Direct Comparison between Satellite Electric Field Measurements and the Visual Aurora

DANIEL W. SWIFT

Geophysical Institute, University of Alaska, Fairbanks, Alaska 99701

DONALD A. GURNETT

Department of Physics and Astronomy
University of Iowa, Iowa City, Iowa 52242

Electric field data from two passes of the Injun 5 satellite, one corresponding to magnetically quiet conditions and one corresponding to substorm conditions, are compared with simultaneous all-sky camera data from College, Alaska. In each case, a significant deviation of the electric field from the expected **V × B** field (where **V** is the satellite velocity) was evident, and a distinct electric field reversal could be identified. In the region of substantial electric field equatorward of the electric field reversal a diffuse auroral arc was observed during the magnetically quiet pass, and auroral patches were observed during the substorm pass. In the substorm case the electric field reversal occurred very near a discrete auroral arc at the poleward side of the diffuse arcs and patches. Comparison of the quiet time and substorm cases suggests that the convection electric field penetrates deeper into the magnetosphere during a substorm.

There have been many satellite measurements of electric fields across the auroral and polar cap regions [*Cauffman and Gurnett*, 1971; *Frank and Gurnett*, 1971; *Heppner*, 1972; *Gurnett and Frank*, 1973]. However, relatively little has been published to show the relation between the visual aurora and the electric fields measured by a satellite. In this paper, we report on the analysis of two events for which all-sky camera (ASC) data from College, Alaska, and electric field data from the University of Iowa Injun 5 satellite were simultaneously available. Because of the limited altitude range (less than 1500 km) for which satisfactory electric field measurements could be obtained from Injun 5 and the inherent seasonal, weather, and moonlight restrictions on all-sky camera measurements, the possibilities for obtaining simultaneous data were very limited. From the films from 6 ASC stations in intermittent operation during the 21-month operational life of Injun 5, these two cases were the only events suitable for a detailed analysis.

Comparisons between electric field and auroral image data have been made by using other techniques. The barium technique [*Föppl et al.*, 1968] permits rather detailed comparisons between the electric field and the image data at the location of the artificial barium clouds. *Wescott et al.* [1969] have tracked ionized barium releases in the midst of an active aurora. They found that the auroral electric field is approximately perpendicular to the auroral forms and that the magnitude of the electric field is diminished within the forms.

Another technique is the use of balloon-borne instrumentation to detect the horizontal component of the electric field near the 30-km level of the atmosphere [*Mozer*, 1971; *Kelley et al.*, 1971]. This method has the advantage that the electric field can be observed for a time span covering several substorm cycles and the disadvantage that the electric field measured represents an average over a relatively large region (~100 km) at auroral altitudes. The results of the balloon-borne experiments indicate that the westward component of the electric field is relatively steady, whereas the north-south component appears to change sign at the onset of a substorm.

Satellite electric field measurements provide a unique type of coverage for studying the spatial distribution of electric fields. Since a satel-

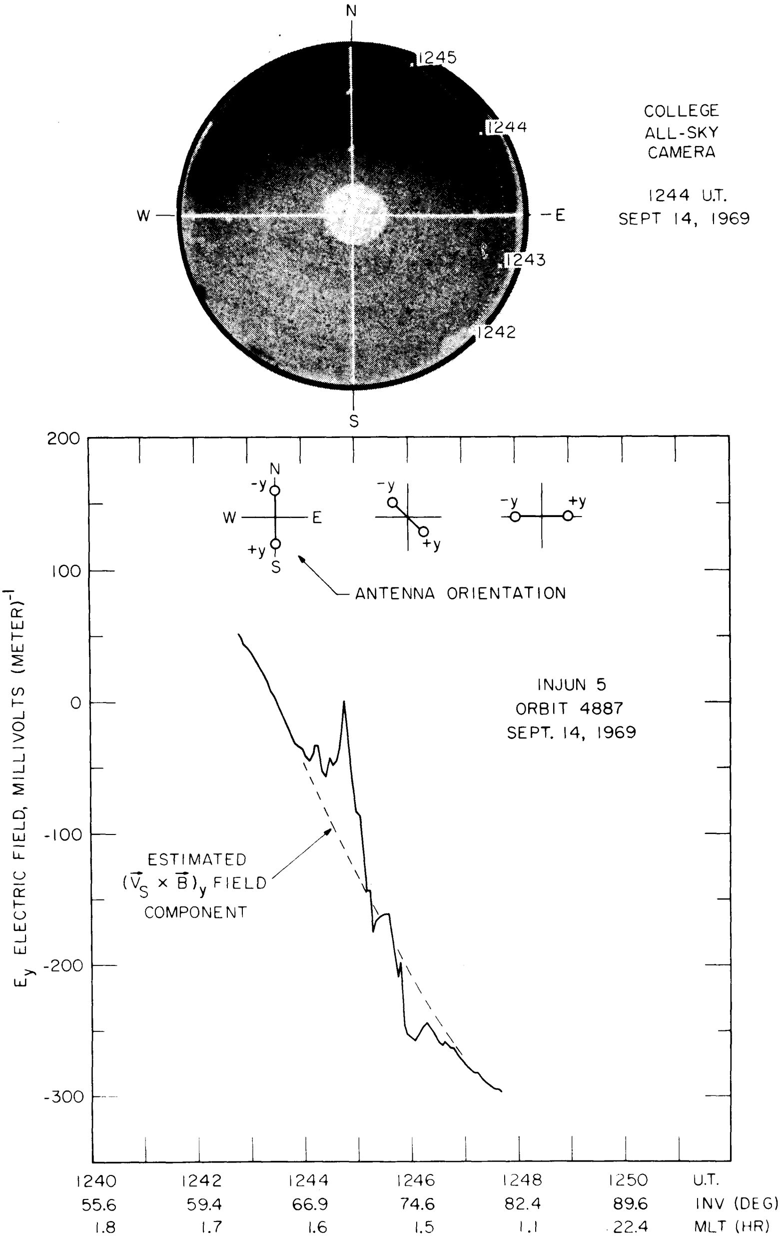

Fig. 1(*a*). Simultaneous College ASC negative photograph and Injun 5 electric field data for September 14, 1969. The intersection of the magnetic field line passing through Injun 5 and the 110-km level of the ionosphere is plotted at 4-sec time intervals.

lite can cross the auroral oval in a time short compared to the time of an auroral substorm, the satellite data yield primarily the spatial dependence of the electric field along the satellite's trajectory, in contrast to the primarily temporal coverage of the balloon-borne technique. Also, satellite electric field measurements can be more readily identified with specific auroral forms, assuming the field lines are equipotentials, because of the comparatively poor spatial resolution of the balloon-borne measurements.

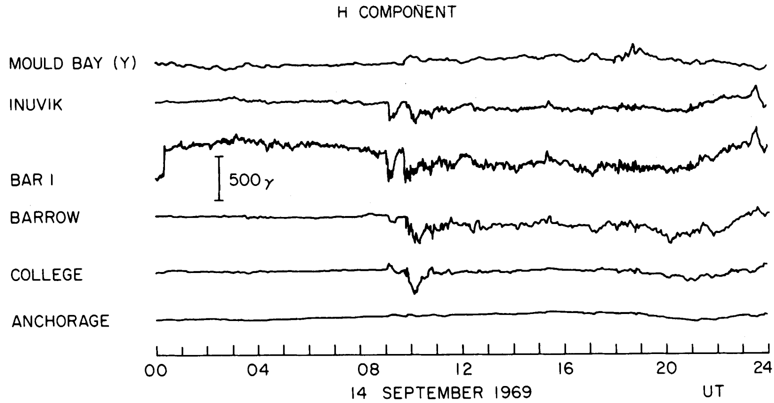

Fig. 1(*b*). Magnetograms covering the time period of the data shown in Figure 1(*a*).

Data Analysis

The reduction and processing of the electric field data have been described by *Cauffman and Gurnett* [1971] and will not be repeated here. In order to associate the electric field data with the auroral photographic data, it was assumed that the magnetic field lines are equipotentials between the altitude of the spacecraft and the altitude of the auroral light emission. A field line–tracing program was used to calculate the point where the magnetic field line passing through the spacecraft intersects the 110-km level of the ionosphere. The 110-km level was taken as the altitude of the lower border of the auroral light emission, since it represented an average of the altitude (90 to 130 km) at which the lower border most frequently occurs. The zenith and azimuth angles of the point where the field line through the spacecraft intersects the 110-km level as seen from the ASC station were calculated and transformed into ASC coordinates. A transparent overlay showing the spacecraft trajectory projected onto the 110-km level was prepared. A contact print that superposed the ASC transparency and the spacecraft trajectory overlay at the 110-km level was then made to facilitate the identification of features on the ASC photograph with corresponding variations at the spacecraft.

The conversion from zenith angle to the radial distance on the ASC photograph is derived from a table relating the radial position of stars with the computed zenith angle of stars, assuming that the ASC mirror and lens system is axially symmetric (A. Belon and G. Romick, personal communication, 1972). Careful examination of the image of the bridge supporting one of the mirrors, which shows up on the ASC photograph as cross hairs, indicates the existence of axial asymmetries amounting to about 1° of angle. Other sources of error could result from misalignment of the camera, but these are not expected to exceed 1° for the College ASC data used in this report.

The Injun 5 orbital calculation was considered accurate to about 0.1° in latitude (R. Brechwald, personal communication, 1972). As a result, the Injun 5 position could be in error by as much as 6 km when projected onto the 110-km level. This error could result in an uncertainty in the apparent zenith angle by as much as 3° when the Injun 5 field line is near the zenith. This error would not be significant near the horizon. Another source of error in the interpretation of the data is in the registration between the Injun 5 overlay and the ASC photograph. This uncertainty is related to the asymmetrical distortion, and it is estimated that this error could amount to 1°. Finally, deviations between the true height and the assumed height of the auroral lower borders can cause significant errors, especially near the horizon. For example, at a zenith angle of 85°, a deviation of 1 km from the assumed auroral height of 110 km would result in a 5-km displacement of the position of the aurora from the observer.

Results of Observations

The main results of this study are shown in Figures 1(*a*) and 2(*a*), which show negative ASC prints and the projection of the Injun 5 trajectory onto the 110-km level. The top of the

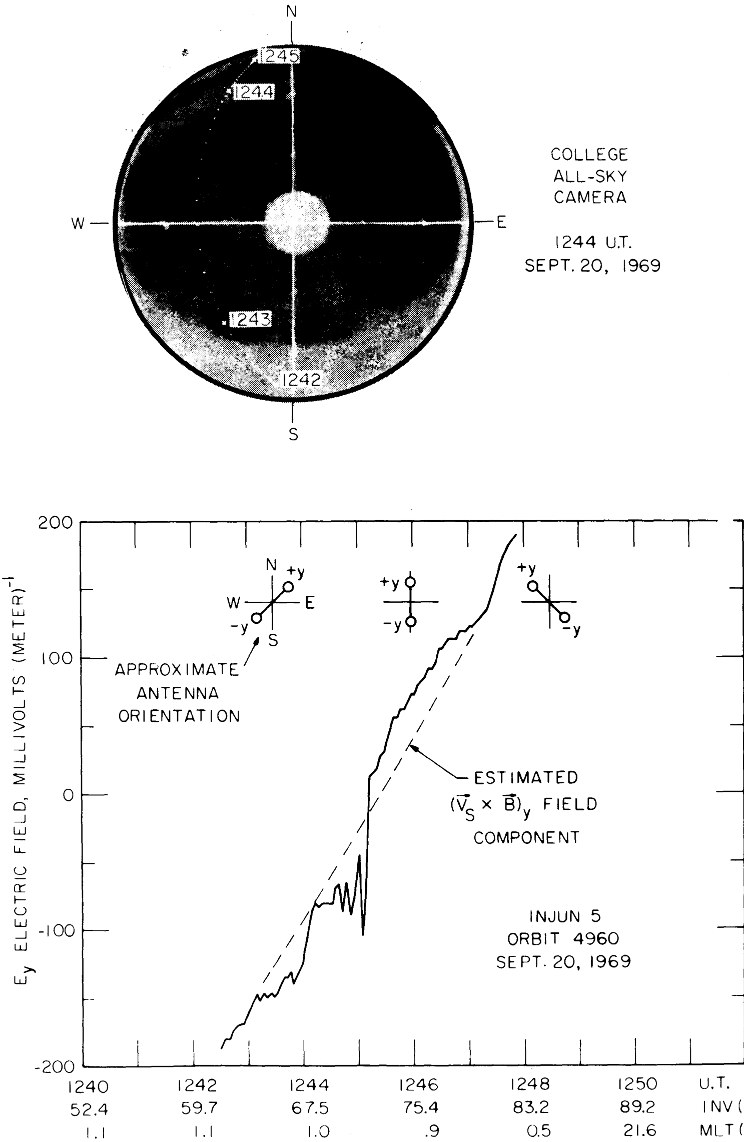

Fig. 2(*a*). Same as Figure 1(*a*), except that the data correspond to an Injun 5 pass near College on September 20, 1969.

ASC photograph corresponds to magnetic north, which is 27.5° east of geographic north at College. Successive points of the spacecraft trajectory are 4 sec apart. The time of the ASC photograph was selected as closely as possible to the time at which the satellite passed latitudinally over the center of the auroral activity. The measured electric field component along the y axis of the spacecraft, which is parallel to the electric antenna axis, is shown below the ASC photograph. This electric field includes the sum of the ionospheric electric field plus the $\mathbf{V}_s \times \mathbf{B}$ field due to the spacecraft motion through the ionosphere. The estimated $\mathbf{V}_s \times \mathbf{B}$ field component along the antenna axis, computed in a coordinate system rotating with the earth, is indicated by the smooth dashed curve. Any deviation of the measured electric field component from the $\mathbf{V}_s \times \mathbf{B}$ field is indicative of an ionospheric electric field. The approximate orientations of the electric

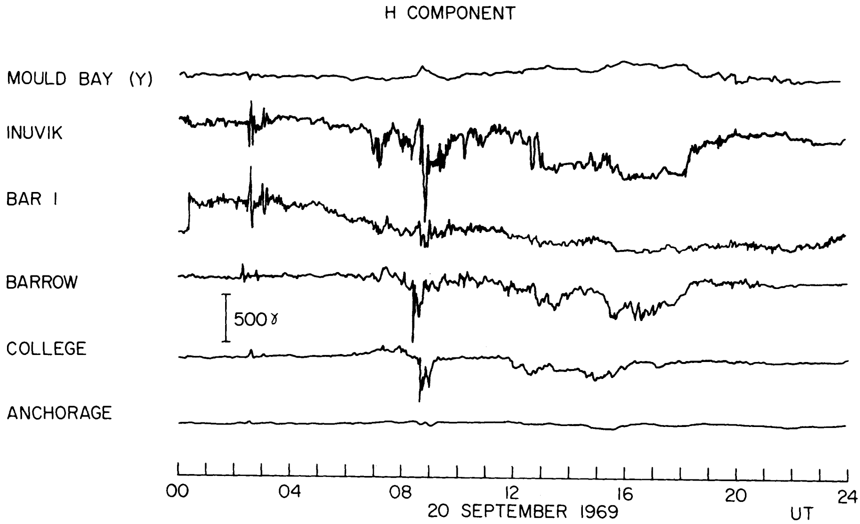

Fig. 2(*b*). Magnetogram covering the time period of the data shown in Figure 2(*a*).

antenna axis relative to magnetic north are indicated at various points during the pass by the antenna sketch (indicating the $+y$ and $-y$ axes of the spacecraft) at the top of the electric field data panel. Figures 1(*b*) and 2(*b*) show magnetograms from the Alaska meridian chain of stations to indicate the substorm activity during the periods of interest.

As can be seen from the magnetograms in Figure 1(*b*), the period around 1200 UT on September 14 is relatively quiet, the last substorm having occurred about two hours earlier. The College 30-mHz riometer showed no detectable absorption. The diffuse arc evident in the northern horizon of the ASC photograph in Figure 1(*a*) was virtually stationary from 1200 UT until the time (1244 UT) at which the ASC photograph was taken. The only discernable changes in the ASC data during the 45 min preceding the ASC photograph in Figure 1(*a*) were the appearance of some rayed forms poleward of the diffuse arc and an eastward-propagating wavelike structure on the poleward boundary of the diffuse arc.

Examination of the electric field data indicates that the first departure of the measured electric field from the estimated $\mathbf{V} \times \mathbf{B}$ field occurs at approximately 1244 UT, just after the spacecraft passes into the diffuse auroral form. At this time the electric antenna is detecting a southward electric field component. The peak in the electric field occurs at 12h 44m 45s UT, just after the satellite passes poleward of the arc. Unfortunately, the poleward edge of the diffuse arc cannot be easily distinguished because of contamination by morning twilight. The measured electric field component reverses direction, from SW to NE, between 1245 and 1246 UT. During this interval the satellite is almost on the northern horizon, and if there is an aurora form associated with this reversal it cannot be discerned because of the twilight background. It can, however, be said that the electric field reversal occurs poleward of the diffuse aurora.

From the magnetograms in Figure 2(*b*) it can be seen that the electric field and auroral observations of Figure 2(*a*) were made during a substorm of moderate intensity. The substorm activity began at approximately 1200 UT. At this time there was a bright thin arc on the northern horizon and a diffuse arc aligned east-west passing about 30° poleward of the zenith. By 1208 UT, the southern edge of the diffuse arc had moved into the zenith, and there was rapid motion in the auroral bands on the northern horizon. By 1222 UT, the equatorward edge of the diffuse arc was 45° south of the zenith, and auroral patches began to appear. At the time of the ASC photograph in Figure 2(*a*) (1244 UT) the College 30-mHz riometer indicated 1.1 db of absorption, and auroral patches were appearing at the equatorward edge of the region of diffuse glow 60° to the south of the zenith. These patches were drifting toward the NE at approximately 300 m sec^{-1}. This velocity was determined by tracking the patch in the NE quadrant nearest the center of the photograph. The patches had a tendency to fade out and reappear again over a time scale of about 4 min, so that it is difficult to track a single patch for more than 2 or 3 min. The electric field corresponding to this 300-m sec^{-1} drift velocity in 15 mv m^{-1} and is directed southeastward.

As the spacecraft proceeds farther northward, the electric field decreases to a very low value at about 12h 44m 15s UT in the region between the diffuse glow and the discrete auroral band on the northern horizon. As the satellite approaches this discrete auroral band the electric field again deviates negative, indicating a southward electric field. During the interval from about 12h 44m 30s to 12h 45m 05s UT several distinct wavelike oscillations are evident in the electric field data with a period of about 10 sec. These oscillations reach maximum amplitude at about 1245 UT, just equatorward of the electric field reversal, which occurs at about 12h 45m 05s UT. Wavelike oscillations of this type, with apparent horizontal wavelengths of ~100 km, have been repeatedly observed in the Injun 5 electric field data just equatorward of the electric field reversal [*Gurnett*, 1970, Figure 6]. Comparison of the electric field data with the ASC data indicates that the electric field oscillations occur as the satellite is passing through the auroral band. Because of the very low elevation angle on the ASC photograph at this time, there is no way to determine whether there is any corresponding structure in the auroral band. Unfortunately, at this time there were no ASC stations operating to the north of College that could provide a better view of this band. The electric field reversal appears to occur near the poleward boundary of the auroral band. Poleward of the electric field reversal and the discrete auroral band the electric field component is northward with magnitude of about 35 mv m^{-1}.

The above discussion has focused on the identification of auroral forms with the electric field data without regard to the possible errors in projecting the satellite location onto the ASC photograph. There are several possible sources of error. First, the satellite position may be significantly in error. Although the satellite position should be accurate to within a few seconds or about 10 km along the trajectory, it is possible that larger errors could occur in specific cases. The first detectable electric field at 12h 43m 08s UT and the subsequent decrease to near zero at 12h 44m 15s UT could be made to coincide almost exactly with the boundaries of the diffuse glow if the times on the ASC photograph were displaced earlier by about 20 sec. This displacement would place the electric field reversal at 12h 43m 05s UT in almost exact coincidence with the center of the discrete auroral band on the northern horizon. Since the discrete auroral band probably corresponds to an 'inverted V' electron precipitation band, similar to that discussed by *Ackerson and Frank* [1972], these observations would be in agreement with the direct charged particle/field measurements by *Frank and Gurnett* [1971] and *Gurnett and Frank* [1973], which place the 'inverted V' precipitation band very nearly coincident with the electric field reversal location. Unfortunately, for the pass being considered the spacecraft is operating in the low data rate mode, and direct charged particle measurements cannot be obtained with sufficient resolution to resolve the uncertainty in this case.

A second significant source of error is the assumed height of the aurora. The poleward edge of the auroral band on the northern horizon is at a zenith angle of 84°, which makes the position determination on the ASC photograph highly sensitive to the assumed height of the lower border. An error in the assumed height of the lower border of 20 km would result in an error of 12 sec in the time assigned to the position of the satellite at this zenith angle. This means that if the assumed lower border of the aurora were increased to 130 km altitude, as might be expected for the softer inverted V electron energy spectrums believed to be associated with this type of auroral arc, the satellite would pass poleward of the discrete auroral band at 12h 45m 12s UT ± 10 sec.

A third source of error is the distortion and alignment in the camera optics and the overall alignment of the all-sky camera. It is estimated that this error could accumulate to as much as 2°. At a zenith angle of 84° this would correspond to a timing error of 16 sec. If this error were added to the timing error attributed to the possible increased height of the auroral arc, the satellite would pass through the auroral band essentially coincident with the electric field reversal.

As a result of the uncertainties discussed here, we cannot positively identify the exact relationship between the electric field reversal and the auroral band on the northern horizon. It does, however, appear certain that the discrete auroral band was located within approximately 100 km, or less, of the electric field reversal position.

Conclusions

One of the principal results of this paper is that the equatorward boundary of the detectable electric field (>10 mv m^{-1}) coincides with the equatorward boundary of the diffuse arc. Within the region of diffuse glow the electric field intensity increases as the satellite moves poleward, reaching a maximum near the poleward boundary of the diffuse arc. In one of the cases analyzed an electric field reversal occurs near a discrete auroral band that lies poleward of the diffuse arc. *Wescott et al.* [1969] reported that electric fields were significantly reduced in auroral forms. Our results are consistent with theirs to the extent that a peak in the electric field is observed in the dark region somewhat poleward of the diffuse arc. However, we observe no reduction in the electric field intensity that could be attributed to the presence of the diffuse arc. The College ASC was too far away from the discrete auroral band on the northern horizon for us to draw any conclusions about the detailed relationship between this form and the electric field. Finally, it is worth noting that there is no appreciable difference in the maximum electric field intensity between the example corresponding to quiet conditions (Figure 1*a*) and the example corresponding to disturbed conditions (Figure 2*a*).

One interesting implication of our identification of the equatorial extent of the detectable convection electric field with the equatorward extent of the diffuse arc, under both quiet and disturbed conditions, is that the equatorward motion of the diffuse arc during a substorm reflects the deeper penetration of the stronger convection electric field in the magnetosphere. This is in agreement with the observations of *Carpenter and Stone* [1967] who reported an inward motion of whistler ducts in association with a substorm.

Swift [1971] and *Jaggi and Wolf* [1973] carried out numerical calculations of the motion of a radiation belt in a self-consistent electric field. The results of the calculations indicated that the radiation belt would polarize and greatly reduce the magnitude of the convection electric field in the inner magnetosphere. *Swift* [1971] pointed out that the shielding effect of the radiation belts could be reduced if the ionosphere were sufficiently conducting to drain off the space charge associated with the radiation belt. This would permit the stronger convection electric field to penetrate deeper into the magnetosphere. The presence of the convection electric field and the enhanced conductivity of the ionosphere would result in strong electric currents in the ionosphere, giving rise to a signature of the substorm, namely, the magnetic bay. Our interpretation is supported by the association between the convection electric field and the diffuse arc and by the equatorward motion of the diffuse arc during the substorm.

Acknowledgments. We would like to thank Mr. Kerry Shore of the University of Iowa for sorting through the extensive files of Injun 5 data to locate times of possible all-sky camera coverage.

This work was supported in part by the Atmospheric Sciences Section of the National Science Foundation under NSF grant GA-29158X to the University of Alaska. The Alaska meridian chain of stations was supported by NSF grant GA-1506. The Injun 5 data reduction and analysis was supported by the National Aeronautics and Space Administration under contracts NAS5-10625, NAS1-8141, and NAS1-2973 and grants NGL16-001-002 and NGR-16-001-043; and by the Office of Naval Rsearch under contract N00014-68-A-0196-0003.

* * *

The Editor wishes to thank F. S. Mozer and A. Pedersen for their assistance in evaluating this paper.

References

Ackerson, K. L., and L. A. Frank, Correlated satellite measurements of low-energy electron precipitation and ground-based observations of a visible auroral arc, *J. Geophys. Res.*, *77*, 1128, 1972.

Carpenter, D. L., and Keppler Stone, Direct detection by a whistler method of the magnetospheric electric field associated with a polar substorm, *Planet. Space. Sci.*, *15*, 395, 1967.

Cauffman, David P., and Donald A. Gurnett, Double-probe measurement of convection electric fields with the Injun 5 satellite, *J. Geophys. Res., 76,* 6014, 1971.

Föppl, H., G. Haerendel, L. Haser, R. Lüst, F. Melzner, B. Meyer, H. Neuss, H.-H. Rabbin, E. Reiger, J. Stöker, and W. Stoffergen, Preliminary results of electric field measurements in the auroral zone, *J. Geophys. Res., 73,* 21, 1968.

Frank, L. A., and D. A. Gurnett, Distribution of plasma and electric fields over the auroral zones and poplar caps, *J. Geophys. Res., 76,* 6829, 1971.

Gurnett, D. A., Satellite measurements of DC electric fields in the ionosphere, *Particles and Fields in the Magnetosphere,* edited by B. M. McCormac, p. 239, D. Reidel, Dordrecht, Netherlands, 1970.

Gurnett, D. A., and L. A. Frank, Observed relationships between electric fields and auroral particle precipitation, *J. Geophys. Res., 78,* 145, 1973.

Heppner, J. P., Polar cap electric field distributions related to the interplanetary magnetic field direction, *Rep. X-645-72-216,* Goddard Space Flight Center, Greenbelt, Md., 1972.

Jaggi, R. K., and R. A. Wolf, Self-consistent calculation of the motion of a sheet of ions in the magnetosphere, *J. Geophys. Res., 78,* 2852, 1973.

Kelley, M. C., J. A. Starr, and F. S. Mozer, Relationship between magnetospheric electric fields and the motion of auroral forms, *J. Geophys. Res., 76,* 22, 1971.

Mozer, F. S., Origin and effects of electric fields during isolated magnetospheric substorms, *J. Geophys. Res., 76,* 7595, 1971.

Swift, Daniel W., Possible mechanisms for the formation of the ring current belt, *J. Geophys. Res., 76,* 2276, 1971.

Wescott, E. M., J. D. Stolarik, and J. P. Heppner, Electric fields in the vicinity of auroral forms from motions of barium vapor releases, *J. Geophys. Res., 74,* 3469, 1969.

(Received February 12, 1973;
accepted June 29, 1973.)