowcasting convection velocity in the high-latitude ionosphere using statistical models, *J. Atmos. Solar-Terr. Phys.,* **61**, 841−855, 1999.

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

**Pinnock, M., A. S. Rodger, J. R. Dudeney, F. Rich, and K. B. Baker,** High spatial and temporal resolution observations of the ionospheric cusp, *Ann. Geophysicae.,* **13,** 919, 1995.

**Provan, G., T. K. Yeoman, and S. E. Milan,** CUTLASS Finland radar observations of the ionospheric signatures of flux transfer events and the resulting plasma flows, *Ann. Geophysicae.,* **16,** 1411−1422, 1998.

**Ridley, A. J., L. Gang, C. R. Clauer, and V. O. Papitashvili,** Ionospheric convection during nonsteady interplanetary magnetic field conditions, *J. Geophys. Res.,* **102,** 14,563−14,579, 1997.

**Ridley, A. J., L. Gang, C. R. Clauer, and V. O. Papitashvili,** A statistical study of the ionospheric convection response to changing interplanetary magnetic field conditions using the assimilative mapping of ionospheric electrodynamics technique, *J. Geophys. Res.,* **103,** 4023−4039, 1998.

**Ridley, A. J., L. Gang, C. R. Clauer, and V. O. Papitashvili,** Reply, *J. Geophys. Res.,* **104,** 4393−4396, 1999.

**Ruohoniemi, J. M., R. A. Greenwald, K. B. Baker, J-P Villain, C. Hanuise, and J. Kelly,** Mapping high-latitude plasma convection with coherent HF radars, *J. Geophys. Res.,* **94,** 13,463−13,477, 1989.

**Ruohoniemi, J. M., and R. A. Greenwald,** The response of the high-latitude convection to a sudden southward IMF turning, *Geophys. Res. Lett.,* **25,** 2913−2916, 1998.

**Ruohoniemi, J. M., S. G. Shepherd, and R. A. Greenwald,** The response of the high-latitude ionosphere to IMF variations, *J. Atmos. Solar-Terr. Phys.,* **64**, 159−171, 2002.

**Saunders, M. A, M. P. Freeman, D. J. Southwood, S. W. H. Cowley, M. Lockwood, J. C. Samson, C. J. Farrugia, and T. J. Hughes,** Dayside ionospheric convection changes in response to long-period interplanetary magnetic field oscillations: determination of the ionospheric phase velocity, *J. Geophys. Res.,* **97,** 19,373−19,380, 1992.

**Siscoe, G. L., and T. S. Huang,** Polar cap inflation and deflation, *J. Geophys. Res.,* **90,** 543−547, 1985.

**Shepherd, S. G., R. A. Greenwald, and J. M. Ruoheniemi,** A possible explanation for rapid, large-scale ionospheric responses to southward turnings of the IMF, *Geophys. Res. Lett.,* **26,** 3197−3200, 1999.

**Smith, P. R., P. L. Dyson, D. P. Monselesan, R. J. Morris,** Ionospheric convection at Casey, a southern polar cap station, *J. Geophys. Res.,* **103,** 2209−2218, 1998.

**Taylor, J. R., T. K. Yeoman, M. Lester, M. J. Buonsanto, J. L. Scali, J. M. Ruohoniemi, and J. D. Kelly,** Ionospheric convection during the magnetic storm of 20-21 March 1990, *Ann. Geophysicae.,* **12,** 1174−1191, 1994.

**Todd, H., S. W. H. Cowley, M. Lockwood, and D. M. Willis,** Response time of the high-latitude dayside ionosphere to sudden changes in the north-south component of the IMF, *Planet. Space Sci.,* **36,** 1415-1428, 1988.

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

**Voronkov, I., E. Friedrich, and J. C. Samson,** Dynamics of the substrom growth phase as observed using CANOPUS and SuperDARN instruments, *J. Geophys. Res.,* **104,** 28,491−28,505, 1999.

**Watanabe, M., N. Sato, R. A. Greenwald, M. Pinnock, M. R. Hairston, R. L. Rairden, and D. J. McEwen,** The ionospheric response to interplanetary magnetic field variations: Evidence for rapid global change and the role of preconditioning in the magnetosphere, *J. Geophys. Res.,* **105,** 22,955–22,977, 2000.

# Figure Captions

**Fig. 1.** The locations of the Halley and TIGER field of views (FOVs) mapped to MLT and AACGM latiude during the three case studies analysed here: ~06 UT on 12 February, 2000 (purple), ~15 UT, 01 April, 2000 (blue), and ~18 UT, 24 September, 2000 (brown). Magnetic noon (12 h) is at top, magnetic dawn (06 h) to the right, and the clock dial is also labelled with UT along beam 4 (black) of the TIGER radar. Flow vectors given by the IZMEM convection model for ($B_x$, $B_y$, $B_z$) = (0, −5, −5) nT are also superimposed for reference.

**Fig. 2. a** The IMF $B_y$ (blue) and $B_z$ (red) components in GSM co-ordinates measured with 16-s time resolution on board the ACE spacecraft during 0515 to 0730 UT, 12 February, 2000. The data have been shifted to noon-sector ionospheric response times, as explained in the text. **b** LOS Doppler velocities measured along TIGER beam 4 for the same time interval as the IMF. The Doppler velocities were colour-coded using the adjacent colour key (e.g., the colour for 100 m $s^{-1}$ actually means 50 m $s^{-1}$ < $v_{los}$ ≤ 100 m $s^{-1}$). Doppler velocities for echoes automatically identified as "ground scatter" were excluded in this study. The abscissa was annotated with nominal values of MLT separated by 30 min (small typeface), but the tick marks are at 2-min intervals of UT. **c** Similar to part b, except the LOS Doppler velocities measured along Halley beam 8. **d** Line plots of LOS Doppler velocity averaged over ranges 1600 to 2200 km for TIGER beam 4 (red), range 1300 to 3555 km for TIGER beam 0 (black), and ranges 750 to 1600 km for Halley beam 8 (blue).

**Fig. 3. a–f** Time sequence of full-scan plots of colour-coded LOS Doppler velocity measured by TIGER (top foot prints) and the Halley radar (bottom foot prints). The full scans were projected onto a polar plot of MLT and magnetic latitude. The start times of individual full scans are shown above and below the footprints. Note that magnetic noon is toward the top right and magnetic midnight toward the bottom left.

**Fig. 4. a** Two-dimensional flow vectors estimated along TIGER beam 4 using the beam-swinging technique at 2-min time resolution during 0530 to 0700 UT on 12 February, 2000. The scale for an eastward flow of 300 m $s^{-1}$ is shown in the top right-hand corner. The solid dots correspond to the time and latitude of the velocity estimate, and the flows are directed along the lines going away from the dots. Flows directed toward the top are poleward and toward the right, eastward. **b** The corresponding flow vectors estimated along Halley beam 8 using the same technique.

**Fig. 5. a** Perturbations in the geomagnetic $X$ (solid curve), $Y$ (dashed curve), and $Z$ (dotted curve) components of the Davis magnetometer measured during 0515 to 0730 UT on 12 February, 2000. **b, c** The same except for Casey and Macquarie Island, respectively. The relative location of these ground-based magnetometers was shown in Fig. 1.

**Fig. 6. a** The IMF $B_y$ (blue) and $B_z$ (red) components measured with 16-s resolution on board the ACE spacecraft during 1400 to 1800 UT, 01 April, 2000. **b** LOS Doppler velocities measured along Halley beam 8 for the same time interval as the IMF. The same annotation scheme as in Fig. 2b was used, except tick marks are at 4-min intervals of UT. **c** LOS Doppler velocities measured along TIGER beam 4. **d** Line plots of LOS Doppler velocity averaged over ranges 2100 to 2700 km for Halley beam 8 (red), and ranges 1000 to 2500 km for TIGER beam 4 (blue). To improve the legibility of the figure, the curves for Halley beam 8 and TIGER beam 4 were displaced by –250 and +250 m $s^{-1}$, respectively.

**Fig. 7. a** Two-dimensional flow vectors estimated along Halley beam 8 using the beam-swinging technique at 2-min time resolution during 1500 to 1700 UT on 01 April, 2000. The same plotting technique as in Fig. 4 was used, except the scale shown in the top left-hand corner was changed to 200 m $s^{-1}$. Velocities with magnitudes >500 m $s^{-1}$ have been drawn in bold. **b** The corresponding flow vectors estimated along TIGER beam 4. Velocities with magnitudes >300 m $s^{-1}$ have been drawn in bold.

**Fig. 8. a** The IMF $B_y$ (blue) and $B_z$ (red) components measured with 16-s resolution on board the ACE spacecraft during 1730 to 2000 UT, 24 September, 2000. IMP8 measurements of the solar-wind dynamic pressure (nPa) have been superimposed, but were similar to those measured by ACE. **b** LOS Doppler velocities measured along Halley beam 8. Tick marks on the abscissa are at 2-min intervals of UT. **c** LOS Doppler velocities measured along TIGER beam 4. **d** Line plots of LOS Doppler velocity averaged over ranges 800 to 2600 km for Halley beam 8 (red), ranges 800 to 2600 km for Halley beam 10 (black), and ranges 1000 to 2500 km for TIGER beam 4 (blue). To improve the legibility of the figure, the curves for Halley beam 8 and TIGER beam 4 were displaced by –350 and +350 m $s^{-1}$, respectively.

**Fig. 9. a** Two-dimensional flow vectors estimated along Halley beam 8 using the beam-swinging technique at 2-min time resolution during 1730 to 1900 UT on 24 September, 2000. **b** The corresponding flow vectors estimated along TIGER beam 4.

**Table 1.** Summary of solar-wind discontinuities and HF radar response times.

| Time/Date | Solar-Wind Discontinuity | Dayside Response | Nightside Response | Ionospheric Delay |
|---|---|---|---|---|
| ~0601 UT, 12th February, 2000 | $B_z$, +11 to –16 nT in 25 min, $B_y$, –14 nT and slowly decreasing, minor dynamic pressure variations | <0601 UT, 1627 MLT, 72°S Mag. Clarity good | 0608 UT, 0322 MLT, 70°S Mag. Clarity very good | >7 min |
| ~1525 UT, 1st April, 2000 | $B_z$, +7 to –5 nT in 4 min, $B_y$, –4 nT and slowly decreasing, minor dynamic pressure variations | 1525 UT, 1240 MLT, 83°S Mag. Clarity excellent | ~1536, 1558 UT, 0224 MLT, 73°S Mag. Clarity poor | ~8–11 min, ~33 min, (84 min) |
| ~1800 UT, 24th September, 2000 | $B_z$, –4 to 3 nT in 19 min, $B_y$, +3 to –10 nT in the same time, minor dynamic pressure variations | 1801 UT, 1515 MLT, 75°S Mag. Clarity excellent | ~1818 UT, 0443 MLT, 70°S Mag. Speculative | ~17 min |
| ~1822 UT, 24th September, 2000 | $B_z$, +3 to –5 nT in 4 min, $B_y$, –9 to +3 nT in the same time, dynamic pressure decrease, –4.8 nPa in <7 min | 1825+6 UT, 1540 MLT, 75°S Mag. Clarity good | 1825+9 UT, 0451 MLT, 70°S Mag. Clarity good | ~0–3 min |