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A Comparison of Model Predictions for Plasma Convection in the Northern and Southern Polar Regions

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Abstract. We have presented model calculations to show how the plasma flow distributions in the northern and southern polar regions differ when viewed from a geographic inertial frame. This reference frame was selected because it is the natural frame for geophysical plasma flow measurements, there being well-known velocity corrections for either satellite or ground-based observations. Although the magnetic invariant latitude, magnetic local time reference frame is better suited to studying magnetospheric processes, a transformation from the geographic inertial frame to this magnetic frame requires both a spatial and velocity transformation, and since the latter correction has generally been neglected, we prefer to present our results in the geographic inertial frame. However, we also present some of our results in the magnetic frame, taking account of the complete transformation. Our convection model includes the offset between the geographic and geomagnetic poles, the tendency of plasma to corotate about the geographic poles, and a dawn/dusk magnetospheric electric field mapped to a circle about a center offset by 5° in the antisunward direction from the magnetic pole. We considered both uniform and asymmetric magnetospheric electric field configurations. Our asymmetric electric field distribution contained an enhanced field in the dawnside northern hemisphere in conjunction with an enhanced field in the duskside southern hemisphere. From our study we have found the following: (1) In the geographic inertial frame the plasma flow patterns in both hemispheres exhibit significant variations with universal time because of the relative motion of the geomagnetic and geographic poles. (2) This universal time variation is greater in the southern polar region than in the northern polar region because of the greater displacement between the geomagnetic and geographic poles. (3) For the case of a uniform magnetospheric electric field the universal time dependence of the plasma flow distributions in the two hemispheres is similar, but there is a phase shift of about half a day between them. (4) For the case of an asymmetric magnetospheric electric field this half-day phase shift is still noticeable, but there are significant differences between northern and southern hemisphere convection patterns. (5) The transformation of plasma convection patterns from the geographic inertial to the geomagnetic quasi-inertial frame results in the same convection pattern for both hemispheres for the case of a uniform magnetospheric electric field, but results in different convection patterns for the two hemispheres for the more common case of an asymmetric electric field configuration. (6) Because the magnetospheric electric field distributions in the northern and southern polar regions are generally asymmetric, erroneous conclusions can be drawn about plasma convection patterns if data taken along satellite tracks from the northern and southern polar regions are overlaid. This is true whether the overlaying is done in the geomagnetic quasi-inertial frame or the geographic inertial frame.

Introduction

The complex signatures observed in the high-latitude ionospheres associated with the plasma density, plasma drift, and currents are known to be related to the magnetospheric electric field which maps into these high-latitude regions. Sojka et al. [1979a] modeled the result of mapping a dawn-dusk, cross-tail magnetospheric electric field into the ionosphere about the geomagnetic pole, which was offset by 11.4° from the geographic pole. In addition, the tendency of the ionospheric plasma to corotate about the geographic pole was included. This simple model led to a number of rather important conclusions: (1) The plasma convection pattern observed either by satellites or from the ground shows a UT dependence because of the motion of the geomagnetic pole about the geographic pole. (2) The UT variation of the plasma flow pattern occurs on a time scale that is comparable to satellite orbital periods and that is much less than typical plasma convection flow times over the polar cap. (3) In the geographic inertial frame the main region of very low speed flow is not centered at 1800 local time (LT) but moves from about 1300 to 2300 LT during the course of a day. (4) In the geographic inertial frame a throatlike feature appears at certain universal times owing to the relative motion of the geographic and geomagnetic poles. (5) For magnetospheric cross-tail potentials typical of quiet conditions a region of low-speed flow appears in the dawn polar cap sector; this feature is also UT dependent.

In order to determine the extent to which our simple convection model could account for specific observations, plasma convection patterns predicted by our model were compared to those observed simultaneously at Chatanika, Alaska, and Millstone Hill, Massachusetts [Sojka et al., 1980]. These two incoherent scatter facilities operated over the same period of 4 days in June 1978 and provided data sets which were averaged to 24 hours in order to minimize the effects of individual substorms. As a result of the comparison an additional feature was added to the model in order to improve the agreement with the data. Instead of being mapped about the geomagnetic pole the magnetospheric electric field was mapped about a point 5° from the geomagnetic pole along the midnight magnetic meridian, as had been suggested earlier by others [cf. Feldstein, 1963; Meng et al., 1977; Meng, 1979]. With this modification, good agreement was obtained between our simple convection model and the different diurnal patterns observed simultaneously at Chatanika and Millstone Hill.

The latitudinal coverage from both of these sites is limited: very little data are obtained from the polar cap. Auroral latitudes are extensively covered by Chatanika and Millstone Hill, but the mapping of the magnetospheric electric field into this region of the ionosphere is severely modified by complex current systems. In the polar cap the mapping is more direct, which results in plasma flow distributions that are more easily related to the magnetospheric electric field. To study this polar region in more detail, Sojka et al. [1979b] calculated diurnal patterns of plasma drift velocities which would be observed by European Incoherent Scatter facility (EISCAT) and by a possible incoherent scatter radar site at Sondre Stromfjord, Greenland. Four different magnetospheric electric field configurations were considered, including a constant cross-tail electric field, asymmetric electric fields with enhancements on the dawnside and duskside of the polar cap, and an electric field pattern that is not aligned parallel to the noon-midnight magnetic meridian. The different electric field configurations were shown to produce signatures which are easy to identify in the plasma convection pattern; hence it should be possible to obtain valuable information on the magnetospheric electric field directly from convection patterns. The variation of the latitude defining the polar region boundary enables the area into which the magnetospheric electric field is mapped to be defined, while detailed measurements of the flow pattern in this polar region would also indicate how the magnetospheric electric

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field is distributed. Measuring the local times at which flow reversal regions occur would differentiate between the relative importance of interplanetary magnetic field effects and a more general rotation of the electric field in the ionosphere.

Satellites in high inclination orbits do cross the polar regions. However, owing to the characteristics of such orbits, they obtain data over only limited times and locations, which makes two-dimensional comparisons with model predictions difficult without extensive long-term averaging. On the other hand, satellites do have the advantage of being able to observe alternately the northern and southern hemispheres; however, interpretation of these data requires an understanding of the inherent differences between plasma convection patterns in the two hemispheres. In this study we focus attention on the differences expected to be found in comparing plasma convection patterns in the northern and southern hemispheres. The differences due to different offsets between the geographic and geomagnetic poles [Bond, 1968] are studied by considering a quiet time uniform magnetospheric electric field model. The antisymmetric merging of the interplanetary magnetic field with the geomagnetic field in the northern and southern hemispheres [Heppner, 1973] is also considered by using a model of the magnetospheric electric field which contains enhanced flow in the dawnside northern hemisphere in conjunction with enhanced flow in the duskside southern hemisphere.

The comparison of corresponding northern and southern hemisphere convection patterns is done in a geographic inertial frame because it is a natural frame for geophysical plasma flow measurements, there being well-known velocity corrections for either satellite or ground-based observations. However, we also discuss the form of the plasma flow patterns in a magnetic quasi-inertial frame, which is defined such that the z axis is parallel to the dipole axis and the sun lies in the x-z plane. This latter reference frame is closely related to the commonly used invariant latitude, magnetic local time (MLT) reference frame. The transformation of the plasma flow pattern between the geographic inertial frame and the magnetic quasi-inertial frame involves both a spatial and velocity transformation. To emphasize the effect of the velocity transformation we compare plasma flow velocities along a simulated satellite trajectory in both the geographic inertial frame and the magnetic quasi-inertial frame for alternate traversals of the northern and southern polar caps.

Plasma Convection Model

The plasma convection model that we used previously consists of a basic model [Sojka et al., 1980] to which adjustments have been made to reproduce different features of the magnetospheric convection electric field. This basic convection model includes the offset of 11.4° between the geographic and geomagnetic poles, the tendency of plasma to corotate about the geographic pole, and a constant dawn-dusk magnetospheric electric field mapped to a circle about a center offset by 5° in the antisunward direction from the magnetic pole. The radius of the circle corresponds to 17° of latitude, and the electric potentials are aligned parallel to the noon/midnight meridian within the circle. Equatorward of the circle the potential diminishes meridionally and inversely as the fourth power of sine magnetic colatitude.

To study the differences between northern and southern hemisphere convection patterns with this model it is necessary to define the location of the magnetic north and south poles. In our previous calculations dealing with the northern hemisphere we represented the magnetic field by a dipole field with the geographic location of its axis at a latitude of 78.6° north and a longitude of -69.8° east; these values were taken from the international geomagnetic reference field 1965.0 [Mead, 1970]. The higher-order components of the magnetic field model can lead to significant shifts in the location of the magnetic poles in the geographic frame. Bond [1968] contrasts the location of the southern and northern hemisphere magnetic polar regions. He indicates that the northern pole is at a geographic latitude of 80° north and longitude -79.6° east, a difference of only 1.4° of latitude from that of the dipole axis used above. A more significant difference arises in the southern hemisphere, where the geographic latitude is 74.5° south and longitude 126° east, a difference of 4.1° of latitude from the dipole axis. In addition, the longitudes are such that the two poles are separated by 206° rather than 180° for a dipole field. Because the coordinates given by Bond [1968] for the location of the north magnetic pole do not differ significantly from our previously adopted values, we retained the earlier values of Sojka et al. [1979a]. However, for the location of the south magnetic pole we adopted Bond's coordinates.

The first electric field model that we considered in this study was our basic model [Sojka et al., 1980] with a total potential drop of 20 kilovolts to represent very quiet magnetic conditions. The purpose of this model was to ascertain the effects on the convection pattern of the different magnetic pole locations in the two hemispheres.

For our second model we considered an asymmetric dawn-dusk electric field distribution. This model was used to simulate the effect of different interplanetary magnetic field orientations upon the magnetospheric electric field distribution. Heppner [1973] shows the most commonly observed dawn-dusk electric field distributions. A significant feature of these data is that the enhanced electric field if found in the morning sector for one hemisphere is found in the evening sector for the other hemisphere. For our asymmetric electric field model we chose the case of an enhanced electric field in the morning sector for the northern hemisphere and evening sector for the southern hemisphere. The enhancement was modeled by keeping a constant electric field over most of the polar cap and then allowing the electric field to increase linearly to lower latitudes in the sector of enhanced field.

Plasma Flow Directions and Speed Distributions

In this section we present plasma flow distributions in the polar ionosphere for both the northern and southern hemispheres and for the two electric field models discussed in the previous subsection. The plasma speeds are calculated in the geographic latitude, local time frame and the results are displayed in polar diagram form. Geographic local time is marked by hourly tick marks and latitude by circles every 10° from the pole to 40°. For each hemisphere and each of the two models there are four plots, corresponding to four different UT's. These four times are at 6-hour intervals and are such that the magnetic north pole lies on the midnight, dawn, noon, and dusk geographic meridians in turn. Because the magnetic south pole longitude is approximately 180° from that of the north pole, the respective southern hemisphere magnetic pole locations are noon, dusk, midnight, and dawn. To aid comparison of the plasma convection patterns in the southern and northern hemispheres, we present the polar plots with the same local time orientation. This presentation corresponds to the views obtained by 'looking' down on the northern hemisphere and through the earth to the southern hemisphere. For both hemispheres, noon is at the top of the polar diagram and dawn on the right.

The Uniform Magnetospheric Electric Field Model

Figure 1 shows the plasma flow directions and speed distributions for the northern and southern hemispheres for the case of a uniform electric field with a total cross-tail potential of 20 kV. The column on the left shows the UT dependence of the plasma flow distribution as seen in the geographic northern hemisphere. On the right of Figure 1 are the corresponding results for the southern hemisphere. In all eight polar diagrams the location of the magnetic pole is indicated by either the letter N or S for the northern and southern poles, respectively. Gray scale shading is used to show the regions where the horizontal plasma flow speed

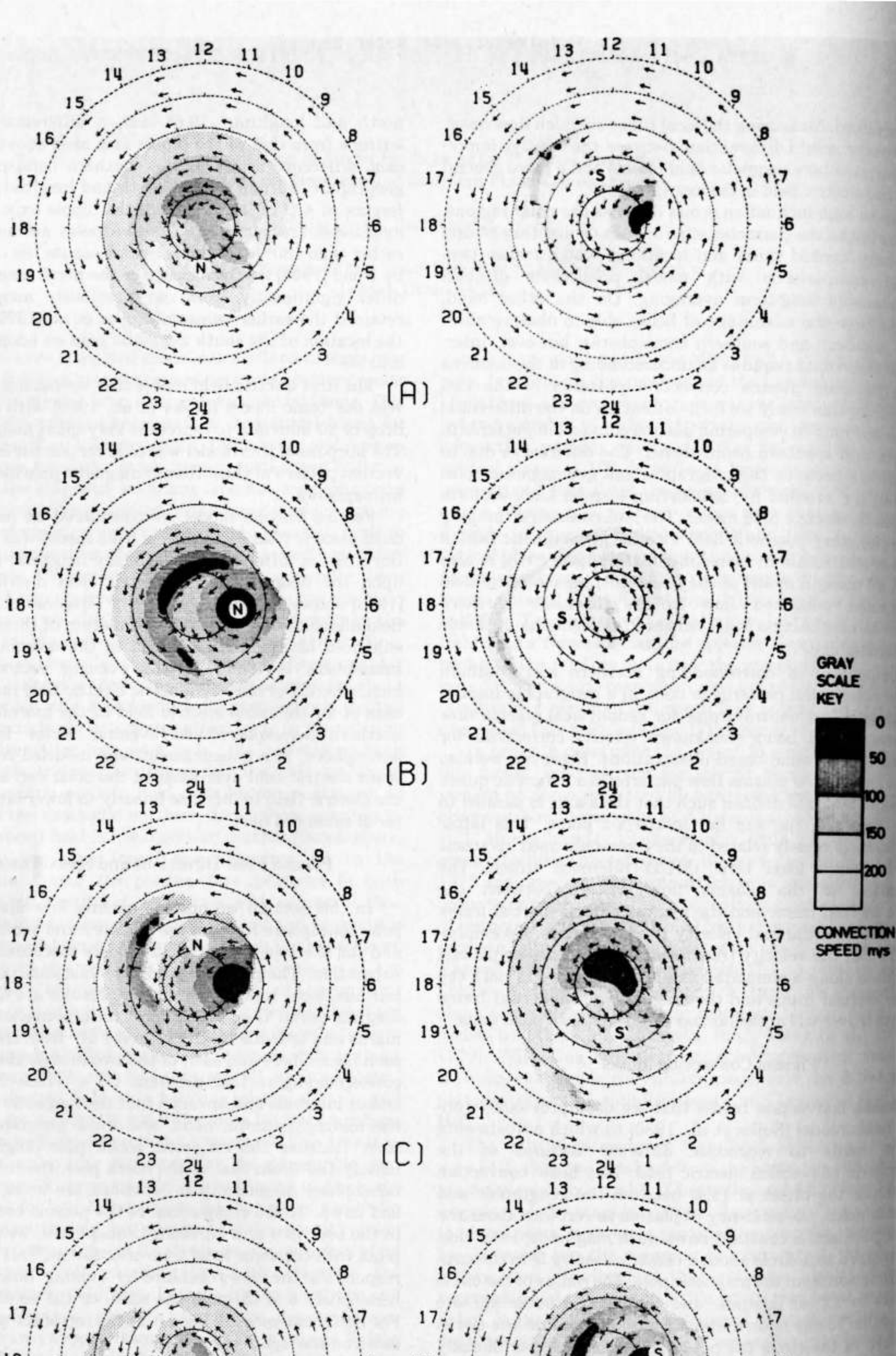

Fig. 1. Plasma flow directions and speed distributions viewed in the geographic inertial frame for the northern (left panel) and southern (right panel) hemispheres are shown for four universal times. The four universal times correspond to the magnetic poles (shown by N or S) being positioned such that the north pole is on the (a) midnight, (b) dawn, (c) noon, and (d) dusk meridians. For easy comparison both polar regions are displayed as if viewed from a point above the northern geographic pole. The shading corresponds to intervals of convection speed, the darkest tone corresponding to the lowest speed interval, and the arrows are unit vectors indicating flow direction. The coordinate system is represented by dashed circles at intervals of 10° of latitude and tick marks at intervals of 1 hour of local time. The total cross-tail potential is 20 kV.

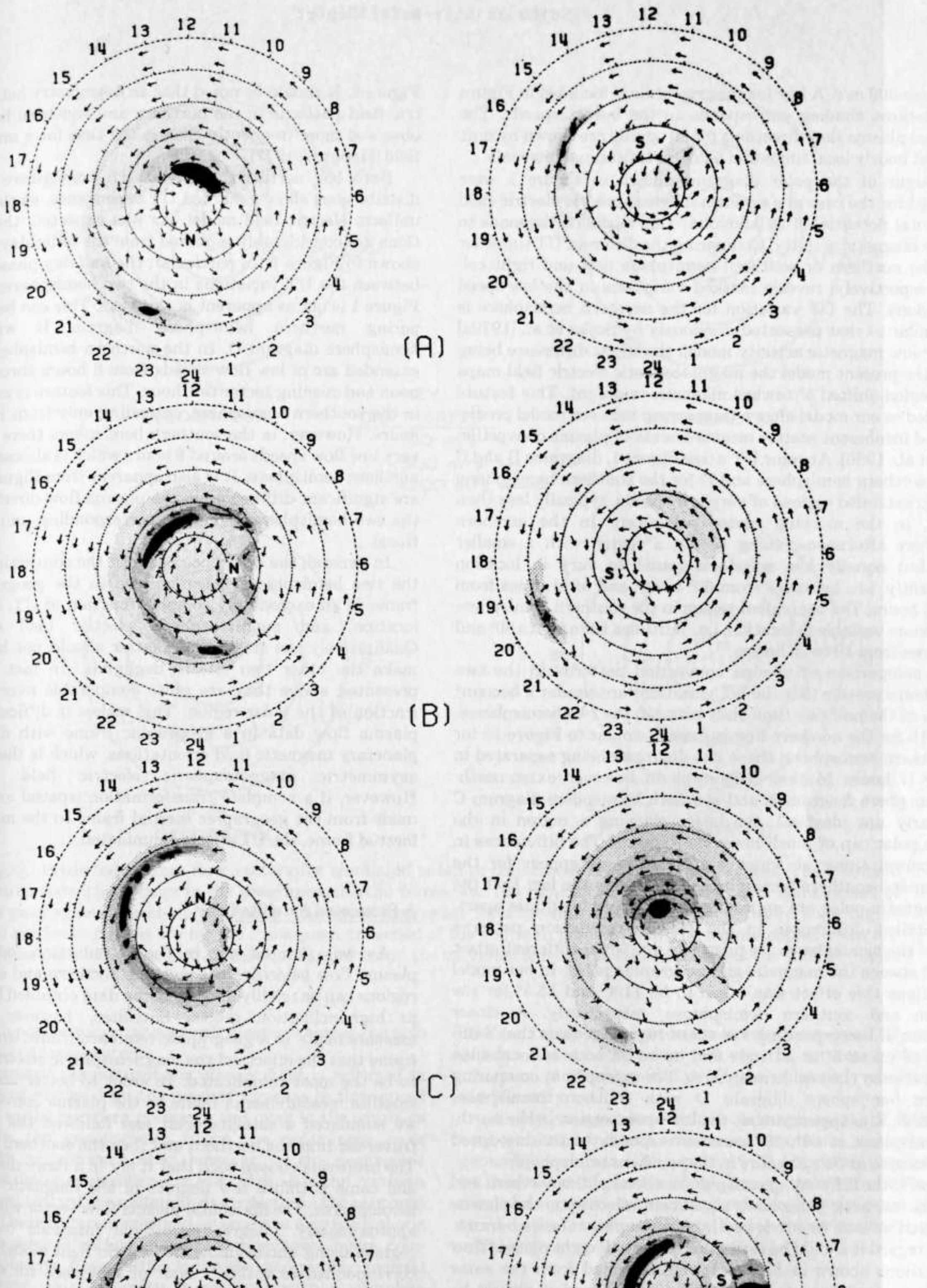

Fig. 2. Plasma flow directions and speed distributions viewed in the geographic inertial frame for the northern (left panel) and southern (right panel) hemispheres are shown for four universal times. The format for this figure is the same as that for Figure 1. For these calculations an asymmetric magnetospheric electric field was used in both the northern and southern hemispheres; in the northern hemisphere the electric field was enhanced on the dawnside, while in the southern hemisphere it was enhanced on the duskside. The total cross-tail potential is 64 kV.

is less than 300 m/s. A key for the gray scale is included in Figure 1; the darkest shading corresponds to the lowest speeds. The horizontal plasma flow directions for all speeds are shown by unit vectors at hourly local times and 5-degree latitudinal intervals.

All eight of the polar diagrams shown in Figure 1 were calculated for the case of a uniform magnetospheric electric field with a total potential of 20 kilovolts. This model corresponds to very low magnetic activity. Comparing the different UT times for either the northern or southern hemisphere (left and right columns, respectively) reveals marked variations in the low-speed flow regions. The UT variation for the northern hemisphere is very similar to that presented previously by Sojka et al. [1979a] for their low magnetic activity model, the slight difference being that in the present model the magnetospheric electric field maps into a region shifted 5° toward magnetic midnight. This feature was added to our model after a comparison between model predictions and incoherent scatter measurements of plasma convection [Sojka et al., 1980]. At some UT's (see Figure 1, diagrams B and C for the northern hemisphere and D for the southern hemisphere) there are extended regions of very low speeds, typically less than 50 m/s, in the morning sector polar cap. In the northern hemisphere afternoon-evening sector, a region with a smaller extent but equally low speeds is found to vary in location significantly, i.e., latitudes from 60° to 80° and local times from 11 to 23 hours. The equivalent region in the southern hemisphere is even more variable in location, i.e., latitudes from 55° to 80° and local times from 10 to 25 hours.

The comparison of plasma convection patterns in the two hemispheres reveals that the UT variations are similar if account is taken of the half day time shift between the two hemispheres. Figure 1b for the northern hemisphere is similar to Figure 1d for the southern hemisphere, these two diagrams being separated in time by 12 hours. Marked differences do, however, exist; northern hemisphere diagram A and southern hemisphere diagram C are clearly not identical, the latter showing a region in the dayside polar cap of much lower flow speeds. The differences in the apparent times at which similar patterns appear for the northern and southern hemispheres result from the fact that the two magnetic poles are approximately 180° of longitude apart. The detailed differences in the plasma convection patterns between the hemispheres are primarily due to the different offset angles between the magnetic and geographic poles. In our model calculations this offset was taken to be 11.4° and 15.5° for the northern and southern hemispheres, respectively. A closer inspection of corresponding low-speed regions reveals that a difference of up to 5° in latitude and up to an hour in local time exists between the two hemispheres. For example, in comparing northern hemisphere diagram D with southern hemisphere diagram B, it is apparent that the low-speed region in the northern hemisphere at 60°, 19 hours corresponds to the low-speed region located at 55°, 20 hours in the southern hemisphere.

Clearly, the different geographic locations of the northern and southern magnetic poles has a significant effect upon the plasma flow distributions when viewed in a geographic reference frame. In this regard it should be remembered that all eight plasma flow distributions shown in Figure 1 were obtained from the same uniform magnetospheric electric field model, and it should be noted that all eight distributions transform into the same convection pattern (two-cell plus stagnation point at 1800 MLT) in the magnetic quasi-inertial frame [see Sojka et al., 1979a], provided both spatial and velocity transformations are made.

The Asymmetric Magnetospheric Electric Field Model

Figure 2 shows the plasma flow distributions for the case of an asymmetric magnetospheric electric field model with enhanced flow in the dawnside northern hemisphere in conjunction with enhanced flow in the duskside southern hemisphere. These results were calculated for a total cross-tail electric potential of 64 kV, and the presentation format is the same as that for Figure 1. It should be noted that an asymmetry between the electric field patterns in the northern and southern hemispheres is observed more frequently than is the case for a uniform electric field [Heppner, 1977].

Both the northern and southern hemisphere plasma flow distributions show a marked UT dependence, as they did for the uniform electric field model. As was expected, these UT variations are considerably modified from the quiet day distributions shown in Figure 1. In particular, the half-day phase relationship between the UT variations in the two hemispheres presented in Figure 1 is not as apparent in this case. This can be seen by comparing northern hemisphere diagram B with southern hemisphere diagram D. In the northern hemisphere there is an extended arc of low flow speeds from 8 hours through the afternoon and evening sector to 1 hour. This feature is more restricted in the southern hemisphere, extending only from 12 hours to 23 hours. However, in the southern hemisphere there is a region of very low flow speeds around 6 hours which is almost absent in the northern hemisphere. It is also apparent from Figure 2 that there are significant differences in the plasma flow directions between the two hemispheres (compare corresponding unit vector directions).

In general, the difference between the convection patterns in the two hemispheres, when viewed in the geographic inertial frame, is an exceedingly complex function of UT, magnetic pole location, and magnetospheric electric field configuration. Qualitatively the effect of the latter should not be assumed to make the other two effects negligible. In fact, for the case presented above they are quite comparable over a significant fraction of the polar region. This makes it difficult to compare plasma flow data in a geographic frame with different interplanetary magnetic field orientations, which is the source of the asymmetric magnetospheric electric field distributions. However, if a complete transformation (spatial and velocity) is made from the geographic inertial frame to the magnetic quasi-inertial frame, the UT effect is eliminated.

A Simulated Satellite Orbit

As was pointed out in the introduction, comparisons of plasma flow velocities between the northern and southern polar regions can be readily done by using data obtained from satellites in high-inclination orbits. Satellites, however, make their measurements in a geographic reference frame, and it is in this frame that the effects of the magnetospheric electric field appear to be the most complicated. In order to better understand how satellite measurements relate to the plasma convection pattern we simulated a satellite orbit and followed the satellite as it traversed first the northern and then the southern polar regions. The orbit was chosen such that it lay in a dawn-dusk orientation and came within a few degrees of the magnetic poles in both hemispheres. The horizontal plasma flow vector was computed at approximately 2-degree latitudinal intervals over the polar regions using our asymmetric electric field model. A UT which corresponded to within 1 hour of that used for diagrams C in Figure 2 was used.

Figure 3 shows the orbital track and horizontal plasma flow vectors over the northern and southern polar regions in both the geographic inertial and geomagnetic quasi-inertial frames. The two diagrams on the left are for the geographic north (upper) and geographic south (lower) polar regions, while the two diagrams on the right are the corresponding satellite tracks in the geomagnetic quasi-inertial frame. Dots represent the locations on the orbit track at which the plasma flow velocities were calculated. The flow speeds are represented by vectors whose lengths increase linearly with speed; a key for the speeds is included in Figure 3. Each of the four diagrams is a polar plot of local time and latitude; local time is indicated by hourly tick marks and latitude by circles at 10° intervals. In all four diagrams the pole is marked with either NP or SP, indicating the

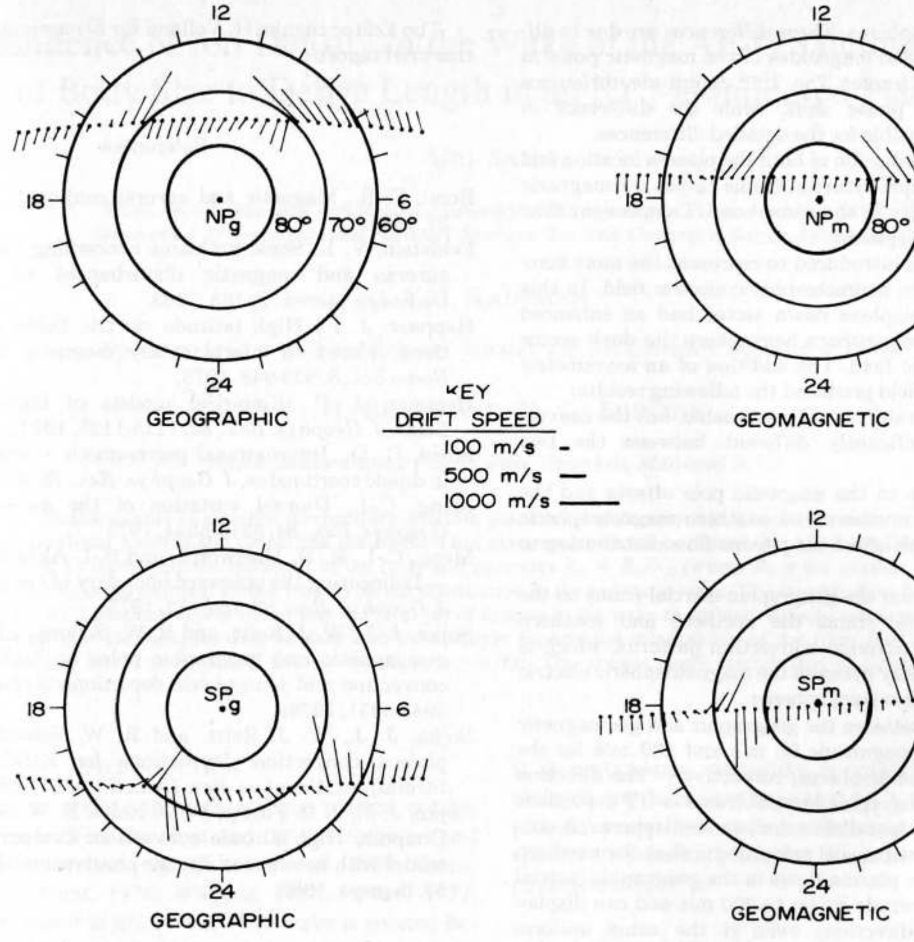

Fig. 3. Predicted plasma flow vectors for simulated satellite trajectories over the polar regions. The left-hand figures show the vectors in the geographic inertial frame, and the right-hand figures show them transformed to the geomagnetic quasi-inertial frame. The upper figures are for a satellite traversal of the northern polar region and the lower figures are for the subsequent traversal of the southern polar region. The magnetospheric electric field model is the same as that used for Figure 2, and the universal time of the traversal is near the time of Figure 2c.

north or south pole; a subscript g or m indicates whether the pole is a geographic or magnetic pole.

The asymmetric magnetospheric electric field is reflected in the diagrams of Figure 3 by the marked increase in flow speed toward dawn in the northern polar cap and dusk in the southern polar cap. In the geomagnetic frame the polar caps have predominantly antisunward flow; however, in the geographic frame the flow deviates significantly toward dusk in the northern hemisphere and toward the midnight-dawn sector in the southern hemisphere. These differences would, even if the magnetospheric electric fields were identical in both hemispheres, make comparisons of plasma flows difficult in the geographic inertial frame. However, this difficulty is resolved with a complete (spatial and velocity) transformation to the geomagnetic quasi-inertial frame.

Large flow vectors do not differ significantly in the geographic inertial and geomagnetic quasi-inertial frames. This is because the difference is related to the relative motion between the two frames, which can be derived from the corotation speed of the magnetic poles about the geographic axis. In the northern hemisphere the displacement of 11.4° gives rise to a speed of 96 m/s, while in the southern hemisphere the displacement of 15.5° yields a speed of 130 m/s. These two speeds, for the magnetic poles, represent the magnitude of the vector which is added to the plasma drift speed in transforming from one frame to the other. The direction associated with the speed of the geomagnetic pole is a function of location and UT, and for plasma flow speeds in the 1000-m/s range this correction is relatively small. However, for plasma flow speeds below 500 m/s the correction changes the direction and magnitude of the plasma velocity vector significantly.

Finally, we note that because the magnetospheric electric field configurations in the northern and southern polar regions are generally asymmetric [Heppner, 1977], erroneous conclusions can be drawn about plasma convection patterns if satellite tracks from the northern and southern polar regions are overlaid. This is true whether the overlaying is done in the geomagnetic quasi- inertial or geographic inertial frame.

Conclusion

We have presented model calculations to show how the plasma flow distributions in the two polar regions differ when viewed from a geographic inertial frame. Our first model consisted of a uniform magnetospheric electric field which was mapped into a circular region offset 5° in the antisunward direction from the magnetic pole in each hemisphere. From this study the comparison of northern and southern hemisphere plasma flow distributions led to the following conclusions:

1. The UT dependence of the gross plasma flow distributions in the two hemispheres is similar, but there is a phase shift of about half a day between them. Even taking account of this half-day phase shift these plasma flow distributions reveal differences of up to 5° in latitude and an hour in local time between similar

features in the two hemispheres. These differences are due to differences in the latitudes and longitudes of the magnetic poles in the geographic inertial frame. The 180° longitude difference results in the half-day phase shift, while the difference in latitudes is mainly responsible for the detailed differences.

2. A complete transformation of both the plasma location and velocity from the geographic inertial frame to the geomagnetic quasi-inertial frame results in the same non-UT dependent flow distribution for both hemispheres.

Our second model was introduced to represent the more common case of a nonuniform magnetospheric electric field. In this model the northern hemisphere dawn sector had an enhanced electric field, while in the southern hemisphere the dusk sector had the enhanced electric field. The addition of an asymmetric magnetospheric electric field produced the following results:

1. The half-day phase shift is still noticeable, but the convection patterns are significantly different between the two hemispheres.

2. The difference due to the magnetic pole offsets and the asymmetry between the northern and southern magnetospheric electric field patterns both affect the plasma flow distribution to a comparable extent.

3. In transforming from the geographic inertial frame to the geomagnetic quasi-inertial frame the northern and southern hemispheres still reveal different convection patterns, which is due solely to the asymmetry between the magnetospheric electric field distributions in the two hemispheres.

The relative motion between the geographic and geomagnetic frames is a velocity of magnitude 96 m/s and 130 m/s for the northern and southern hemispheres, respectively. The direction of this velocity in the geographic inertial frame is UT dependent and is approximately antiparallel in the two hemispheres. A consequence of these two antiparallel velocities is that the northern and southern hemisphere plasma flows in the geographic inertial frame can differ in magnitude by up to 200 m/s and can display significantly different directions even if the same uniform magnetospheric electric field is mapped into the two polar ionospheres.

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