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RESPONSE TIME OF THE HIGH-LATITUDE DAYSIDE IONOSPHERE TO SUDDEN CHANGES IN THE NORTH–SOUTH COMPONENT OF THE IMF

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Abstract—The time scale of the response of the high-latitude dayside ionospheric flow to changes in the North–South component of the interplanetary magnetic field (IMF) has been investigated by examining the time delays between corresponding sudden changes. Approximately 40 h of simultaneous IMF and ionospheric flow data have been examined, obtained by the *AMPTE-UKS* and *-IRM* spacecraft and the EISCAT "Polar" experiment, respectively, in which 20 corresponding sudden changes have been identified. Ten of these changes were associated with southward turnings of the IMF, and 10 with northward turnings. It has been found that the corresponding flow changes occurred simultaneously over the whole of the "Polar" field-of-view, extending more than 2° in invariant latitude, and that the ionospheric response delay following northward turnings is the same as that following southward turnings, though the form of the response is different in the two cases. The shortest response time, 5.5 ± 3.2 min, is found in the early- to mid-afternoon sector, increasing to 9.5 ± 3.0 min in the mid-morning sector, and to 9.5 ± 3.1 min near to dusk. These times represent the delays in the appearance of perturbed flows in the "Polar" field-of-view following the arrival of IMF changes at the subsolar magnetopause. Overall, the results agree very well with those derived by Etemadi *et al.* (1988, *Planet. Space Sci.* **36**, 471) from a general cross-correlation analysis of the IMF B_z and "Polar" beam-swinging vector flow data.

1. INTRODUCTION

The time scale of the response of the magnetosphere–ionosphere system to changes that occur in the solar wind and interplanetary magnetic field (IMF) has been studied for many years by examining the correlations which occur between ground geomagnetic disturbance and various functions of the interplanetary parameters (Schatten and Wilcox, 1967; Arnoldy, 1971; Tsurutani and Meng, 1972; Burton *et al.*, 1975b; Holzer and Slavin, 1979, 1982, 1983; Baker *et al.*, 1981, 1983; Clauer *et al.*, 1981; Akasofu *et al.*, 1982; Meloni *et al.*, 1982; Murayama, 1982; Bargatze *et al.*, 1985; Tsurutani *et al.*, 1985). These studies have consistently shown that magnetic disturbance indices such as K_P, D_{ST}, AE and AL respond primarily to the North–South component of the IMF (B_z), as expressed, for example, by the "half-wave rectifier" function of Burton *et al.* (1975a), or the "epsilon parameter" of Perreault and Akasofu (1978). This finding indicates that the basic causative process which underlies geomagnetic activity is reconnection between the magnetospheric field and the IMF, as first discussed by Dungey (1961). It has also been consistently shown that the magnetic disturbance "output" lags the solar wind/IMF "input" by some 30–60 min, with some indication of smaller delays of ~ 15 min during more disturbed times (Baker *et al.*, 1981, 1983; Clauer *et al.*, 1981; Bargatze *et al.*, 1985). However, these disturbance indices respond primarily to the current systems which are set up or enhanced during magnetospheric storms and substorms, such that the time delays obtained correspond principally to the time taken to induce instability in the geomagnetic tail following flux transfer from the dayside.

The time scale on which the flux transfer and associated magnetospheric and ionospheric convection responds to IMF B_z appears to be much shorter. Certainly, the close correlation observed at the dayside magnetopause between large magnetic shears and reconnection signatures indicates that no substantial delays are involved in the underlying coupling processes at the boundary (Rijnbeek *et al.*, 1984; Berchem and Russell, 1984; Paschmann *et al.*, 1986). Correspondingly, in a study of the variations of the high-latitude *DP*-2 current system, believed to represent the geomagnetic counterpart of general ionospheric convection, Nishida (1968) found a geomagnetic response delay of 7 ± 1 min after southward IMF turnings impinged on the bow shock. Since the time taken for the IMF change to arrive at the dayside magnetopause from the shock was probably ~5 min, the implied response of the magnetosphere–ionosphere system to the arrival of southward fields at the magnetopause boundary is very rapid indeed, no more than a few minutes. Similar short time scales have also been inferred from case studies of individual intervals of high-latitude geomagnetic disturbance and their relation to concurrent variations of the IMF (Pellinen *et al.*, 1982; Nishida and Kamide, 1983; McPherron and Manka, 1985; Clauer and Kamide, 1985).

It has also become possible in recent years to measure ionospheric flows directly using incoherent scatter radars such as the Millstone Hill, Sondrestromfjord and EISCAT systems, but the multi-point scans generally employed for convection studies, while having broad latitudinal coverage, have insufficient time resolution (typically ~15 to ~30 min) to allow examination of a few-minute response delays (e.g. Oliver *et al.*, 1983; Foster and Doupnik, 1984; Clauer *et al.*, 1984; Alcaydé *et al.*, 1986). The EISCAT "Polar" experiment was therefore devised with the aim of determining horizontal flows to the North of the transmitter site at Tromsø with a significantly improved temporal resolution, though with restricted spatial coverage (van Eyken *et al.*, 1984; Willis *et al.*, 1986). Line-of-sight velocity profiles are determined every 15 s in the invariant latitude range ~71° to ~74°, while beam-swinging is used to find the horizontal vector flows with a temporal resolution of 2.5 min.

In 1984 and 1985 a series of "Polar" experiment runs was conducted in coordination with observations of the solar wind and IMF by the *AMPTE-UKS* and *-IRM* spacecraft. As a result, ~40 h of simultaneous data were acquired spanning the dayside in the dawn to early evening local time zone (~07:00–19:30 M.L.T.). Initial examination of these data showed that clear, prompt, responses of the ionospheric flow to the North–South component of the IMF were indeed observed (Rishbeth *et al.*, 1985; Lockwood *et al.*, 1986; Todd *et al.*, 1988). From a cross-correlation analysis of IMF B_z and the ionospheric flows observed by EISCAT at ~14:00 M.L.T. in one particularly well-defined event Willis *et al.* (1986) found a response delay between corresponding signals on the spacecraft and in the ionosphere (for the dominant westward flow component) of 11 ± 1 min. Since the IMF propagation time from the spacecraft to the subsolar magnetopause has been determined to be 7 ± 1 min during that interval (Etemadi *et al.*, 1988), the implied propagation time from the subsolar magnetopause to the "Polar" field-of-view is only 4.0 ± 1.5 min. These event studies have subsequently been followed up by Etemadi *et al.* (1988), who performed a general cross-correlation analysis between the beam-swinging vector flows and IMF B_z (a "half-wave rectifier" function actually being employed), using the full combined "Polar"/*AMPTE* data set. From the peaks in the correlograms it was found that in the noon to mid-afternoon sector (~12:00–~15:00 M.L.T.) the dominant westward flow component responds to changes in IMF B_z on time scales of only $\sim 4 \pm 2$ min, in agreement with the result of Willis *et al.* (1986) for one event, lengthening to between ~5 and 10 min in the immediate pre-noon and late-afternoon hours.

In this paper we return to the determination of response delays from the examination of corresponding sharp changes observed in the IMF and in the ionospheric flow, but using a much larger number of individual events contained in the "Polar"/*AMPTE* data set than has been analyzed in this way hitherto. Results derived on this basis are clearly less representative of the data as a whole compared with those derived from a general cross-correlation analysis, but the technique does have a number of advantages. First, it is possible to extend the M.L.T. coverage of the results into regions where the ionospheric flow speed does not respond greatly to changes in IMF B_z, such that clear peaks do not appear in the correlation analysis. In the "Polar" field-of-view such conditions occur in the mid-morning sector where the East–West component of flow reverses in sign, and also in the mid-afternoon to evening sector, where the westward flows of the contracted convection cells which are present when IMF B_z is positive happen to have similar speeds to those of the expanded cells which are present when IMF B_z is negative (Etemadi *et al.*, 1988). However, visual examination of the data may then reveal a more subtle response in the flow. In the latter case, for example, a sudden change in the latitudinal gradient of the flow speed may occur, resulting from a change in the size of the flow pattern, which can be related to a change in concurrent interplanetary conditions. A second advantage of examining sharp changes is that the response to sharp southward turnings of the IMF may be considered separately from the response to sharp northward turnings, to examine whether there are any systematic differences. Third, the results also provide a useful check on the response times derived from the general cross-correlation analysis of the beam-swinging data, and should indicate whether there are any differences in the response to sharp, as opposed to more general variations in the IMF.

This report thus presents the results of a study in which the EISCAT "Polar"/*AMPTE* data set has been used to investigate the ionospheric delay time by examining the response to sudden changes in IMF B_z. In the next two sections we provide further details of the "Polar" experiment and the data which it provides, while in Section 4 we present the results of the study and compare them with the cross-correlation results derived by Etemadi *et al.* (1988).

2. THE EISCAT "POLAR" EXPERIMENT

In the EISCAT "Polar" experiment, the radar is continuously directed at a low elevation angle (21.5°) to the North of the transmitter site at Tromsø, such that the beam passes obliquely through the *F*-region ionosphere. To obtain range (latitudinal) resolution along the beam, the backscatter signal is divided into a number of contiguous gates. Gate 1 is centred at a range of 525 km, a height of 211 km and an invariant latitude of 70.8°. The centres of the subsequent gates are displaced along the beam by 75 km, corresponding to increments of 34 km in height and 0.6° in invariant latitude. The data are continuously integrated for 15 s and then recorded, thus setting the limiting time resolution of the experiment. Depending on the density of the ionosphere, an adequate signal-to-noise ratio is then usually obtained in the first four or five gates in these 15 s measurements, corresponding to the invariant latitude range from $\sim 71°$ to $\sim 73°$.

Although the 15 s values of ionospheric densities, temperatures, and line-of-sight velocities are the basic information that the "Polar" experiment provides, considerable additional information is obtained by periodically swinging the azimuth of the beam, so that the horizontal vector flow may be estimated. The azimuths of the two dwell positions employed are symmetrically displaced by 12° on either side of the *L*-shell meridian at Tromsø (geographic azimuth 344°), such that equivalent gates along the two directions are centred at nearly equal invariant latitudes, as given above. In combining the data from the two scattering volumes (which are separated in longitude by ~ 220 km for gate 1, increasing to ~ 310 km for gate 4), it is assumed that the magnetic North–South and East–West components of the flow transverse to the field are the same in the two volumes, and that they vary slowly over the cycle time of the experiment. It is also assumed that the field-aligned component of flow is zero. In general, the latter flow component is expected to be small compared with the flow transverse to the field, and the experiment is in any case insensitive to such flows because of the large aspect angle between the radar beam and the field direction ($\sim 74°$). With these assumptions it is therefore obvious from the geometry of the experiment that the mean of the line-of-sight velocities observed in the two look directions determines the North–South component of flow, while their difference determines the East–West component. The radar dwells for 2 min at each azimuth and takes 30 s to swing between them, so that a full cycle of 2 dwells and 2 swings takes 5 min. The 15 s data thus consist of eight consecutive values at a fixed azimuth, followed by two measurements while the radar is moving. A latitude profile of the horizontal vector flow is then obtained every 2.5 min by combining the dwell-averaged line-of-sight velocities obtained in each dwell with the average of those obtained during the two adjacent dwells at the other azimuth. The latter average is taken in order to form an appropriately time-centred value. In this study the 15 s line-of-sight velocities form the primary data set for the determination of ionospheric response delays, but vectors derived from the beam-swinging algorithm described above will be quoted in the discussion of individual examples in the next section.

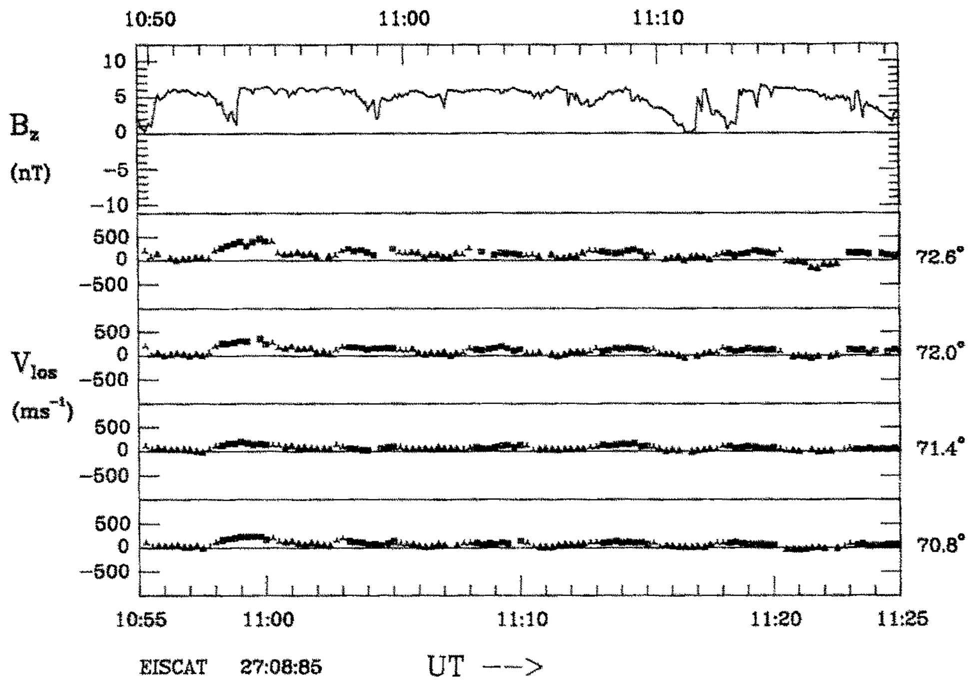
3. FLOW MODULATION BY IMF B_z AND DETERMINATION OF RESPONSE DELAYS

The flows observed within the "Polar" field-of-view are consistent with a twin-vortex pattern whose centre is offset from the magnetic pole towards the nightside, as might have been expected. Examination of the beam-swinging vector velocity data (Willis *et al.*, 1986) and the line-of-sight velocity data (Todd *et al.*, 1988) shows that in the early morning hours rapid irregular eastward flows are generally observed, corresponding to the central part of the "dawn" cell auroral zone flow. As the radar rotates with the Earth the field-of-view passes into the equatorward part of this region, such that the flows weaken and exhibit a strong poleward gradient in the vicinity of the dawn meridian. Smoother flows, sometimes with weak ULF wave activity, are observed in this part of the flow pattern. Between this time and the early afternoon the radar is generally located equatorward of the main auroral zone flows. In this region the flows are observed to be relatively weak, gradientless and sporadic, and directed mainly eastwards before about ~09:00 M.L.T. and westward thereafter. Entry into the "dusk" cell auroral zone flow in the vicinity of noon is recognized by stronger, smooth westward flows with a poleward gradient. With increasing local time, flow speeds continue to grow, until in the mid- to late-afternoon they maximize in conjunction with the disappearance of the poleward gradient, corresponding to a location near the central peak of the dusk auroral zone flow region. Flows here are characteristically variable on time scales of a few minutes, especially when IMF B_z is negative. Towards the dusk meridian the flow speeds generally decline again, become smoother and show an equatorward gradient as the field-of-view passes into the poleward part of the region of westward flow, and moves towards the polar cap region. Finally, in the early evening hours the polar cap boundary region may be observed. Here the flows are again weak and have no strong gradient.

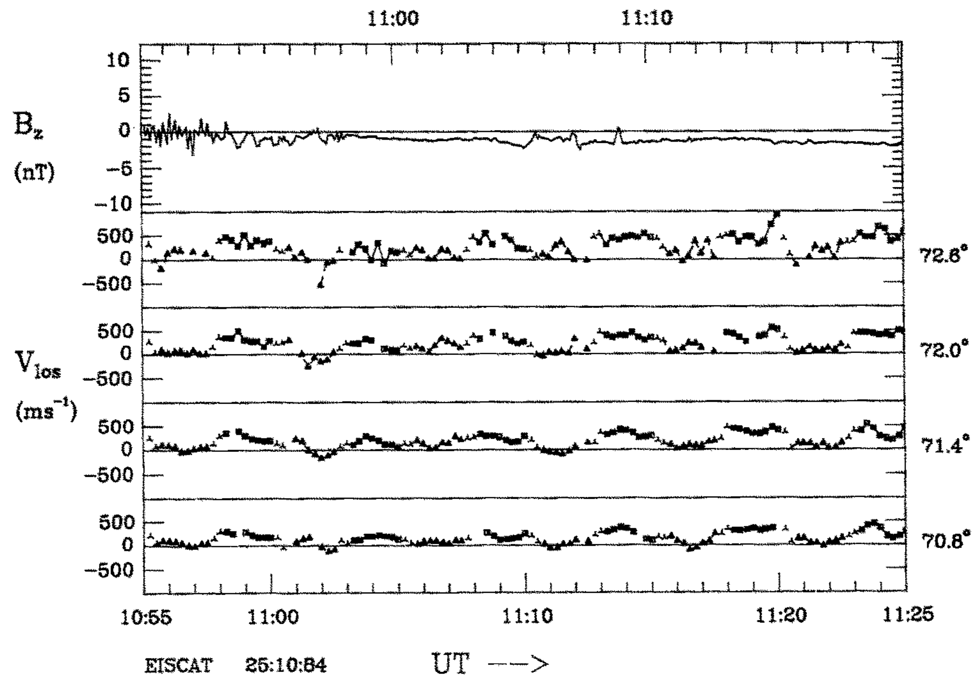
While the above sequence of flows is usually observed during each of the "Polar" runs, the local times at which the various types of flow occur can vary by several hours, due to changes in the flow pattern which are associated with IMF B_z. As IMF B_z becomes increasingly negative the principal changes that occur are an expansion in the size of the flow cells, and an increase in the peak flow speed. Thus, for example, the features of the dusk convection cell mentioned above occur earlier, and the peak speeds are higher, when IMF B_z is negative than when it is positive (see e.g. Etemadi et al., 1988). As a consequence, the form of the flows observed at any particular local time depends on IMF B_z.

Figures 1 and 2 illustrate the strong control which IMF B_z exerts on the auroral zone flows in the "Polar" field-of-view. Each figure consists of two plots showing data for the same 30 min U.T. (M.L.T.) interval obtained on different days when IMF B_z had different steady values. In Fig. 1 the time interval is 10:55–11:25 U.T., corresponding to the early afternoon local time sector (13:25–13:55 M.L.T.), while in Fig. 2 the interval is 14:20–14:50 U.T., corresponding to the late afternoon sector (16:50–17:20 M.L.T.). At the top of each of these plots we show 5 s IMF B_z data and in the lower panels the 15 s "Polar" line-of-sight velocities. (Note from the time scale at the top of the plots that the IMF B_z data have been lagged by a few minutes relative to the "Polar" data, as will be discussed further below.) The upper panels in both figures show that plot (a) in each case corresponds to a period when IMF B_z was positive (being ~5 nT in Fig. 1 and ~1–3 nT in Fig. 2), whereas plot (b) corresponds to a period when IMF B_z was negative (~ −1 to −2 nT in both figures). The "Polar" data in the lower panels are plotted in the format of Todd et al. (1988), with data from "azimuth 1" (directed West of the L-shell meridian at 332° geographic) being shown by squares, data from "azimuth 2" (directed East of the L-shell meridian at 356° geographic) by triangles, and the data obtained during radar swings by the inverted Y symbols. Occasional gaps in these data result from a failure of the analysis programme to find a satisfactory fit to the backscatter signal autocorrelation function in these cases. The height of individual velocity panels in each plot corresponds to ± 1 km s^{-1}, and positive values indicate flow away from the radar. Consequently, since the squares usually have a larger value than the triangles in this data, with a generally positive mean value, it is apparent from the above discussion that the flows observed are generally directed north-westward, corresponding to the auroral zone of the "dusk" cell, as expected for this local time sector.

However, distinct differences between the plots are also evident, which result from the IMF B_z modulation of the flow pattern, in line with the discussion above. In Fig. 1a (IMF B_z positive) the flows are weak, smooth and gradientless, typical of the region between (equatorward of) the main auroral zone flows, while at the same local time in Fig. 1b (IMF B_z negative) they are much stronger, wavier, and exhibit a pronounced poleward gradient in flow speed, typical of the "dusk" cell equatorward of the auroral zone peak. For example, at ~11:10 U.T. (~13:40 M.L.T.) analysis of the beam-swinging data in Fig. 1a indicates that the velocity vectors in gates 1 to 4 are 210, 160, 230 and 220 m s^{-1} at azimuths 70°, 60°, 70° and 40°, respectively, while at the same time in Fig. 1b the equivalent vectors are 480, 670, 750 and 860 m s^{-1}, all at azimuth 75°. (The azimuth of the flow given here is defined with respect to the L-shell meridian, with 0° representing northward flow along the meridian, and +90° and −90° westward and eastward flow, respectively, transverse to the meridian.) Similarly, at the later local time shown in Fig. 2, flows are moderate, smooth and exhibit a weak poleward gradient in flow speed in Fig. 2a (IMF B_z positive), corresponding to the region just equatorward of the peak in the "dusk" cell auroral zone flow, while at the same local time the flows are much faster (in the lower gates), more variable and with a strong equatorward gradient in flow speed in Fig. 2b (IMF B_z negative), corresponding to the poleward part of the "dusk" cell auroral zone and the boundary of the polar cap. At ~14:35 U.T. (~17:05 M.L.T.) the velocity vectors in gates 1 to 4 are 330, 320, 360 and 580 m s^{-1} at azimuths 75°, 70°, 70° and 80° in Fig. 2a, and 750,



(a)



(b)

FIG. 1. PLOTS OF EISCAT "POLAR"/*AMPTE* DATA FOR THE SAME TIME INTERVALS (10:55–11:25 U.T., CORRESPONDING TO 13:25–13:55 M.L.T.) OBSERVED ON TWO DIFFERENT DAYS (27 AUGUST 1985 AND 25 OCTOBER 1984 IN (a) AND (b), RESPECTIVELY).

The top panel in each plot shows 5 s averages of the IMF B_z field component in GSM coordinates, measured by the *AMPTE-IRM* magnetometer in (a) and by the *AMPTE-UKS* magnetometer in (b). The lower four panels show the 15 s line-of-sight velocity components measured in the lowest four "Polar" range gates, the panels being labelled by the invariant latitude of the centre of the gate. Squares show measurements made at "azimuth 1" (332° geographic), triangles at "azimuth 2" (356° geographic), while the inverted Y symbols show measurements made during antenna swings. Flows away from the radar are taken as positive. The typical uncertainties in these line-of-sight velocity measurements, estimated as in Todd *et al.* (1988), are 15, 20, 35, and 55 m s^{-1} in plot (a), and 20, 35, 65, and 130 m s^{-1} in plot (b), for gates 1 to 4, respectively. The IMF data have been shifted in time relative to the EISCAT data to take account of the propagation time of the IMF signal from the spacecraft to the subsolar magnetopause [by 5.5 min in (a) and 4.9 min in (b)].

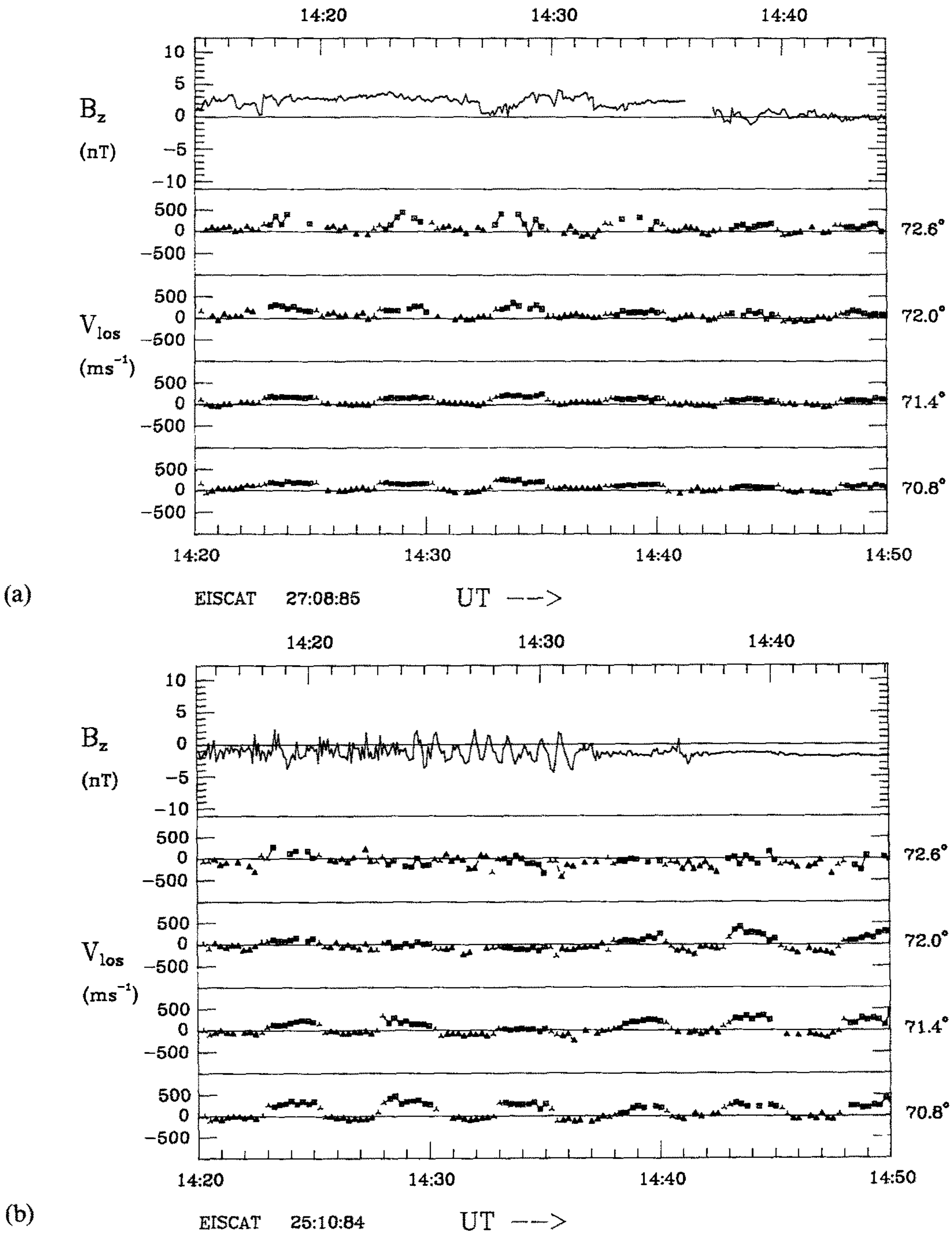


FIG. 2. AS FOR FIG. 1 EXCEPT FOR THE INTERVAL 14:20–14:50 U.T. (16:50–17:20 M.L.T.). The typical uncertainties in the line-of-sight velocity components are 20, 30, 60, and 105 m s^{-1} in plot (a), and 40, 35, 60, and 120 in plot (b) for gates 1 to 4, respectively. The IMF data have been shifted by 5.5 min in Fig. 2a and 4.9 min in Fig. 2b.

420, 220 and 150 m s^{-1} at azimuths 85°, 90°, 100° and 145° in Fig. 2b. These results and inferences are all in good accord with the studies of the IMF dependence of the "Polar" flows and their variability on short time scales presented by Etemadi *et al.* (1988) and Todd *et al.* (1988), though the relationship between the ionospheric flow and IMF B_z has not previously been illustrated in this way.

Figures 1 and 2 thus convincingly demonstrate the close control exerted by IMF B_z on the form of the "Polar" flows observed at any particular local time. When changes take place in IMF B_z, transitions in the flow must also occur, the time scale of which is the principal item of interest here. It is clear, however, that the nature of these transitions will depend on local time. Thus, for example, in the noon sector we expect to observe positive correlations between southward IMF B_z and "Polar" flow speeds resulting from transitions between the weak flows equatorward of the dayside auroral zone and the westward flows in the "dusk" cell auroral zone equatorward of the peak, as indicated by Fig. 1. However, in the late afternoon and dusk sector both positive and negative correlations may be observed simultaneously in the field-of-view, due to transitions between the central and poleward parts of the "dusk" cell auroral zone, as illustrated by Fig. 2. In the post-dusk early evening sector, negative correlations may also be observed across the entire field-of-view, corresponding to observations in the poleward part of the "dusk" cell auroral zone and the polar cap boundary (not illustrated).

Examples of such transitions in the "Polar" data may be found in the previous publications by Rishbeth *et al.* (1985) and Todd *et al.* (1988). Here in Fig. 3 we show two previously unpublished examples, which serve to show how the response time has been determined. Figure 3a shows the ionospheric response to a northward IMF turning observed in the mid-afternoon sector on 29 August 1985 (12:12–12:42 U.T., corresponding to ~14:42–15:12 M.L.T.), where the data has been presented in the same format as the plots in Figs 1 and 2. It can be seen in the upper panel of the figure that a sharp change in IMF B_z was observed by the *AMPTE-IRM* spacecraft at ~12:13:3 U.T. Because the time taken by the IMF signal to propagate from the spacecraft (located upstream from the bow shock) to the subsolar magnetopause is comparable to the ionospheric response time (a few minutes), the IMF propagation time must be carefully estimated. Here we have used the propagation delays calculated by Etemadi *et al.* (1988) for the "Polar"/*AMPTE* data set, based on the position of the spacecraft and that of the bow shock and magnetopause, the latter being determined from empirical models and concurrent solar wind density and flow speed values [see Etemadi *et al.* (1988) for full details]. In Fig. 3a the IMF propagation time is estimated to have been 5.3 min (with a probable uncertainty of ±1 min), and the time scale of the IMF data in Fig. 3a has been shifted relative to the EISCAT data by this amount, as can be seen by comparing the time scales shown on the upper (*AMPTE*) and lower (EISCAT) borders of the plot. (The shifts in the time scales in Figs 1 and 2 were calculated using similar considerations.) All the ionospheric response delays quoted in this paper are thus relative to the estimated time at which the IMF change reached the subsolar magnetopause, which in the present case is 12:18.6±1.0 U.T.

Turning now to the "Polar" data, in the mid-afternoon sector we expect to observe the weak smooth flows of the equatorward border of the dusk auroral zone flow region when IMF B_z is a few nT positive, while when IMF B_z is a few nT negative the field-of-view should correspond to the region just equatorward of the peak flow in this region where the speeds should be much stronger and more variable (e.g. Etemadi *et al.*, 1988; Todd *et al.*, 1988). At the beginning of the interval, where IMF B_z is negative, the flows are indeed strong and somewhat variable, and exhibit a poleward gradient indicative of a location equatorward of the peak flow. At ~12:15 U.T., for example, the beam-swinging velocity vectors in gates 1 to 4 are 1190, 1350, 1580 and 2160 m s^{-1}, at azimuths 75°, 75°, 80° and 80°, respectively. After ~12:20 U.T., however, the flow speed clearly undergoes a monotonic decline, reaching 560, 580, 700 and 810 m s^{-1}, all at azimuth 75°, at ~12:33 U.T. The decrease is temporarily reversed by a flow speed increase observed in the "azimuth 1" dwell centred on ~12:39 U.T. which seems to be unrelated to concurrent IMF conditions, and which appears to have characteristics similar to the "flow burst" events discussed by Todd *et al.* (1986, 1988), especially in the higher gates (not shown). However, in the next "azimuth 1" dwell (also not shown) the speed is further reduced to values below those quoted above for ~12:33 U.T. Thus, as expected, the northward turning of the field initiates a decline in the flow speed in this sector, occurring on time scales of ~15 min. For purposes of this study, however, we require the time at which the flow speed starts to decline. Examination of the data shows that the decline starts in all gates at some time between the "azimuth 1" dwells centred on ~12:19 and ~12:24 U.T. The timing cannot be made more precise than this in the present instance because the flow is very nearly perpendicular to the

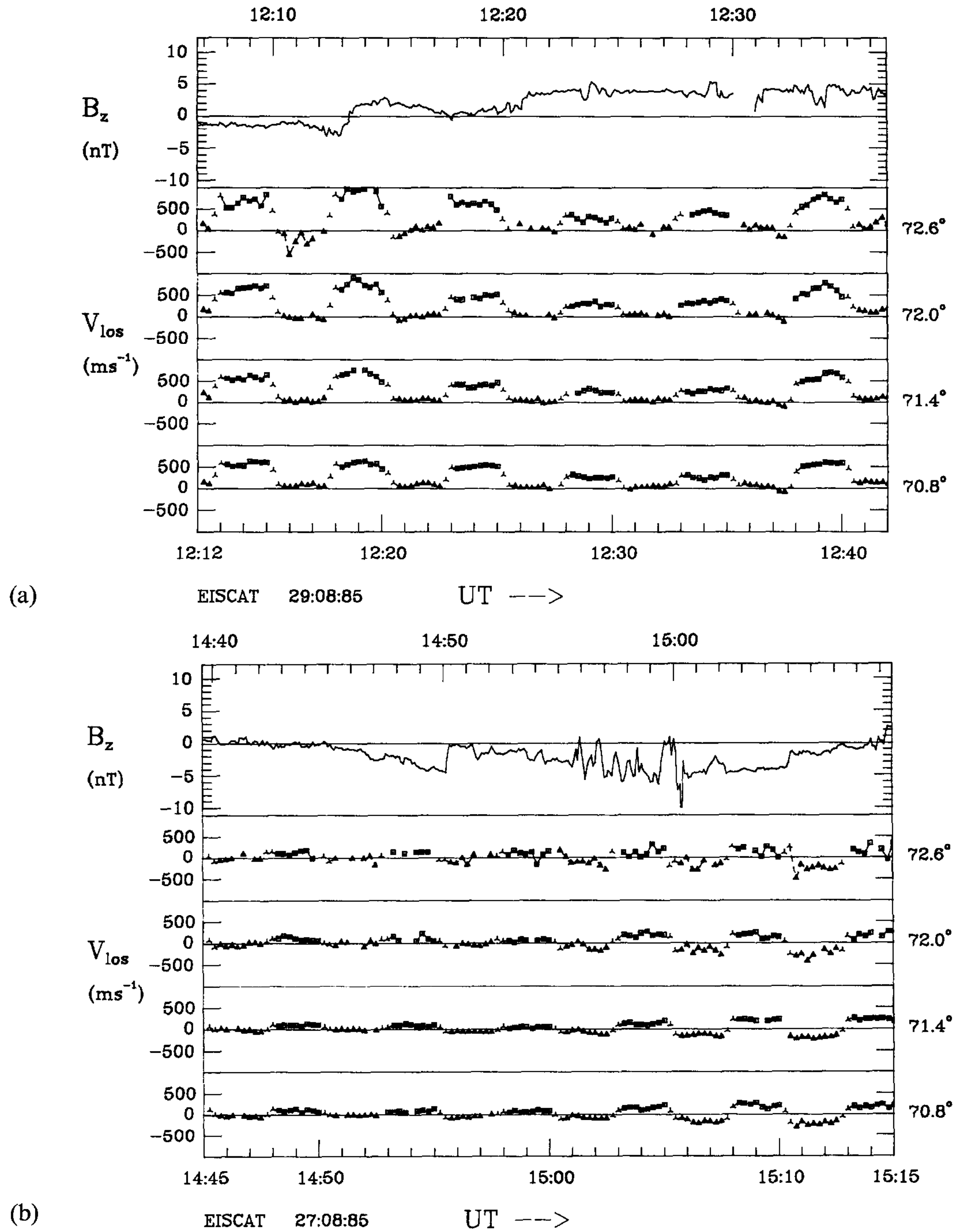


FIG. 3. EISCAT "POLAR"/*AMPTE-IRM* DATA ILLUSTRATING THE RESPONSE OF THE IONOSPHERIC FLOW TO A SHARP NORTHWARD [PLOT (a)] AND A SHARP SOUTHWARD [PLOT (b)] TURNING OF THE IMF, OBSERVED ON 29 AND 27 AUGUST 1985, RESPECTIVELY.

The format of the plots is the same as in Fig. 1. The uncertainties in the line-of-sight velocity components are 20, 30, 30, and 100 m s^{-1} in plot (a), and 20, 35, 60, and 120 m s^{-1} in plot (b) for gates 1 to 4, respectively. The IMF data have been shifted by 5.3 min in Fig. 3a and by 5.5 min in Fig. 3b.

direction of the radar beam at "azimuth 2", and shows little response in this direction thoughout. In this case, therefore, we take the ionospheric response to start at $12:21.5 \pm 1.5$ min. Combining this with the time estimated above at which the IMF change reached the subsolar magnetopause, we find an ionospheric response time of

$$(12:21.5 \pm 1.5) - (12:18.6 \pm 1.0) = 2.9 \pm 1.8 \text{ min.}$$

This value compares favourably with the "spot" result of 4.0 ± 1.5 min discussed in the introduction which was obtained from the analysis of another event in the same local time zone by Willis *et al.* (1986), and with the results of the general cross-correlation analysis of Etemadi *et al.* (1988), who found a lag of 4.6 ± 3.4 min for the westward flow for the 2 h interval centred on 14:30 M.L.T. The latter lag represents the average of all gates where a positive correlation was found, computed with the individual values weighted according to the reciprocal of the square of the estimated error. The quoted uncertainty is the standard deviation from the weighted mean. The weighted gate-averaged lag is given because the individual values do not vary systematically from gate to gate. Our examination of individual events, such as that discussed here, also shows no measureable differences in the delays across the field-of-view, so that only one value is again quoted.

Figure 3b shows the ionospheric response to a more gradual southward turning, observed by EISCAT in the late afternoon sector on 27 August 1985 (14:45–15:15 U.T., corresponding to 17:15–17:45 M.L.T.). This interval directly follows that shown in Fig. 2a (and overlaps it by 5 min), from which it can be seen that IMF B_z had previously been positive for a lengthy period (~ 1 h) before decreasing to zero at 14:37 U.T., and then turning southward at $14:45 \pm 1$ U.T. The IMF propagation delay is estimated to be 5.5 ± 1 min on this day (Etemadi *et al.*, 1988), so that the southward turning reached the subsolar magnetopause at $14:50.5 \pm 1.4$ U.T. Prior to the southward turning the ionospheric flows were weak, with a weak poleward gradient, but subsequently strengthened and became nearly uniform across the field-of-view. For example, at $\sim 14:55$ U.T. the flow vectors in gates 1 to 4 were 290, 290, 270 and 340 m s^{-1} at 90°, 85°, 85° and 85°, while at $\sim 15:10$ U.T. they were 940, 980, 910 and 980 m s^{-1} at 90°, 90°, 95° and 95°. The discussion of Fig. 2 and the statistical results of Etemadi *et al.* (1988) suggest that a transition into the poleward part of the dusk auroral zone region should occur for strongly negative IMF B_z at this local time (see e.g. Fig. 2b), while the enhanced flows actually observed correspond to the central part of this region, suggesting that the flow pattern was smaller than average at that time. Nevertheless, this does not impair our ability to determine the time at which the ionospheric response occurred, which is judged to have been at some time between the "azimuth 1" dwells centred on $\sim 14:59$ and $\sim 15:04$ U.T. in all gates, i.e. at $15:01.5 \pm 1.5$ U.T. The ionospheric response delay is thus determined as

$$(15:01.5 \pm 1.5) - (14:50.5 \pm 1.4) = 11.0 \pm 2.1 \text{ min.}$$

Again, this result is in good agreement with the statistical results of Etemadi *et al.* (1988), who find a lag for westward flows of 10.0 ± 2.3 min for the 2 h interval centred on 17:00 M.L.T. In the Etemadi *et al.* study, a good correlation was obtained in only the first two gates in this M.L.T. interval, and the uncertainty in the lag quoted is the standard error in the weighted mean.

We finally note that in the example shown in Fig. 3b, the enhancement of the flow after the southward turning occurred somewhat gradually over an interval of ~ 5 min. This behaviour probably relates to the rather gradual nature of the southward IMF turning. More usually, a southward turning results in a sharp, enduring enhancement in the flow, as seen in the examples presented by Rishbeth *et al.* (1985) and Todd *et al.* (1988). This contrasts with the usual response of the flow to northward turnings of the IMF, which initiate gradual changes which take place over a few tens of minutes. However, even in these cases an initial sharp partial change is usually present, as seen in Fig. 3a, from which the start time of the ionospheric response can be readily determined. Thus in all cases the ionospheric response delay has been measured from the time at which the IMF signal is estimated to have reached the subsolar magnetopause and the *start* time of the associated flow changes in the ionosphere.

Having described and illustrated the methods employed in this study, in the next section we describe the results of a general study of the ionospheric response delay to the sharp changes which occur in the EISCAT "Polar"/*AMPTE* data set.

4. IONOSPHERIC RESPONSE DELAY

Using the methods outlined in the previous section, the ~ 40 h of simultaneous EISCAT "Polar"/*AMPTE* data have been examined for the presence of sharp associated changes from which the ionospheric response delay can be determined. The overall coverage of the simultaneous data is shown vs M.L.T. in the histogram displayed at the top of Fig. 4. This shows that the data is confined to the interval $\sim 06:45$–$\sim 19:45$ M.L.T., spanning the equatorward

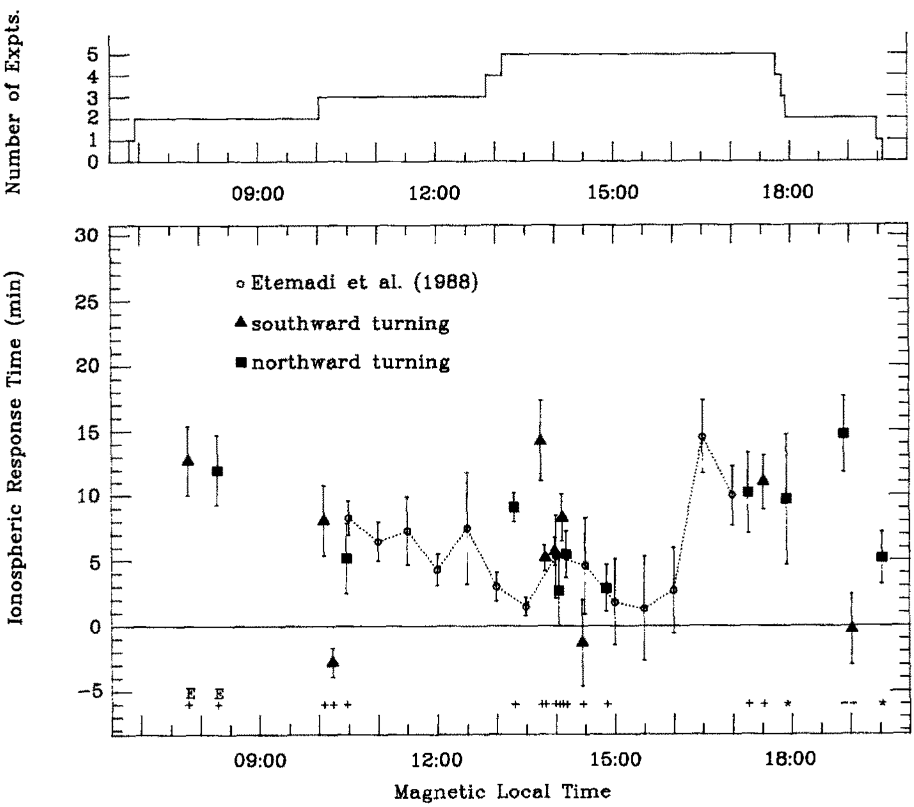


FIG. 4. THE UPPER PANEL SHOWS A HISTOGRAM OF THE LOCAL TIME COVERAGE OF THE SIMULTANEOUS EISCAT "POLAR"/*AMPTE-UKS* AND *-IRM* DATA SET.

The few-minute propagation time of the IMF from the spacecraft to the subsolar magnetopause has been incorporated. The lower panel shows a plot of the ionospheric response time vs M.L.T., determined from the response to sudden northward and southward turnings of the IMF (solid squares and triangles, respectively). The symbols plotted beneath each point indicate the type of correlation observed, "+" for a positive correlation between the flow speed and negative IMF B_z, "−" for a negative correlation, and "*" for the former in the nearer gates and the latter in the farther gates. "E" indicates eastward ionospheric flow, the points not so marked involve westward flow. The open circles joined by dotted lines represent a summary of the results obtained by Etemadi *et al.* (1988) from cross-correlation analysis of the beam-swinging vector "Polar" data.

part of the "dawn" cell auroral zone, the weak flow region between (equatorward of) the main dayside flows, the "dusk" cell auroral zone flow, and the dusk polar-cap boundary region. The histogram is the same as that shown previously by Etemadi *et al.* (1988) (their Fig. 1), except that coverage starts ~1.5 h earlier in this study because of the recent availability of *AMPTE-IRM* data for the early parts of the EISCAT experiments conducted on 25 and 27 October 1984. The few-minute IMF propagation times have also been incorporated in the present version of the diagram.

In this data set a total of twenty clear associated changes have been identified from which the response delay can be determined, ten related to southward turnings of the IMF and ten to northward turnings, shown by solid triangles and squares, respectively in the lower panel of Fig. 4. The symbols underneath each data point indicate the type of ionospheric response from which the delay has been determined; "+" for a positive correlation between the flow speed and negative IMF B_z, "−" for a negative correlation, and "*" for the simultaneous occurrence of the former in the nearer gates and the latter in the farther gates (c.f. Fig. 2). From the discussion in the previous section it is not surprising that the data points in Fig. 4 corresponding to the observation of negative and mixed correlations are confined to the dusk and early evening sector. All of the ionospheric responses involve observation of the westward flows of the "dusk" auroral zone, with the exception of the first two points marked additionally with "E", indicating that the flows observed were the eastward flows in the auroral zone of the "dawn" cell.

It can be seen that the M.L.T. coverage of these events has distinct gaps despite the relatively uniform coverage of the data, the gaps occurring between ~11:00 and 13:00 M.L.T. and between ~15:00 and 17:00 M.L.T. The noon gap occurred by chance, in that the IMF happened to vary relatively smoothly in all the three experiments which cover this interval. However, several sudden IMF changes did occur in the late afternoon gap but could not be used because the related flow changes are relatively weak in this sector (corresponding to the central part of the "dusk" cell auroral zone), and their onset time was masked by the large-amplitude, short-period flow variations which occur in this region, as mentioned in the previous section. In addition, eleven sudden flow changes were identified in the "Polar" data which do not appear to be related to concurrent variations of IMF B_z. Of these, six are short-lived "flow burst" events resembling the types described by Todd *et al.* (1986, 1988), while two changes which are more enduring may be associated with variations in IMF B_y rather than in IMF B_z. Overall, however, the correspondence between changes in the "Polar" flows and in IMF B_z is very good indeed, as previously reported by Willis *et al.* (1986), Etemadi *et al.* (1988) and Todd *et al.* (1988).

Turning now to the response time results shown in the lower panel of Fig. 4, it can be seen that the values determined from the individual events generally show good consistency. In particular, within the estimated uncertainties there seems to be no significant difference between the response delays following sharp northward and sharp southward turnings of the IMF. However, three points do diverge significantly from the general trends, namely two with negative (unphysical) response times which occur at ~10:00 and ~19:00 M.L.T., together with the large positive value determined at ~14:00 M.L.T. (The negative value at 14:30 M.L.T. is consistent with the neighbouring points, within the error bars). It is possible that the IMF propagation time from the spacecraft to the magnetopause has been incorrectly estimated for these cases, or that incorrect associations have been made between near-concurrent changes in the IMF and ionospheric flow. With the neglect of these points, the mean response delay determined from the three main groups of points are 9.5 ± 3.0 min for the interval 07:30–10:30 M.L.T., 5.5 ± 3.2 min for 13:00–15:00 M.L.T., and 9.5 ± 3.1 min for 17:00–19:30 M.L.T. (With the inclusion of these three points the times are 2.1 ± 7.5, 6.2 ± 4.2 and 7.9 ± 4.8 min, respectively.) The values quoted here are the mean and standard deviation of the individual delay determinations, weighted according to the reciprocal of the square of the error. Overall, the data clearly suggest that the response delay is ~5 min in the early- to mid-afternoon sector, increasing to ~10 min in the mid-morning and dusk M.L.T. sectors. The weighted mean and standard deviation of all twenty response delays is 5.5 ± 5.2 min.

To facilitate a comparison of the response delays obtained here with the cross-correlation lag times determined by Etemadi *et al.* (1988), the open circles joined by dashed lines in the lower panel of Fig. 4 show a summary of the latter results. These have been determined from overlapping 2 h segments of the data in which each gate has been treated separately. The lag times from gates 1 to 5, where they can be determined, have then been averaged together (again weighted according to the reciprocal of the square of the error), to produce the open circles. As previously discussed by Etemadi *et al.* (1988), the M.L.T. coverage of the cross-correlation lag times is limited principally to the region of strong positive correlations between auroral zone flows and the southward component of the IMF, thus eliminating the availability of results in the mid-morning sector where the East–West component of flow reverses in sign, and from the region of mixed and negative correlations in the dusk and early evening sectors. The technique employed here, which is not so restricted, can then be seen to extend the coverage of these results to earlier and later local times, by more than 2 h in each case. [Note, however, that the data from which the two "E" points were determined here were not available to Etemadi *et al.* (1988), as previously mentioned.]

It can be seen from this comparison that the only direct overlap between the two sets of results occurs in the early- to mid-afternoon M.L.T. sector, where good agreement is obtained. The gate-averaged cross-correlation lag time for the 2 h interval 13:00–15:00 M.L.T. is 5.2 ± 2.7 min, compared with 5.5 ± 3.2 min given above for the corresponding group of points obtained from the analysis of sudden changes. In addition, although there is no significant direct overlap at earlier and later local times, the cross-correlation lag times do increase from values of a few minutes in the mid-afternoon sector towards ~10 min at the limits of the range of these results, thus approaching the corresponding values determined here. Overall, therefore, it is clear that our results are in good agreement with those obtained by Etemadi *et al.* (1988). We therefore conclude that there are no significant differences between response times determined from corresponding sudden changes in the IMF and ionospheric flow as observed in the 15 s line-of-sight "Polar" data, and those determined from cross-correlation analysis of the general beam-swinging vector data.

5. SUMMARY AND DISCUSSION

In this paper we have examined the response time of ionospheric flows to changes that occur in the North–South component of the IMF by examining corresponding sudden changes that occur in the EISCAT "Polar"/*AMPTE* data set. The main flow cells observed by the "Polar" experiment on the dayside become larger and the flow speed increases as IMF B_z becomes increasingly negative, such that changes in the field lead to changes in the speed and in the form of the flows observed in the "Polar" field-of-view, the nature of which depends strongly on M.L.T. It is the time scale on which these changes take place that is the main item of interest here. Response times can also be investigated by cross-correlation analysis of the "Polar" beam-swinging velocity vector data, such as has recently been presented by Etemadi *et al.* (1988). Although rather less general, the analysis of corresponding sudden changes, performed mainly by visual inspection of the "Polar" 15 s line-of-sight velocities, provides an independent check on the cross-correlation results, and can extend them in a number of significant ways.

The main points we wish to emphasize are as follows.

(a) The response of the ionospheric flows to sharp southward and northward turnings of the IMF are different. A southward turn usually produces an enduring change in the flow with a sharp onset (few tens of seconds). A northward turn often produces a smaller sudden change, followed by a slower monotonic variation on a time scale of ~ 15 min. This difference is not unexpected, since although flows may be rapidly excited by the onset of reconnection and the production of new open flux at the dayside magnetopause, this flux will remain open and will continue to drive ionospheric flows for some time after reconnection ceases. Weak residual flows of a few hundred m s^{-1} may also be maintained for a few tens of minutes by the neutral wind flywheel effect.

(b) Changes in flow occur simultaneously across the "Polar" field-of-view, to within the resolution set by the time scale of the change. Clear sharp changes are observed to be simultaneous on time scales of a few tens of seconds. This confirms the finding of Etemadi *et al.* (1988) that there is no significant latitude dependence of the cross-correlation lags, and indicates that the flows develop in a coherent temporal fashion on a large spatial scale, rather than for example by a simple latitudinal expansion and enhancement of a pre-existing flow pattern. For example, a flow pattern expansion of a few hundred m s^{-1} would translate to time scales of more than 10 min for particular features of the flow to cross the field-of-view, much longer than is observed (except following northward turnings of the IMF as mentioned above).

(c) No significant differences are found between the ionospheric response delays following sudden southward and sudden northward turnings of the IMF when the ionospheric delays are timed from the sudden changes in flow which occur in both cases. This finding presumably reflects a rapid onset and a similarly rapid cessation of coupling at the dayside magnetopause as the IMF turns southward and northward, respectively.

(d) Taking responses to northward and southward turnings together, the ionospheric response delay is 5.5 ± 3.2 min in the early- to mid-afternoon sector (13:00–15:00 M.L.T.), increasing to 9.5 ± 3.0 min in the mid-morning sector (07:30–10:30 M.L.T.), and 9.5 ± 3.1 min at dusk (17:00–19:30 M.L.T.). These results are in excellent overall accord with those determined by Etemadi *et al.* (1988) from cross-correlation analysis of the "Polar" beam-swinging vector data, though the latter are restricted in M.L.T. to the regions of strong positive correlation between ionospheric flow speed and negative IMF B_z. It should be noted that these response delays are rather longer than the Alfvén-wave travel time from the magnetopause to the dayside ionosphere, which is approximately 1 min as determined from the characteristic period of the ULF waves observed in this vicinity. It thus appears that it typically takes an interval of several minutes for the changes of flow which result from coupling at the magnetopause to propagate (at speeds of several km s^{-1}) from the initially perturbed region of the ionosphere near noon to the "Polar" field-of-view. On a similar basis we might also expect to find longer response delays with increasing local time away from noon, in basic agreement with the results derived here, and displayed in Fig. 4.

A simple physical picture which may form a basis for understanding these results has been described by Lockwood *et al.* (1986). It is supposed that the onset of reconnection at the dayside magnetopause, which follows a southward turning of the IMF, results in the formation of a patch of newly opened flux adjacent and equatorward of the pre-existing polar cap boundary near noon, to the North of the "Polar" field-of-view. The patch then expands at a rate determined by the voltage associated with the reconnection process (i.e. the rate of change of open flux), which, for voltages of ~ 100 kV will be several km s^{-1} for the first ~ 10 min. After one or two Alfvén-wave travel times (1–2 min), the magnetic stresses associated with the newly opened flux tubes will excite a new twin-vortex pattern of rapid flows, which then similarly expands as the patch grows. Ultimately, of course, the flows expand over the whole polar region to form the pattern appropriate to the new IMF B_z value. If the "Polar" field-of-view is initially located, say, ~ 1000 km equatorward to the initial patch, then a further ~ 3 min delay would be introduced by a southward expansion speed of ~ 5 km s^{-1}, compatible with the shortest delays determined here. At this speed the disturbance would propagate across the nearest four gates of the "Polar" field-of-view (shown in the figures here) in ~ 40 s (i.e. less than three 15 s data points). Increasing delays would then occur away from the noon sector as the patch also expands in local time, reaching a delay of ~ 10 min at the dawn–dusk meridian for similar expansion speeds. In the analysis of one flow enhancement observed in the afternoon sector, Lockwood *et al.* (1986) deduced an eastward enhancement speed of 2.6 ± 0.3 km s^{-1} using Polar data, which is consistent with this suggestion. This picture therefore seems to provide a reasonable overall basis on which to interpret our results, with their details (e.g. the post-noon response delay minimum) presumably being related to the detailed geometry of the expanding patch of the flows relative to the "Polar" field-of-view. However, quantitative modelling and comparison with high resolution flow data is required to elucidate the details of this picture, and to determine whether it is fully compatible with the observations.

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REFERENCES

Alcadyé, D., Caudal, G. and Fontanari, J. (1986) Convection electric fields and electrostatic potential over 61° $< \Lambda <$ 72° invariant latitude observed with the European incoherent scatter facility: initial results. *J. geophys. Res.* **91**, 233.

Akasofu, S.-I., Carbary, J. F., Meng, C.-I., Sullivan, J. P. and Lepping, R. P. (1982) A high time resolution study of the solar wind–magnetosphere energy coupling function. *Planet. Space Sci.* **30**, 537.

Arnoldy, R. L. (1971) Signature in the interplanetary medium for substorms. *J. geophys. Res.* **76**, 5189.

Baker, D. N., Hones, E. W., Jr., Payne, J. B. and Feldman, W. C. (1981) A high-time resolution study of interplanetary parameter correlations with *AE*. *Geophys. Res. Lett.* **8**, 179.

Baker, D. N., Zwikl, R. D., Bame, S. J., Hones, E. W., Jr., Tsurutani, B. T., Smith, E. J. and Akasofu, S.-I. (1983) An *ISEE* 3 high time resolution study of interplanetary parameter correlations with magnetospheric activity. *J. geophys. Res.* **88**, 6230.

Bargatze, L. F., Baker, D. N., McPherron, R. L. and Hones, E. W., Jr. (1985) Magnetospheric impulse response for many levels of geomagnetic activity. *J. geophys. Res.* **90**, 6387.

Berchem, J. and Russell, C. T. (1984) Flux transfer events on the magnetopause: spatial distribution and controlling factors. *J. geophys. Res.* **89**, 6689.

Burton, R. K., McPherron, R. L. and Russell, C. T. (1975a) The terrestrial magnetosphere: a half-wave rectifier of the interplanetary electric field. *Science* **189**, 717.

Burton, R. K., McPherron, R. L. and Russell, C. T. (1975b) An empirical relationship between interplanetary conditions and D_{st}. *J. geophys. Res.* **80**, 4204.

Clauer, C. R., McPherron, R. L., Searls, C. and Kivelson, M. G. (1981) Solar wind control of auroral zone geomagnetic activity. *Geophys. Res. Lett.* **8**, 915.

Clauer, C. R., Banks, P. M., Smith, A. Q., Jorgensen, T. S., Friis-Christensen, E., Vennerstrom, S., Wickwar, V. B., Kelly, J. D. and Doupnik, J. (1984) Observation of IMF and ionospheric plasma convection in the vicinity of the dayside polar cleft. *Geophys. Res. Lett.* **11**, 891.

Clauer, C. R. and Kamide, Y. (1985) *DP* 1 and *DP* 2 current systems for the March 22, 1979 substorms. *J. geophys. Res.* **90**, 1343.

Dungey, J. W. (1961) Interplanetary field and the auroral zones. *Phys. Rev. Lett.* **6**, 47.

Etemadi, A., Cowley, S. W. H., Lockwood, M., Bromage, B. J. I., Willis, D. M. and Lühr, H. (1988) The dependence of high-latitude 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.

van Eyken, A. P., Rishbeth, H., Willis, D. M. and Cowley, S. W. H. (1984) Initial EISCAT observations of plasma convection at invariant latitudes 70°–77°. *J. atmos. terr. Phys.* **46**, 635.

Foster, J. C. and Doupnik, J. R. (1984) Plasma convection in the vicinity of the dayside cleft. *J. geophys. Res.* **89**, 9107.

Holzer, R. E. and Slavin, J. A. (1979) A correlative study of magnetic flux transfer in the magnetosphere. *J. geophys. Res.* **83**, 3831.

Holzer, R. E. and Slavin, J. A. (1982) An evaluation of three predictors of geomagnetic activity. *J. geophys. Res.* **87**, 2558.

Holzer, R. E. and Slavin, J. A. (1983) Reply. *J. geophys. Res.* **88**, 4955.

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

McPherron, R. L. and Manka, R. H. (1985) Dynamics of the 10:54 U.T. March 22, 1979 substorm event: CDAW 6. *J. geophys. Res.* **90**, 1175.

Meloni, A., Wolfe, A. and Lanzerotti, L. J. (1982) On the relationship between interplanetary quantities and the global auroral electrojet index. *J. geophys. Res.* **87**, 119.

Murayama, T. (1982) Coupling function between solar wind parameters and geomagnetic indices. *Rev. Geophys. Space Phys.* **20**, 623.

Nishida, A. (1968) Coherence of geomagnetic *DP* 2 fluctuations with interplanetary magnetic variations. *J. geophys. Res.* **73**, 5549.

Nishida, A. and Kamide, Y. (1983) Magnetospheric processes preceding the onset of an isolated substorm: a case study of the March 31, 1978 substorm. *J. geophys. Res.* **88**, 7005.

Oliver, W. L., Holt, J. M., Wand, R. H. and Evans, J. V. (1983) Millstone Hill incoherent scatter observations of auroral zone convection over $60° < \Lambda < 75°$: Average patterns vs K_p. *J. geophys. Res.* **88**, 5505.

Paschmann, G., Papamastorakis, I., Baumjohann, W., Sckopke, N., Carlson, C. W., Sonnerup, B. U. O. and Lühr, H. (1986) The magnetopause for large magnetic shear: *AMPTE/IRM* observations. *J. geophys. Res.* **91**, 11099.

Pellinen, R. J., Baumjohann, W., Heikkila, W. J., Sergeev, V. A., Yahnin, A. G., Marklund, G. and Melnikov, A. O. (1982) Event study on pre-substorm phases and their relation to the energy coupling between the solar wind and magnetosphere. *Planet. Space Sci.* **30**, 371.

Perreault, P. and Akasofu, S.-I. (1978) A study of geomagnetic storms. *Geophys. J. R. astr. Soc.* **54**, 547.

Rijnbeek, R. P., Cowley, S. W. H., Southwood, D. J. and Russell, C. T. (1984) A survey of dayside flux transfer events observed by *ISEE* 1 and 2 magnetometers. *J. geophys. Res.* **89**, 786.

Rishbeth, H., Smith, P. R., Cowley, S. W. H., Willis, D. M., van Eyken, A. P., Bromage, B. J. I. and Crothers, S. R. (1985) Ionospheric response to changes in the interplanetary magnetic field observed by EISCAT and *AMPTE UKS*. *Nature* **318**, 451.

Schatten, K. H. and Wilcox, J. M. (1967) Response of the geomagnetic activity index K_p to the interplanetary magnetic field. *J. geophys. Res.* **72**, 5185.

Todd, H., Bromage, B. J. I., Cowley, S. W. H., Lockwood, M., van Eyken, A. P. and Willis, D. M. (1986) EISCAT observations of bursts of rapid flow in the high latitude dayside ionosphere. *Geophys. Res. Lett.* **13**, 909.

Todd, H., Cowley, S. W. H., Etemadi, A., Bromage, B. J. I., Lockwood, M., Willis, D. M. and Lühr, H. (1988) Flow in the high latitude ionosphere: measurements at 15 s resolution made using the EISCAT "Polar" experiment. *J. atmos. terr. Phys.* **50**, 423.

Tsurutani, B. T. and Meng, C.-I. (1972) Interplanetary magnetic field variations and substorm activity. *J. geophys. Res.* **77**, 2964.

Tsurutani, B. T., Slavin, J. A., Kamide, Y., Zwickl, R. D., King, J. H. and Russell, C. T. (1985) Coupling between the solar wind and the magnetosphere: CDAW6. *J. geophys. Res.* **90**, 1191.

Willis, D. M., Lockwood, M., Cowley, S. W. H., van Eyken, A. P., Bromage, B. J. I., Rishbeth, H., Smith, P. R. and Crothers, S. R. (1986) A survey of simultaneous observations of the high-latitude ionosphere and interplanetary magnetic field with EISCAT and *AMPTE-UKS*. *J. atmos. terr. Phys.* **48**, 987.