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The effect of rapid changes in ionospheric flow on velocity vectors deduced from radar beam-swinging experiments

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Abstract—The effects on the horizontal ionospheric velocity vectors deduced from radar beam-swinging experiments, which occur when changes in the flow take place on short time scales compared with the experiment cycle time, are analysed in detail. The further complications which arise in the interpretation of beam-swinging data, due to longitudinal gradients in the flow and to field-aligned flows, are also considered. It is concluded that these effects are unlikely to seriously compromise statistical determinations of the response time of the flow, e.g. to changes in the north–south component of the IMF, such as have been recently reported by ETEMADI *et al.* (1988, *Planet. Space Sci.* **36**, 471), using EISCAT 'Polar' data.

1. INTRODUCTION

The large scale flow which occurs in the high latitude ionosphere, and its dependence on geophysical conditions such as the direction of the interplanetary magnetic field (IMF) and geomagnetic activity, has been studied intensively in recent years using both space-based and ground-based techniques. Observations from spacecraft are capable of providing rapid snapshots of the flow under particular conditions (HEPPNER, 1977; HEELIS, 1984; BURCH *et al.*, 1985; HEPPNER and MAYNARD, 1987), while ground-based radars provide essentially continuous monitoring of a restricted region, so that response time scales to externally induced changes may be investigated (CLAUER *et al.*, 1984; RISHBETH *et al.*, 1985; WILLIS *et al.*, 1986). Until recently most radar observations of the flow have been made by monostatic (single transmitter–receiver) systems, which use beam-swinging experiments to determine the vector velocity by combining the line-of-sight components measured in two or more pointing directions (DOUPNIK *et al.*, 1972; EVANS *et al.*, 1980; FOSTER *et al.*, 1981, 1982; FOSTER, 1983; OLIVER *et al.*, 1983; FOSTER AND DOUPNIK, 1984; WICKWAR *et al.*, 1984; JORGENSEN *et al.*, 1984). More recently, the tristatic EISCAT system has been used to determine the vector flows directly in a given volume of the ionosphere by the use of three spaced receivers (ALCAYDE *et al.*, 1986; FONTAINE *et al.*, 1986). However, this technique is effective only within a certain distance from the 'centre' of the receiver triangle. At large ranges, the look directions to the scattering volume of all the receivers become sufficiently similar that tristatic vector flow determinations become unreliable. In this case, monostatic beam-swinging must again be used, as in the EISCAT 'Polar' experiment, which was devised to study flows in the vicinity of the dayside cusp, far to the north of the EISCAT transmitter site at Tromsø (VAN EYKEN *et al.*, 1984; WILLIS *et al.*, 1986).

In order to deduce flow vectors from beam-swinging data, several assumptions must be made about the properties of the ionospheric flow. In the 'Polar' experiment, for example, the radar beam is pointed at a low elevation angle (21.5°) to the north of the transmitter site, and swung successively between two azimuths directed 12° on either side of the local *L*-shell meridian. The centres of the *F*-region range gates along the beam are then located at very nearly the same invariant latitude in the two dwell positions, but are displaced in longitude typically by ~250 km, for the nearer gates. To form a velocity vector, the line-of-sight velocity components measured in the same gate at the two azimuths are combined by first assuming that the northward and westward flow components in the two scattering volumes are equal. This will usually be a reasonable assumption in the auroral zone, where flow gradients are principally latitudinally directed. However, if small differences do exist between these components, the computed vector will not simply be the mean of the values at the two locations but will also contain a spurious westward component related to the difference between the northward flows, and a spurious northward component related to the difference between the westward flows, as will be discussed later. The second assumption made in the 'Polar' velocity vector calculation is that the field-aligned component of the flow is zero. In this experiment the radar beam (for the nearer gates) makes an angle of ~73.5° to the field direction so that there is, in fact, some sensitivity to this flow component. The possible effects of non-zero parallel flow then also need to be considered. Finally, using these two assumptions, flow vectors are formed by combining the line-of-sight components measured during each dwell with the average of those measured in the two adjacent dwells at the other azimuth. The third assumption made in the analysis, therefore, is that the flow varies sufficiently slowly compared with the cycle time of the experiment that the linearly interpolated value between two successive dwells at the same azimuth represents a good approximation to the actual flow occurring. In the 'Polar' experiment the full cycle time is 5 min. However, recent analyses of 15 s resolution line-of-sight 'Polar' data have shown that dayside auroral zone flows respond rapidly and sharply to changes in the north–south component of the IMF (LOCKWOOD *et al.*, 1986; TODD *et al.*, 1988). For example, TODD *et al.* (1988) have presented an instance in which a sudden southward turn of the IMF resulted in an acceleration of the ionospheric plasma essentially from rest to line-of-sight speeds in excess of 1 km s^{-1} in 45 s [see their fig. 6(b)]. Such changes are interpreted as resulting from the excitation of a new flow pattern near to noon due to the onset of magnetopause reconnection, which then expands rapidly outwards at speeds of several km s^{-1} (LOCKWOOD *et al.*, 1986), thus setting up a new flow pattern over the radar field-of-view on a time scale which is short compared with the experiment cycle time. Clearly, when such changes take place, the velocity vectors deduced from the algorithm based on the above assumptions will not be simply related to the flows actually occurring in the ionosphere.

In a recent study, ETEMADI *et al.* (1988) have investigated the relationship between ionospheric flows and the north–south component of the IMF by performing a cross-correlation analysis between 'Polar' velocity vectors deduced using the assumptions described above, and simultaneous magnetic field measurements made in the solar wind by the AMPTE-UKS and -IRM spacecraft. It was found that the response time of the flow to southward-directed fields appearing at the dayside magnetopause depends on local time, with the shortest response of 3.9 ± 2.2 min occurring in the westward flows of the dusk cell in the early afternoon sector. (These values are the average and standard deviation of all the response times determined at integer hourly intervals between 1200 and 1500 MLT inclusive, in all gates, weighted in proportion to the inverse of the estimated error in the value. The standard error of the mean is approximately 0.5 min.) The response time of the northward flow component in this sector was found to be a few minutes longer (6.7 ± 2.2 min), as was also the case for both flow components at earlier and later local times. We do not believe that random errors in the derived velocity vectors significantly effect the response times determined by ETEMADI *et al.* (1988), because similar results and similar estimated errors, were derived in all the 'Polar' gates used in the study [gates 1–7; see figs. 6 and 7 of ETEMADI *et al.* (1988)], whereas the signal-to-noise ratio of the measurements varies substantially over this range.

In this paper we will therefore consider whether any systematic sources of error might by present in the response time determinations of ETEMADI *et al.* (1988), which could arise from the assumptions made in the analysis of the beam-swinging data as described above. In particular, we investigate in detail the possible effects associated with the spurious flow vectors which are derived from the beam-swinging algorithm when the large-scale flow varies rapidly compared with the cycle time of the experiment, such as occurs quite often in the 'Polar' data. Specifically, we address the following question. Suppose rapid variations of the large scale flow occur, in which the northward and westward flow components vary in concert with each other, i.e. with exactly the same response time to the IMF. Is it then possible, as a result of rapid changes of the flow, for the beam-swinging algorithm to lead to spurious variations in the derived response times about their true values for either flow component? We will show that in individual cases the answer to this question is clearly 'yes', by up to half an experiment cycle time, but that this effect averages to zero when taken over many flow changes occurring at random phases of the experiment cycle.

We then (in Section 4) briefly consider whether effects of this nature can be produced by either of the other two major assumptions which enter the beam-swinging algorithm, i.e. the assumption of zero longitudinal gradients and zero parallel flows. We argue that the artefacts in the velocity vectors produced by these assumptions are unlikely to be sufficiently large that they will effect the response time results, except perhaps under very unusual conditions.

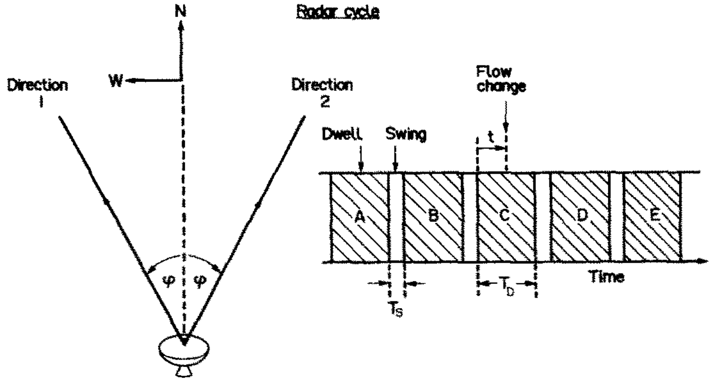

Fig. 1. Sketch of the geometry of the idealized beam-swinging experiment used in the analysis in this paper (left) and its beam-swinging pattern (right). The radar beam is swung successively through an angle of 2ϕ between two pointing positions designated 'direction 1' and 'direction 2', which are equally spaced on either side of the direction towards magnetic north (N). The beams are at low elevation angle and are taken for simplicity to lie in the plane of the flow. The left hand sketch thus corresponds to a view from above the ionosphere, so that west (W) points to the left. In the right hand sketch the hatched areas represent radar dwells (duration T_D) along either of the two pointing directions, while the blank areas represent the intervals (duration T_S) during which the antenna swings between the two pointing directions. If dwells A, C and E are in direction 1, then B and D are in direction 2, and vice versa. The sudden change of ionospheric flow is assumed in the analysis to take place at time t after the start of dwell C, as indicated. This experiment configuration corresponds closely to that of the EISCAT 'Polar' experiment, for which $\phi \simeq 12°$, $T_D = 2$ min and $T_S = 30$ s.

2. EFFECT OF SUDDEN FLOW CHANGES ON BEAM-SWINGING VELOCITY VECTORS

In this section we will consider the effect of an abrupt change in flow on the velocity vectors deduced from an idealized beam-swinging experiment, based on the EISCAT 'Polar' experiment. For this purpose it is sufficient to assume that the radar beam lies in the plane of the flow, and is swung successively between two pointing directions labelled '1' and '2', each displaced by angle ϕ from the direction of the magnetic pole, as shown on the left hand side of Fig. 1. (In the 'Polar' experiment $\phi \simeq 12°$.) Vectors aligned parallel and perpendicular to the bisector of the beam directions will therefore be labelled 'N' (north) and 'W' (west), respectively, with N directed away from the radar transmitter and W directed from beam direction 2 towards beam direction 1 (see Fig. 1). If a uniform steady flow with components v_N and v_W is then present in the plane of the radar beams, the line-of-sight components observed along the two beam directions will be:

$$\vartheta_1 = v_N \cos\phi + v_W \sin\phi \tag{1}$$

$$\vartheta_2 = v_N \cos\phi - v_W \sin\phi. \tag{2}$$

Flow away from the radar transmitter is taken to be positive. Correspondingly, if the line-of-sight velocities are observed to be ϑ_1 and ϑ_2, the ionospheric flow, assumed uniform and steady, is deduced to be:

$$v_N = \frac{(\vartheta_1 + \vartheta_2)}{2\cos\phi} \tag{3}$$

$$v_W = \frac{(\vartheta_1 - \vartheta_2)}{2\sin\phi}. \tag{4}$$

We assume that the radar dwells for a time T_D at each pointing direction, and takes a time T_S to swing between them, such that the full cycle time of the experiment is $2(T_D + T_S)$. In the EISCAT 'Polar' experiment $T_D = 2$ min and $T_S = 30$ s, such that the cycle time is 5 min as previously stated. The experiment time sequence is shown schematically on the right hand side of Fig. 1, where the hatched intervals represent antenna dwells and the blank intervals antenna swings. If dwells A, C and E are in direction 1, then B and D will be in direction 2 and vice versa. Now let us assume that the flow changes suddenly from $\mathbf{v}$ to $\mathbf{v}+\mathbf{V}$ at time t after the start of dwell C, as shown in the figure. Then, assuming that dwell A is in direction 1, the line-of-sight velocities averaged over each dwell will be:

$$\vartheta_A = (v_N \cos\phi + v_W \sin\phi) \tag{5}$$

$$\vartheta_B = (v_N \cos\phi - v_W \sin\phi) \tag{6}$$

$$\vartheta_C = (v_N \cos\phi + v_W \sin\phi) + (1 - t/T_D) \times (V_N \cos\phi + V_W \sin\phi) \quad (7)$$

$$\vartheta_D = (v_N \cos\phi - v_W \sin\phi) + (V_N \cos\phi - V_W \sin\phi) \quad (8)$$

$$\vartheta_E = (v_N \cos\phi + v_W \sin\phi) + (V_N \cos\phi + V_W \sin\phi). \quad (9)$$

If instead dwell A is in direction 2, the sign of the second velocity term in each of the brackets in the above equations is reversed. It should be noted that in equation (7) we have assumed the measured line-of-sight velocity component to be the true mean value during the dwell, which will be the case if the ionospheric electron density remains constant.

As described in the previous section, a flow vector is then reconstructed each experiment half-cycle by combining the line-of-sight component observed in each dwell with the average of those observed in the two adjacent dwells at the other azimuth, using (3) and (4). The time of the vector determination is then assigned to the middle of the central dwell. The deduced velocity values (which will be denoted by starred quantities) corresponding to the middle of dwells A–E will then be:

$$v_N^*(\mathrm{A}) = v_N \quad v_W^*(\mathrm{A}) = v_W \quad (10a,b)$$

$$v_N^*(\mathrm{B}) = v_N + \tfrac{1}{4}(1 - t/T_D)(V_N \pm V_W \tan\phi) = v_N + V_N^*(\mathrm{B}) \quad (11a)$$

$$v_W^*(\mathrm{B}) = v_W + \tfrac{1}{4}(1 - t/T_D)(V_W \pm V_N \cot\phi) = v_W + V_W^*(\mathrm{B}) \quad (11b)$$

$$v_N^*(\mathrm{C}) = v_N + \tfrac{1}{2}[(3/2 - t/T_D)V_N \pm (1/2 - t/T_D)V_W \tan\phi] = v_N + V_N^*(\mathrm{C}) \quad (12a)$$

$$v_W^*(\mathrm{C}) = v_W + \tfrac{1}{2}[(3/2 - t/T_D)V_W \pm (1/2 - t/T_D)V_N \cot\phi] = v_W + V_W^*(\mathrm{C}) \quad (12b)$$

$$v_N^*(\mathrm{D}) = v_N + \tfrac{1}{2}\{[2 - t/(2T_D)]V_N \mp [t/(2T_D)]V_W \tan\phi\} = v_N + V_N^*(\mathrm{D}) \quad (13a)$$

$$v_W^*(\mathrm{D}) = v_W + \tfrac{1}{2}\{[2 - t/(2T_D)]V_W \mp [t/(2T_D)]V_N \cot\phi\} = v_W + V_W^*(\mathrm{D}) \quad (13b)$$

$$v_N^*(\mathrm{E}) = v_N + V_N \quad v_W^*(\mathrm{E}) = v_W + V_W, \quad (14a,b)$$

where upper signs are to be taken if dwell A (and hence C and E) is in pointing direction 1, and lower signs if it is in direction 2. It should be noted that correct velocities are deduced at and before dwell A, and at and after dwell E. However, incorrect velocities are deduced during the three dwells centred on C, the dwell in which the change is assumed to take place, arising from an inevitable mixing of data acquired before and after the change. A minor exception to this statement occurs if the flow change takes place during the antenna swing following dwell C. In this case only the two velocity vectors on either side of the change (i.e. C and D) are compromised, with the vectors deduced being given by putting $t = T_D$ in equations (10)–(14).

The velocities derived from the effected dwells consist of the sum of the 'old' velocity vector **v**, and a perturbation vector $\mathbf{V}^*$ (not necessarily small) whose components V_N^* and V_W^* in turn consist of two terms. The sign of the first term is independent of the pointing direction of the dwell, and its magnitude is proportional to the 'appropriate' velocity component of **V** (i.e. proportional to V_N in the expressions for V_N^* and to V_W in the expressions for V_W^*). This term describes a 'smoothing' of the sharp change in flow into the dwells adjacent to the change. For example, if the change takes place at the exact centre of dwell C, so that $t/T_D = 0.5$, then (neglecting the second 'mixing' terms for the moment), one eighth of the vector **V** appears in dwell B, one half in dwell C and seven eighths in dwell D. The second term in the expressions for $\mathbf{V}^*$, whose sign is dependent on the pointing direction of the dwell, then describes a 'mixing' of the flow components, such that a change in the N component of the flow produces a spurious perturbation in V_W^* in the vicinity of the change (i.e. in the values deduced in dwells B, C and D), while a change in the W component produces a spurious perturbation in V_N^*. It should be noted that the magnitude of these effects depends not only on the magnitude of the flow components V_N and V_W, but also on the angular separation of the two radar beams. In practical experiments this angle will generally be chosen to be quite small in order to minimize the spatial separation of the scattering volumes whose line-of-sight velocities are to be combined. In this case these terms will have a much larger effect on V_W^* than on V_N^*, since the terms in V_N^* are proportional to $\tan\phi$, which is then small, while the terms in V_W^* are proportional to $\cot\phi$, which is large. In the EISCAT 'Polar' experiment where $\phi \simeq 11.6$ (the angle between the beams projected onto the local field-perpendicular plane) we have $\tan\phi = 0.21$, while $\cot\phi = 4.85$, a ratio of 23.6.

The algebraic results given above are illustrated graphically in Fig. 2. Since the initial flow velocity vector $\mathbf{v}$ simply represents a constant baseline to which the perturbation vector $\mathbf{V}^*$ is added, we have here taken $\mathbf{v} = \mathbf{0}$ and consider the sudden onset of flow from initially static conditions. In the three panels of Fig. 2 we have assumed that the ionospheric flow after the onset has the same speed in each case (i.e. we have normalized to the magnitude of $\mathbf{V}$), but has different directions. The parameters of the radar experiment have been chosen to be $T_D = 4T_S$ and $\phi = 12°$, corresponding (very nearly) to 'Polar' values.

Figure 2a shows results for the sudden onset of a pure westward directed flow ($V_N = 0$, $V_W = V$). On the left hand side of the figure we show the values of V_W^* (circles joined by solid lines) and V_N^* (crosses joined by dashed lines) vs. time for ten different phases of the flow onset relative to the beam-swinging cycle. The onset occurs at the centre of each graph where the vertical axis is drawn, while underneath each plot the numbered horizontal lines show the positions of the radar dwells in each pointing direction. The deduced velocity components are plotted at the centre of each dwell. On the right hand side of the figure we present the same information as flow vectors vs. time, where the vertical dashed line indicates the time at which the flow change takes place. The dashed arrows represent the true direction and magnitude of the ionospheric flow (if any) at each point, for purposes of comparison. (The vector drawn at the exact time of onset is the 'value in the mean' $\mathbf{V}/2$, which is always equal to the value deduced from the beam-swinging algorithm at that point, because the smoothing terms then give just one half of the final value in each component, while the mixing terms go to zero). The results for V_W^* show the effect of the 'smoothing' terms alone in equations (11)–(13), since the 'mixing' terms involving V_N are in this case zero. It can be seen that the sharp flow onset is spread over an interval of essentially one experiment cycle time. Conversely, the values of V_N^* arise solely from the 'mixing' terms in this case, and are seen to be very small, as discussed above. In fact the largest absolute value of V_N^* occurring in this case is $V(\tan\phi)/4$ (which for $\phi = 12°$ is just 0.053 V), which occurs when the onset takes place during a beam swing. Consequently, while the flow vectors deduced in the vicinity of the flow change do not have the correct magnitude, they nevertheless do not deviate markedly from the westward direction.

Much larger effects are observed in Fig. 2b, which shows results for the onset of pure northward flow ($V_N = V$, $V_W = 0$). The format of the figure is the same as Fig. 2a, except that for reasons of clarity we have omitted the horizontal bars which indicate the radar dwell periods in the left hand diagram. These are identical to those shown in the corresponding diagrams in Fig. 2a. The results for V_N^* (dashed lines) show a simple 'smoothing' of the flow onset, which is in fact identical to that occuring in the V_W^* component in Fig. 2a. This arises because the effects of 'smoothing' are identical in the two flow components, while the 'mixing' terms are zero in V_W^* in Fig. 2a and also in V_N^* in Fig. 2b [see equations (11)–(13)]. The results for V_W^* in Fig. 2b, however, show that large spurious east–west flow components are now produced (solely by the 'mixing' terms) with magnitudes comparable to V_N^*, thus leading to large angular deflections of the deduced flow vectors. The form of the deflections is highly sensitive to the phase of the beam-swinging cycle at which the flow change takes place. The largest absolute value of V_W^* is $V(\cot\phi)/4$ (which for the parameters of Fig. 2 is 1.18 V), which again occurs when the flow change takes place during a beam swing.

Figure 2c finally shows an intermediate case, for a flow directed 60° west of north, such that the normalized flow components after onset are $V_N/V = 0.5$ and $V_W/V = 0.87$. The major effect seen in V_N^* is again the 'smoothing' of the change (the 'mixing' terms producing only a small effect in this component, as in Figure 2a), while V_W^* shows the combined effect of both 'smoothing' and 'mixing', which can lead to a variety of responses depending on the phase of the experiment cycle at the time of the flow change. In the general case the vectors deduced are just the vector sum of those shown for the onset of pure westward and pure northward flow in Figs. 2a and 2b, appropriately adjusted to the sign and magnitude of V_W and V_N.

3. EFFECT ON CROSS-CORRELATION STUDIES

In the previous section we established the form of the effects produced by sudden changes in ionospheric flow on vector data derived from beam-swinging radar experiments, such as EISCAT 'Polar'. In this section we will now consider whether the spurious vectors produced in the vicinity of these changes can lead to any systematic errors in statistical studies of the ionospheric flow response time to changes, e.g. in the IMF. In particular, in view of the results obtained by Etemadi *et al.* (1988), it is germane to consider whether artificial timing differences could be introduced between the flow components parallel and perpendicular to the bisector of the radar beams (i.e. V_N and V_W, respectively). From the results already presented in Fig. 2 it is clear that for beam geometries

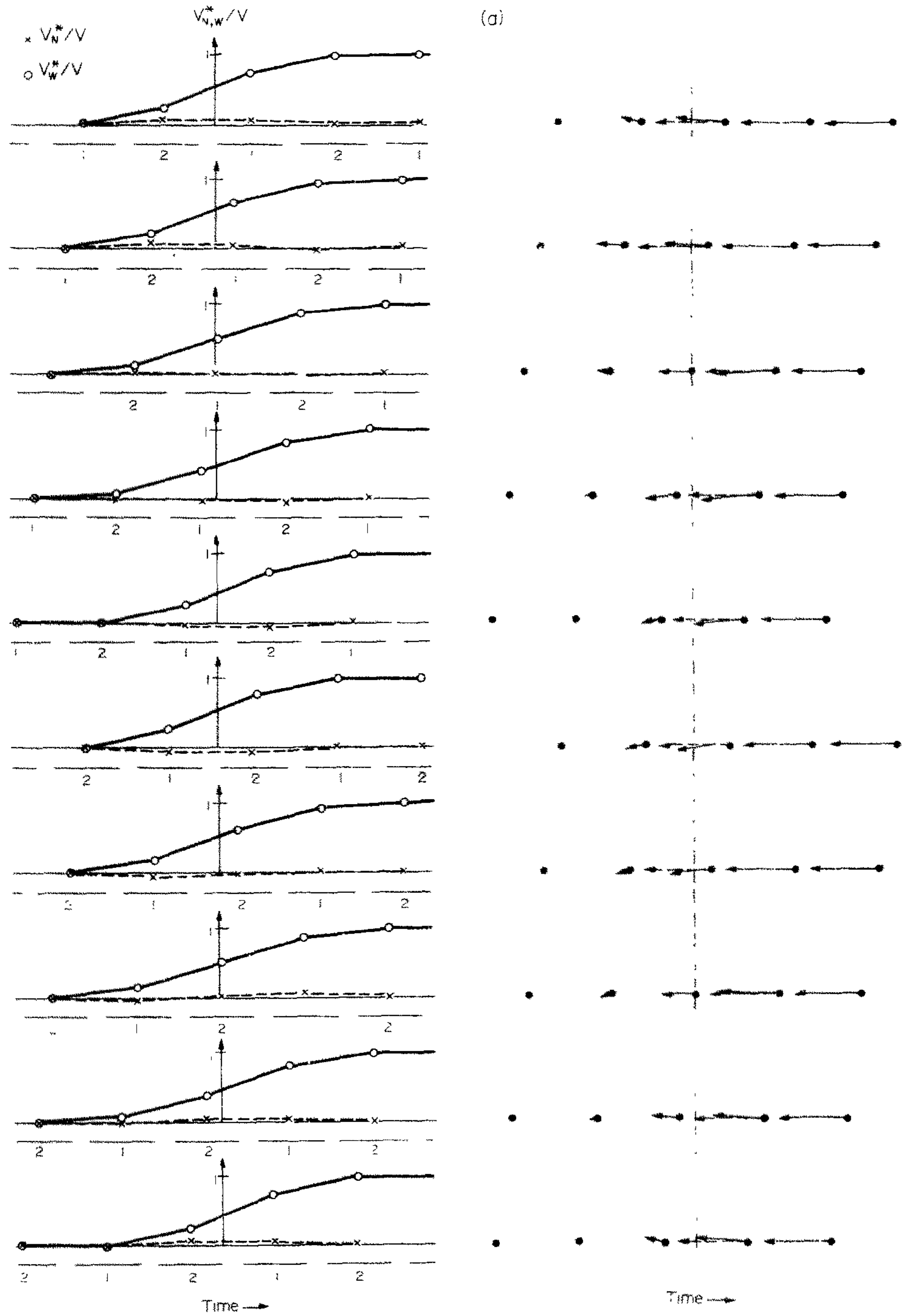

Fig. 2a. The left hand side of the figure shows graphs of V_W^*/V circles joined by solid lines) and V_N^*/V (crosses joined by dashed lines) vs. time, for an abrupt onset of westward flow (perpendicular to the bisector of the radar dwell directions) of magnitude V occurring at various phases of the beam-swinging experiment cycle. The flow onset occurs at the centre of each graph (marked by the vertical axis), while the radar dwells and pointing directions are indicated by the horizontal lines under each graph. The tickmarks along the horizontal axes are at intervals of one experiment half-cycle (duration $T_D + T_S$ with $T_D = 4T_S$). On the right hand side of the diagram the same information is presented as flow vectors, with the flow onset being marked by the vertical dashed line. The vectors are drawn from the middle of the dwell on which they are centred, as for the V_N^* and V_W^* values on the left. The dashed arrows show the actual ionospheric flow (if any), for purposes of comparison.

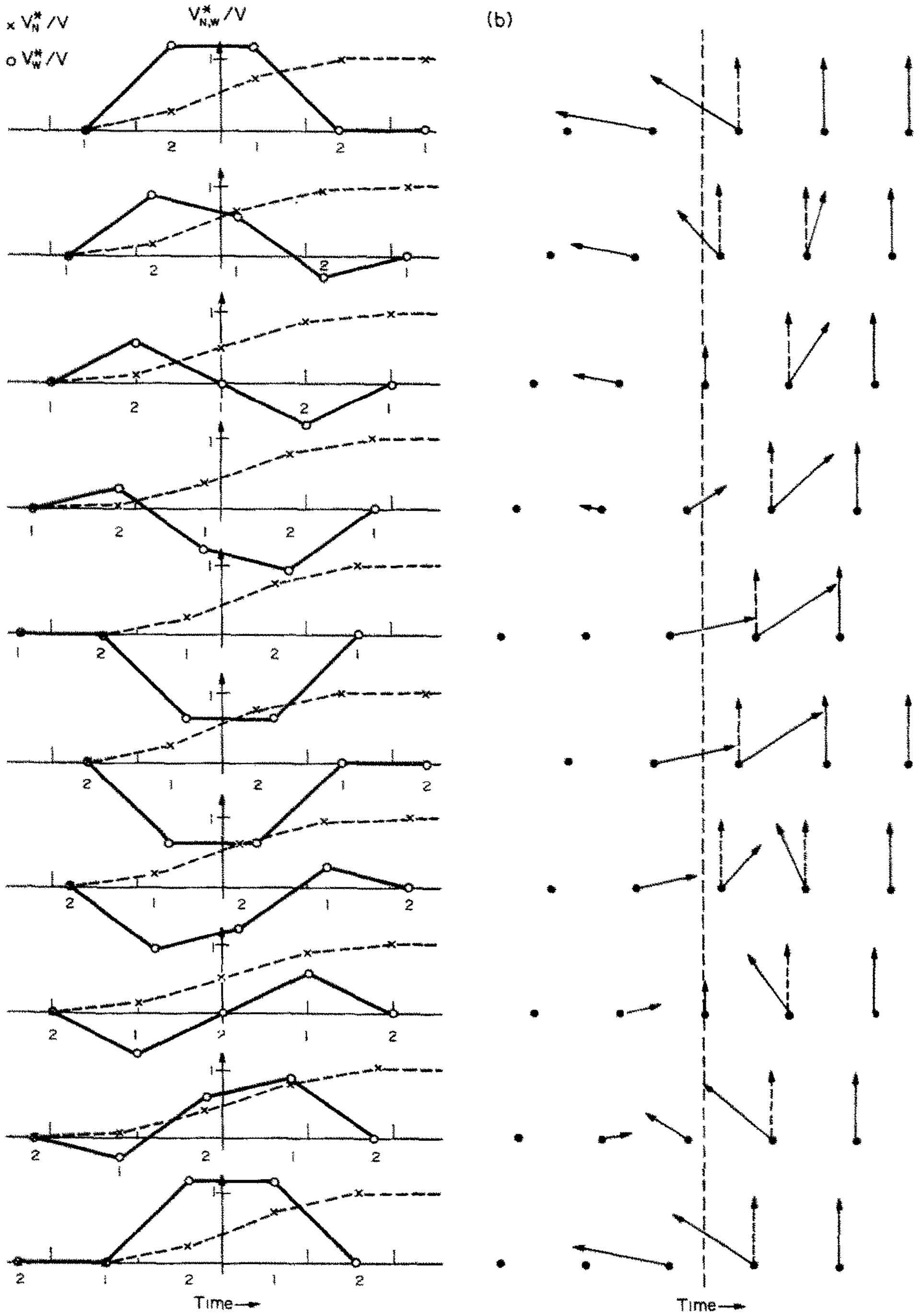

Fig. 2b. As for Fig. 2a, except for the onset of pure northward flow of magnitude V parallel to the bisector of the two radar pointing directions. The horizontal bars marking the dwell durations have, however, been omitted for clarity (they are identical to those in Fig. 2a), only the dwell directions are given.

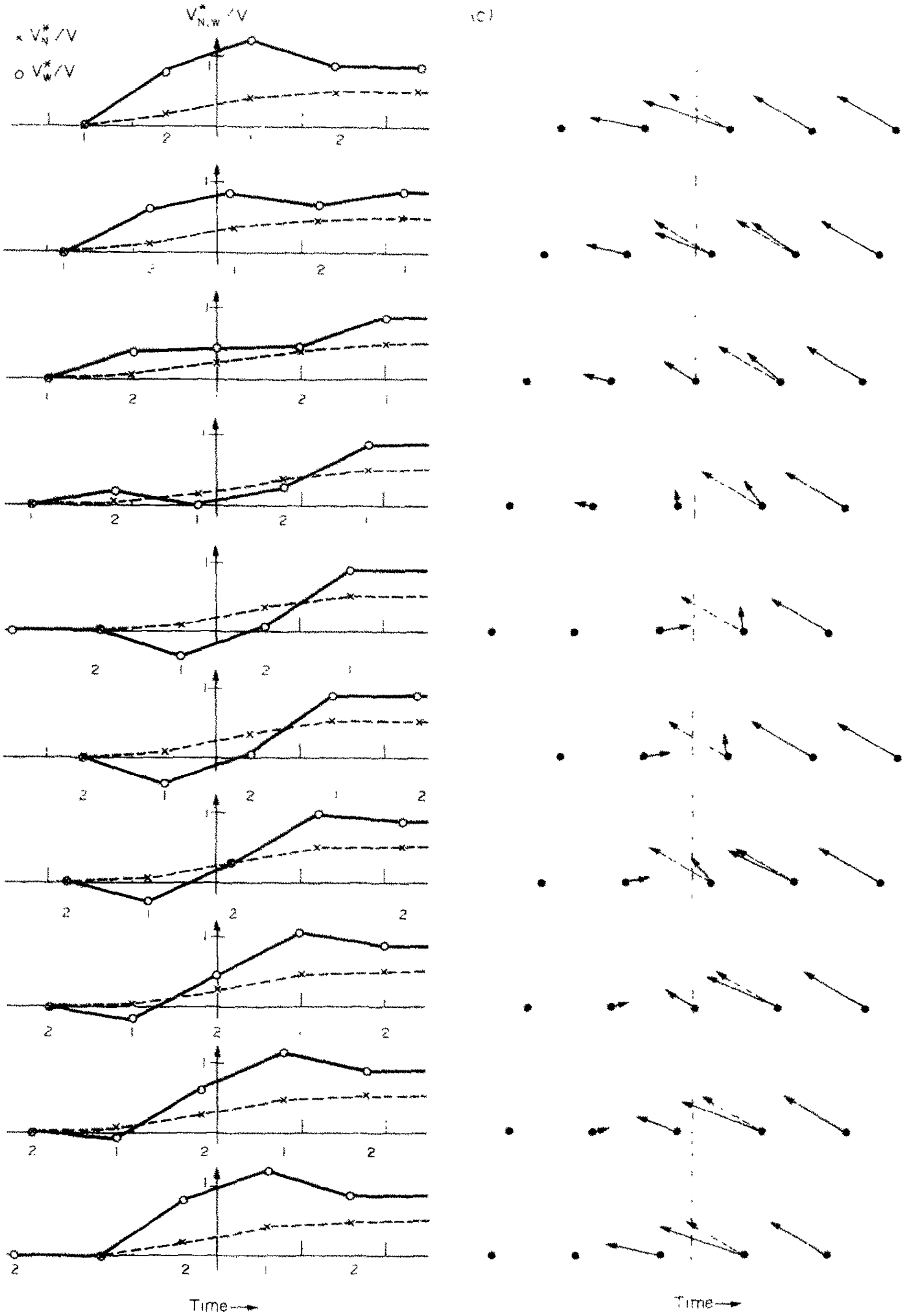

Fig. 2c. As for Fig. 2b, except for the onset of north-westward flow (directed 60° west of north) of magnitude V.

such as 'Polar', where the angular deflections are small about their bisector, little effect is produced in the component along the bisector (north), while spurious shifts can be produced in the transverse component (west), whose form depends on the phase of the radar experiment cycle at the time of the flow change. The first graph of Fig. 2c represents an example where one might conclude that the onset of westward flow occurs earlier than is actually the case, preceeding the onset of northward flow. Conversely, in the fourth and fifth graphs of this figure the westward flow is apprarently delayed compared with the northward component, and occurs later than the true onset. These displacements are, however, limited to half the radar experiment cycle time in either direction (2.5 min in the case of 'Polar').

The difference in the behaviour of the two flow components discussed above arises from the different significance of the 'smoothing' and 'mixing' terms in the two cases. When the angle ϕ between the radar pointing directions is small, the 'mixing' terms are negligible in V_N^*, such that its onset time (taken, e.g. from the point where V_N^* first reaches half its final value) is not changed significantly from the true value. However, the 'smoothing' and 'mixing' terms are generally of equal significance in V_W^* under these conditions, and their mutual interaction can then lead to apparent shifts of the flow onset time. In any statistical study, however, large quantities of data are considered which involve many abrupt changes in flow. Since these changes will take place at random times relative to the radar experiment cycle we may then expect that the effects of 'mixing' will average out, leaving the effects of 'smoothing' alone. Since 'smoothing' effects the two flow components in identical ways we therefore conclude that on average no artificial separation of the response times of the two flow components will result. Further, since the average 'smoothing' effect is symmetrical about the actual onset time (in the sense that the deviation of the deduced values from the actual values are identical for equal times on either side of the onset time) we may also conclude that the response times derived from such data will also suffer no systematic effects. In particular, the lag position of cross-correlation peaks used to determine response times will undergo no systematic shifts from these effects.

In order to illustrate the veracity of these conclusions let us consider [with ETEMADI *et al.* (1988)] the results of an analysis in which beam-swinging ionospheric velocity data are cross-correlated with IMF B_Z values measured simultaneously in the solar wind. In the idealized calculation performed here we assume a B_Z profile which is a square wave with period

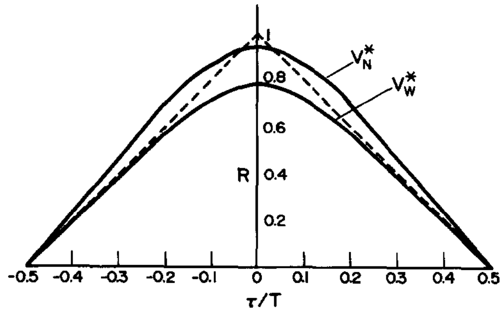

Fig. 3. Cross-correlation coefficient R vs. time lag τ between IMF B_S and V_N^*, and V_W^*, for idealized spacecraft-radar data. It is assumed that in each experiment B_S periodically switches between values of zero and b, remaining at each value for equal intervals of time T, and that (for simplicity) the ionospheric flow responds with zero time delay. The flow is taken to be zero when $B_S = 0$, and to have a magnitude V directed at angle 60° west of north when $B_S = b$. The dashed lines show the R that would result from a perfect measurement of flow, while the solid lines show R for the beam-swinging data taken over many B_S cycles, with all phases of the experiment cycle relative to the onset time being considered equally likely. The parameters corresponding to this plot are $T = 8T_D$, $T_D = 4T_S$ and $\phi = 12°$.

$2T$, such that B_Z cycles between values of $+b$ and $-b$ and changes sign after every interval T. The southward component of the IMF, B_S (defined such that $B_S = \text{mod}\,(B_Z)$ when B_Z is negative, and $B_S = 0$ when B_Z is positive), then cycles between values of zero and $+b$ at intervals of time T. We assume that the ionospheric flow is zero when B_S is zero, but jumps to speed V at some angle relative to north when $B_S = b$, with (for simplicity) no time delay. If we cross-correlate B_S with the flow components V_N and V_W actually occurring in the ionosphere, the correlation coefficient R as a function of time lag τ between the data sets is then the triangular function:

$$R = (1-2\,\text{mod}\,(\tau)/T),$$

which is shown as a function of τ/T in Fig. 3 (dashed line). Note that R peaks at the value 1 at zero time delay, as may have been expected. The introduction of a constant ionospheric response delay into the calculation would simply result in a translation of the curve along the horizontal axis through an interval equal to the delay.

Lengthy but straightforward algebra which is not reproduced here then yields expressions for the cross-correlation coefficients appropriate to the flow components V_N^* and V_W^* which would be deduced from the beam-swinging radar data. In the analysis it was assumed that all phases of the radar cycle are equally represented at the flow changes, when taken over many B_S cycles (or at least over many separate experiments with random initial conditions), and account was taken not only of the average 'smoothing' of the flow changes, but also of the enhanced scatter in the flow data resulting from the 'mixing' terms. The latter effect is responsible for lowering the value of R corresponding to $V_{\parallel}^*$ compared with that for V_N^* (both peaking at values less than unity), as shown by the solid curves in Fig. 3. These were computed using the parameters $\phi = 12^\circ$ and $T_S = 4T_D$, as before, together with a flow direction after onset of 60° west of north (Fig. 2c), and $T = 8T_D$ (this latter implying that the changes in B_Z occur every 16 min if $T_D = 2$ min). It can be seen that the peak in R is lowered and broadened by the effects considered here. However, the most significant result is that the cross-correlation peaks for both V_N^* and $V_{\parallel}^*$ remain at zero lag. This result illustrates the general conclusion reached above that the spurious flow vectors produced in beam-swinging velocity data by sudden changes in a uniform ionospheric flow produce no systematic effect in the derived response times in either the flow components parallel or transverse to the bisector of the radar pointing directions.

4. SUMMARY AND DISCUSSION OF RELATED EFFECTS

In the last two sections we have analysed the effects produced in the flow vectors deduced from an idealized beam-swinging radar experiment by sudden changes in a uniform ionospheric flow (in which northward and westward flow components vary together), which take place on time scales short compared with the experiment cycle time. We note that our assumption of abrupt changes represents a 'worst case' with regard to these effects, which will diminish and disappear as the time scale for flow change increases to become comparable with and longer than the experiment cycle time. It has been shown that the effects introduced by beam-swinging can be divided into two parts, termed 'smoothing' and 'mixing'. 'Smoothing' acts identically on the flow components parallel and perpendicular to the bisector of the radar beams, spreading the sharp flow changes over intervals of approximately half a cycle of the radar experiment on either side of the actual change. The spreading is symmetrical about the latter time, such that, e.g. at the actual time of the flow onset the deduced vector is just one half of the final value. 'Mixing' describes the effect whereby a change in one flow component introduces a spurious temporary perturbation in the other. The form of the effect produced depends on the phase of the radar experiment at which the flow change takes place, and averages to zero when taken over many changes occurring at random phases, then leaving only the effect of 'smoothing'.

The magnitude of the 'mixing' terms is not only proportional to the magnitude of the flow components concerned, but also depends on the angle between the radar pointing directions. When this angle is small (compared with a right angle), as will generally be the case in practical experiments such as 'Polar', the effect of 'mixing' is negligible compared with 'smoothing' in the flow component parallel to the bisector of the radar beams (north). Consequently, in view of the symmetry of the 'smoothing' effect noted above, the onset time of this component (taken from the point where the flow speed reaches half its final value) is not significantly changed. However, large 'mixing' effects then do occur in the flow component perpendicular to the bisector of the radar beams. In combination with the effects of 'smoothing' these can then lead in individual cases, to apparent shifts of the onset time in this component, by up to half an experiment cycle time in either direction relative to the true onset time. However, in statistical studies these effects will average to zero over many flow changes occurring at random phases of the experiment cycle, such as in the study of ETEMADI et al. (1988), where data from several days were combined together in extended MLT bins. The only effect of 'mixing' is then to lower the correlation coefficients associated with the perpendicular flow component relative to the parallel component, due to the larger scatter introduced into the data. These results therefore show that when sharp changes take place in a uniform flow in which the northward and westward flow components vary in concert, no spurious systematic shifts will occur in the response times derived for either flow component due to 'mixing'. In addition, because of the symmetry of the remaining 'smoothing' effects, no systematic shifts are introduced into the response times due to this effect either.

It will be recalled from the introduction, however, that in their cross-correlation study of 'Polar' flows, ETEMADI et al. (1988) did in fact find a systematically longer response time to IMF B_Z changes for the northward component of flow in the dusk auroral zone flow cell, compared with the westward component. In the noon–mid-afternoon sector, for example, where the flow response in the 'Polar' field-of-view is largest, the response time was found to be ~7 min for v_N, and ~4 min for $v_{\parallel}$, the difference thus being comparable to a half cycle time of the 'Polar' experiment (2.5 min). The above analysis shows that this difference cannot be a simple consequence of rapid flow changes leading to spurious vectors. We therefore need now to consider what effects can be produced by the other two major assumptions in the beam-swinging algorithm, i.e. the assumption of zero longitudinal gradient in the flow, and the assumption that the flow along the field is zero. Again, we first focus on the question of whether the effects which result from these assumptions can produce systematic shifts in flow response times in the case where the field-perpendicular flow components, in fact, vary in concert with each other.

Let us therefore consider the effect of a longitudinal gradient in a steady flow, such that the flow components in direction 1 (v_{N1}, v_{W1}) differ from those in direction 2 (v_{N2}, v_{W2}). When the corresponding line-of-sight components given by (1) and (2) are then substituted into (3) and (4), the flow vector derived from the beam-swinging algorithm is given by:

$$v'_N = \tfrac{1}{2}(v_{N1}+v_{N2})+\tfrac{1}{2}(v_{W1}-v_{W2})\tan\phi \quad (15a)$$

$$v'_W = \tfrac{1}{2}(v_{W1}+v_{W2})+\tfrac{1}{2}(v_{N1}-v_{N2})\cot\phi. \quad (15b)$$

In effect, (v'_N, v'_W) is the uniform horizontal flow that would give rise to the same line-of-sight flow components along the two beam directions as does the actual non-uniform flow. The derived flow components consist of two terms analogous to the 'smoothing' and 'mixing' terms in the above temporal analysis, the first being the mean of the corresponding flow components in the two pointing directions, while the second gives spurious flow components in one direction due to longitudinal gradients in the other. If the flow then changes rapidly from one non-uniform pattern to another, with northward and westward components changing at the same time, such that the deduced uniform flow changes from $\mathbf{v}'$ to $\mathbf{v}'+\mathbf{V}'$, then the flow vectors determined during the change are simply given by (10)–(14) with the flow components on the rhs of these expressions simply being replaced by their primed equivalents. A discussion similar to that in Section 3 then follows, from which it is concluded that rapid changes in a non-uniform flow will also not produce spurious differences in the response times of the derived northward and westward components. Since, by hypothesis, both northward and westward flow components vary together, it follows that no systematic response time shifts can be introduced into either flow component by the spatial 'mixing' effect, irrespective of the fact that this effect results in the deduced flow components themselves being in error.

We now turn to consider the effect of field-aligned flows. Although the above analyses assumed for simplicity that the radar pointing directions lay in the plane of the flow, and hence were orthogonal to the magnetic field, in practice this will not be the case for incoherent scatter radar experiments, particularly in order to avoid the possibility of strong coherent echoes. In the 'Polar' experiment the beams in fact lie at an angle of $\sim 73.5°$ relative to the field in the nearer gates, and hence there is some sensitivity to parallel flows. If it is then assumed that the parallel flow is zero, as in the analysis of 'Polar' data, then spurious additional northward and westward flow components will be derived, given by:

$$\Delta v'_N = \frac{(v_{\parallel 1}+v_{\parallel 2})}{2\cos\phi}\tan\delta \quad (16a)$$

$$\Delta v'_W = \frac{(v_{\parallel 1}-v_{\parallel 2})}{2\sin\phi}\tan\delta, \quad (16b)$$

where $v_{\parallel 1}$ and $v_{\parallel 2}$ are the parallel flows in the two pointing directions (positive upwards), and δ is the angle between the radar beam and the field normal (16.5° for 'Polar'), assumed equal in the two directions. If the parallel flows occur in concert with the field perpendicular flows (i.e. they have the same response time to changes in the IMF) then again they will have no effect on response times derived from cross-correlation studies, for the same reason that longitudinal gradients have no effect on the response times under these circumstances. However, if the changes in the parallel flows (which could be due, e.g. to frictional heating) tend to lag behind changes in perpendicular flows, as seems possible, then spurious variations in the field-perpendicular flow would be derived which could clearly influence the response times deduced. The importance of these effects then depends on the magnitudes of the spurious flow components $\Delta v'_N$ and $\Delta v'_W$ relative to the field-perpendicular components in these directions. Results recently presented by WINSER *et al.* (1986) indicate that the upward parallel flow in the auroral zone *F*-region is usually limited to values below ~ 70 m s^{-1}, and even when strong outflows are observed at high altitudes (e.g. several hundred m s^{-1} at 500 km and above), the field-aligned flow at altitudes corresponding to the lower 'Polar' gates ($\sim$200–300 km) remains at or below ~ 100 m s^{-1} (WINSER *et al.*, 1988). If we then take, e.g. $v_{\parallel 2} \simeq 100$ m s^{-1} and $v_{\parallel 2} \simeq 50$ m s^{-1}, such that a large gradient in parallel flow also occurs between the pointing directions, together with $\delta = 16.5°$ and $\phi = 11.6°$, we find $\Delta v'_N \simeq 22.7$ m s^{-1} and $\Delta v'_W \simeq 36.8$ m s^{-1}. These 'maximum' values are more than an order of magnitude less than those typical of field-perpendicular flows in the dusk auroral zone, and consequently will not produce significant effects in either the derived perpendicular flow vectors or response times derived therefrom.

On the basis of the above results we therefore conclude that the effects on beam-swinging velocity vectors of rapid flow variations, longitudinal flow gradients and parallel flows will produce no significant systematic shifts in the response times about their true values for either the northward or westward flow components, in the case where these components in fact vary with the same response time. We therefore also conclude that the difference between the response times of these flow components found by ETEMADI et al. (1988) must be geophysical in origin, indicating, e.g. that following a southward turn of the IMF, westward flows tend to appear first in the post-noon dusk flow cell, turning towards the north-west a few minutes later. Precisely this type of response has, in fact, been reported for one well-studied afternoon 'switch-on' flow event by WILLIS et al. (1986) and TODD et al. (1988). If this effect can be represented simply as separate response times for the two flow components (the northward component having a fixed delay relative to the westward component), then it is again evident that the spurious vectors arising from rapid changes in the flow components will not produce any systematic shifts in the response times about their true values, determined separately for the northward and westward components. This follows from the fact that the mixing terms always average to zero when taken over random flow onset times relative to the experiment cycle, irrespective of when they occur, while the 'smoothing' effect, of course, remains symmetric about the actual flow onset time, separately for each component. Parallel flows are again likely to produce little effect, for the same reasons as given above. However, it is clearly possible for the effects associated with longitudinal gradients to affect the derived response times in this case, since a spurious change in each flow component will then occur when the other component changes due to spatial 'mixing'. This effect will be present independent of whether the flow changes take place rapidly or slowly, relative to the beam-swinging cycle time. The magnitude of the effect may be estimated on the basis of typical afternoon dusk cell flows of $v_N \simeq 200$ m s^{-1} and $v_W = 600$ m s^{-1} [see, e.g. fig. 4c of ETEMADI et al. (1988)], and assuming that the (systematic) difference between the dusk cell flow components in the two 'Polar' pointing directions in a given gate might typically be ~10%. The latter estimate follows from noting that at 'Polar' latitudes the large-scale dusk cell flows vary on spatial scales of a few thousand km, compared with a longitudinal distance of ~250 km between the lower gates in the two 'Polar' pointing directions. The second terms in equations (15) then give a spurious northward flow component of 6 m s^{-1}, and a spurious westward flow component of 47 m s^{-1}. The effect on v_W is therefore certainly much greater than on v_N, but is still less than 10% of the typical mean flow in the westward direction. It is unlikely that an effect of this magnitude will substantially influence response times determined from cross-correlation analysis.

5. CONCLUSIONS

In this paper we have made a detailed examination of the effect of rapid changes in a uniform flow on the velocity vectors deduced from a radar beam-swinging algorithm, such as that used to analyse the results from the EISCAT 'Polar' experiment. If the pointing directions of the radar beams are displaced by only a small angle about their bisector (north), as will often be the case (±12° for 'Polar'), then large spurious temporary variations can be produced in the flow component transverse to the bisector (west), which can shift the apparent time of the change in this component by up to half an experiment cycle time in either direction (±2.5 min for 'Polar'). The onset time of the northward flow component (judged, e.g. from the time when this component reaches half its final value as a result of the 'smoothing' effect) is little changed. However, when taken over many flow changes occurring at random times relative to the beam-swinging cycle, the effects in the transverse component average to zero. Consequently, if the northward and westward flow components do indeed vary in concert with each other, e.g. in response to variations in the IMF, then no systematic spurious shifts in the response times will occur in either flow component due to these effects.

Still assuming that the field-perpendicular flow components vary in concert with each other, we then considered whether systematic response time shifts could be produced by either of the other two main assumptions which are used in the beam-swinging algorithm, i.e. the neglect of longitudinal gradients and of parallel flows. Our results show that rapid variations in a flow with longitudinal gradients again produces no such systematic shift in the response time in this case. The neglect of parallel flows, on the other hand, while in principle able to influence response times if the parallel flows occur with a temporal shift relative to the field-perpendicular flows, will usually produce only a small effect on the latter in an experiment such as 'Polar' where the beam directions are near to orthogonal to the magnetic field.

We therefore conclude that the separation of the northward and westward dusk cell flow response times to changes in IMF B_z, which was found by ETEMADI et al. (1988) from analysis of 'Polar' beam-swinging data, is not an artefact of the beam-swinging algorithm, but arises from geophysical origins.

We consequently considered a flow in which the northward and westward components were assumed to vary with different response times, and again considered whether spurious effects could be produced by the assumptions employed in the beam-swinging algorithm. Our results show that rapid changes in such a flow, assumed uniform in longitude, do not produce any systematic shifts in the response times deduced from either flow component. Averaged over many changes occurring at random times relative to the experiment cycle time, the correct response times will be deduced for each component separately. The effect of parallel flows remain small for the same reasons as above. However, any systematic longitudinal gradient in the perpendicular flow can now affect the response times deduced, because a change in one flow component will produce a spurious enduring change in the other. This effect is, of course, quite independent of the time scale of the flow changes relative to the beam-swinging cycle time. In the case where the radar beams are displaced by only a small angle about magnetic north, the effect on the northward flow component will generally be very small, such that the response time of this flow component is unlikely to be affected. The effect on the westward flow component will generally be much larger, but still small compared with true geophysical effects in that component, provided that the longitudinal difference in the northward flow components between the two radar pointing directions is at the 10–20% level or less, as should generally be the case.

Overall, therefore, the conclusions reached in this study give us additional confidence that the response time results derived by ETEMADI *et al.* (1988) represent true reflections of geophysical conditions and are unlikely to be significantly affected by artefacts associated with the beam-swinging algorithm. Not only is the algorithm incapable of producing spurious systematic shifts of the flow response time between northward and westward components if one in fact does not exist, but it will also give the correct response times for each component separately, should such a shift arise from geophysical effects, at least under usual circumstances.

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REFERENCES

ALCAYDE D., CAUDAL G. and FONTANARI J. 1986 *J. geophys. Res.* **91,** 233.
BURCH J. L., REIFF P. H., MENIETTI J. D., HEELIS R. A., HANSON W. B., SHAWHAN S. D., SHELLEY E. G., SUGIURA M., WEIMER D. R. and WINNINGHAM J. D. 1985 *J. geophys. Res.* **90,** 1577.
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 *Geophys. Res. Lett.* **11,** 891.
DOUPNIK J. R., BANKS P. M., BARON M. J., RINO C. L. and PETRICEKS J. 1972 *J. geophys. Res.* **77,** 4268.
ETEMADI A., COWLEY S. W. H., LOCKWOOD M., BROMAGE B. J. I., WILLIS D. M. and LUHR H. 1988 *Planet. Space Sci.* **36,** 471.
EVANS J. V., HOLT J. M., OLIVER W. L. and WAND R. H. 1980 *J. geophys. Res.* **85,** 41.
VAN EYKEN A. P., RISHBETH H., WILLIS D. M. and COWLEY S. W. H. 1984 *J. atmos. terr. Phys.* **46,** 635.
FONTAINE D., PERRAUT S., ALCAYDE D., CAUDAL G. and HIGEL B. 1986 *J. atmos. terr. Phys.* **48,** 973.
FOSTER J. C. 1983 *J. geophys. Res.* **88,** 981.
FOSTER J. C., DOUPNIK J. R. and STILES G. S. 1981 *J. geophys. Res.* **86,** 11357.
FOSTER J. C., BANKS P. M. and DOUPNIK J. R. 1982 *J. geophys. Res.* **87,** 7513.
FOSTER J. C. and DOUPNIK J. R. 1984 *J. geophys. Res.* **89,** 9107.
HEELIS R. A. 1984 *J. geophys. Res.* **89,** 2873.
HEPPNER J. P. 1977 *J. geophys. Res.* **82,** 1115.
HEPPNER J. P. and MAYNARD N. C. 1987 *J. geophys. Res.* **92,** 4467.
JORGENSEN T. S., FRIIS-CRISTENSEN E., WICKWAR V. B., KELLY J. D., CLAUER C. R. and BANKS P. M. 1984 *Geophys. Res. Lett.* **11,** 887.

LOCKWOOD M., VAN EYKEN A. P., BROMAGE B. J. I., WILLIS D. M. and COWLEY S. W. H. 1986 *Geophys. Res. Lett.* **13**, 72.

OLIVER W. L., HOLT J. M., WAND R. H. and EVANS J. V. 1983 *J. geophys. Res.* **88**, 5505.

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 *Nature* **318**, 451

TODD H., COWLEY S. W. H., ETEMADI A., BROMAGE B. J. I., LOCKWOOD M., WILLIS D. M. and LUHR H. 1988 *J. atmos. terr. Phys.* **50**, 423.

WICKWAR V. B., KELLY J. D., DE LA BEAUJARDIERE O., LEGER C. A., STEENSTRUP F. and DAWSON C. H. 1984 *Geophys. Res. Lett.* **11**, 883.

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 *J. atmos. terr. Phys.* **48**, 987.

WINSER K. J., JONES G. O. L. and WILLIAMS P. J. S. 1986 *J. atmos. terr. Phys.* **48**, 893

WINSER K. J., JONES G. O. L., WILLIAMS P. J. S. and LOCKWOOD M. 1988 *Adv. Space Res.* (in press).