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Joint Magnetometer Array and Radar Backscatter Observations of Auroral Currents in Northern Scandinavia

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Abstract. As a contribution to the International Magnetospheric Study the University of Münster has installed an array of 32 Gough-Reitzel type magnetometers located mostly in Northern Scandinavia. Also for the IMS, the Max-Planck-Institut für Aeronomie at Lindau is operating the **S**candinavian **T**win **A**uroral **R**adar **E**xperiment (STARE) which consists of two nearly identical backscatter radars located near Trondheim (Norway) and Sauvamaki (Finland). For a weak isolated substorm on October 7, 1976 the spatial structure of the electron density irregularities observed by the Trondheim-radar and the equivalent current distribution derived from the magnetic measurements have been compared. A good correspondence has been found between the location and magnitude of the maxima of the horizontal magnetic disturbance and the radar backscatter amplitude for an eastward electrojet. For most of the comparison there appeared also to be good agreement between the direction of the equivalent current and the direction antiparallel to the line-of-sight irregularity drift. This supports the idea that the backscatter irregularities are caused by current driven plasma instabilities and that it is possible to determine auroral ionospheric currents with the backscatter radar technique. However, during periods of enhanced electron precipitation, differences between the drift directions given by the two methods were observed.

Key words: Auroral electrojets – Scandinavian magnetometer array – STARE-radar.

Introduction

As a result of the International Magnetospheric Study (IMS), extensive new arrays of ground based geophysical instrumentation have been installed in northern Scandinavia. Two of these new systems are a two-dimensional array of 32 magnetometers (Küppers et al., 1978) of an improved Gough-Reitzel type (Gough and Reitzel, 1967) and a two station radar auroral experiment – STARE (Greenwald et al., 1977).

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The magnetometers are sensitive to current flows in the polar region. These include horizontal ionospheric currents which are commonly referred to as auroral electrojets and magnetic field aligned currents which are associated with these electrojets. The STARE-radars are sensitive to electrostatic ion waves in the auroral E-region. These waves, often called irregularities, are produced by the combined effect of the two stream (Buneman, 1963; Farley, 1963) and gradient drift (Rogister and D'Angelo, 1970) plasma instabilities. Both of these instabilities require a sufficiently large relative drift between the Hall drifting electrons and the collision dominated ion species. Hence, these instabilities occur within the regions of the auroral electrojets.

During the past several years a number of studies have shown a close correspondence between the location of radar aurora and the location of electrojet currents. Some of these studies have used ground-based magnetometers to locate the currents (e.g. Greenwald et al., 1973, 1975; Tsunoda et al., 1976), whereas others have used the Chatanika incoherent scatter radar to determine the E-region current density (Siren et al., 1977). In both cases a curious linear relationship has, at times, been observed between the electrojet current strength and the intensity of radar auroral backscatter. This relationship has, as yet, not been explained.

In this paper we report the results of a similar study using the 32 magnetometer array and the STARE radar located near Trondheim, Norway. The comparison was done for a three hour period of a substorm on 7 October 1976. We have found, consistent with previous studies, that radar auroral irregularities are collocated with the eastward electrojet currents and that, within our experimental error, the amplitude of radar auroral irregularities associated with the eastward auroral electrojet appears to be linearly related to the intensity of this current.

We have also been able to use the Doppler capabilities of the Trondheim radar to determine if the Doppler shifts of the backscattered signals were consistent with the electrojet current directions obtained from an equivalent current analysis. Since linear plasma theory indicates that radar auroral irregularities have a mean drift in the electron drift direction (e.g. Buneman, 1963; Rogister and D'Angelo, 1970) one would expect the mean drift of the irregularities to be opposite to the Hall-current direction. Having only the Trondheim radar it has not been possible to determine the precise irregularity drift direction. However, we were able to determine if the sign of the Doppler shift was consistent with the current direction. In general eastward electrojet associated irregularities and irregularities in the region of the Harang-discontinuity (Harang, 1946) had Doppler shifts consistent with the electrojet current direction. However, irregularities observed in conjunction with the westward electrojet near the maximum phase of the substorm were found to have drifts inconsistent with the concurrently derived equivalent current directions.

Description of the Instrumentation

The locations of the magnetometers used for this study are shown in Figure 1. Basically, they are located along 5 roughly parallel north-south profiles. The spacing between magnetometers within these profiles varies from 100–150 km.

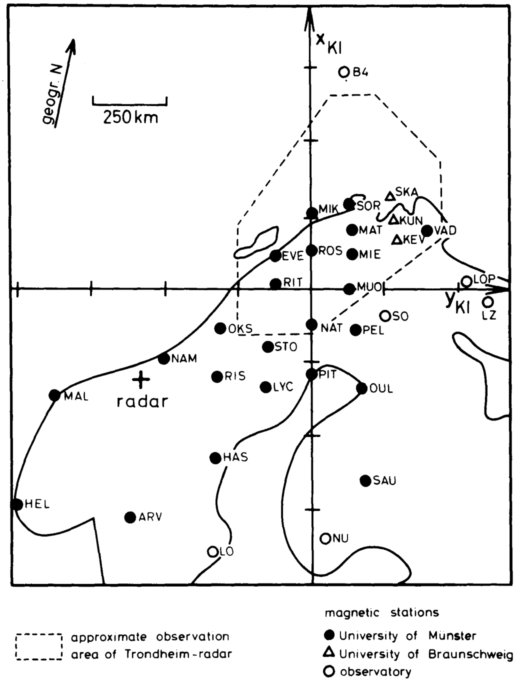

Fig. 1. Locations of magnetic stations used in this study and approximate observation area of Trondheim-radar in the Kiruna-system representation. For explanation of the Kiruna-system see text

A number of additional magnetometers have also been used and are also plotted in the figure. Recently, a more complete description of this magnetometer network has been given by Küppers et al. (1978)

The coordinate system used in Figure 1 has been denoted as the Kiruna-system (Küppers et al., 1978). It is a cartesian system obtained from a stereographic projection of the globe onto a tangential plane centered on Kiruna, Sweden (67.8° N, 20.4° E). The y_{KI}-axis has been chosen so that it is tangential to the projection of the $\phi_c(KI) = 64.8°$ line with ϕ_c being the revised corrected geomagnetic latitiude given by Gustafsson (1970). The x_{KI}-axis is parallel to the revised corrected geomagnetic meridian and is directed approximately 12° west of geographic north.

Again referring to Figure 1, the area enclosed by the dashed lines is the region examined by the central eight beams of the receiving array of the STARE radar near Trondheim. Within this area, the spatial resolution of the radar is approximately 20 km by 35 km by the vertical thickness of the scattering region. Normally, the last dimension is approximately 20 km. The temporal resolution of the radar was set at 60 s during this event.

The STARE radar is designed to measure the intensity and radial Doppler velocity of the radar auroral irregularities within each resolution cell of the scattering volume during each integration period.

The intensity data is corrected for antenna pattern variations, range dependence, and aspect angle dependence. All of these corrections and the methods by which the intensity and Doppler velocity information are obtained are described in detail by Greenwald et al. (1977).

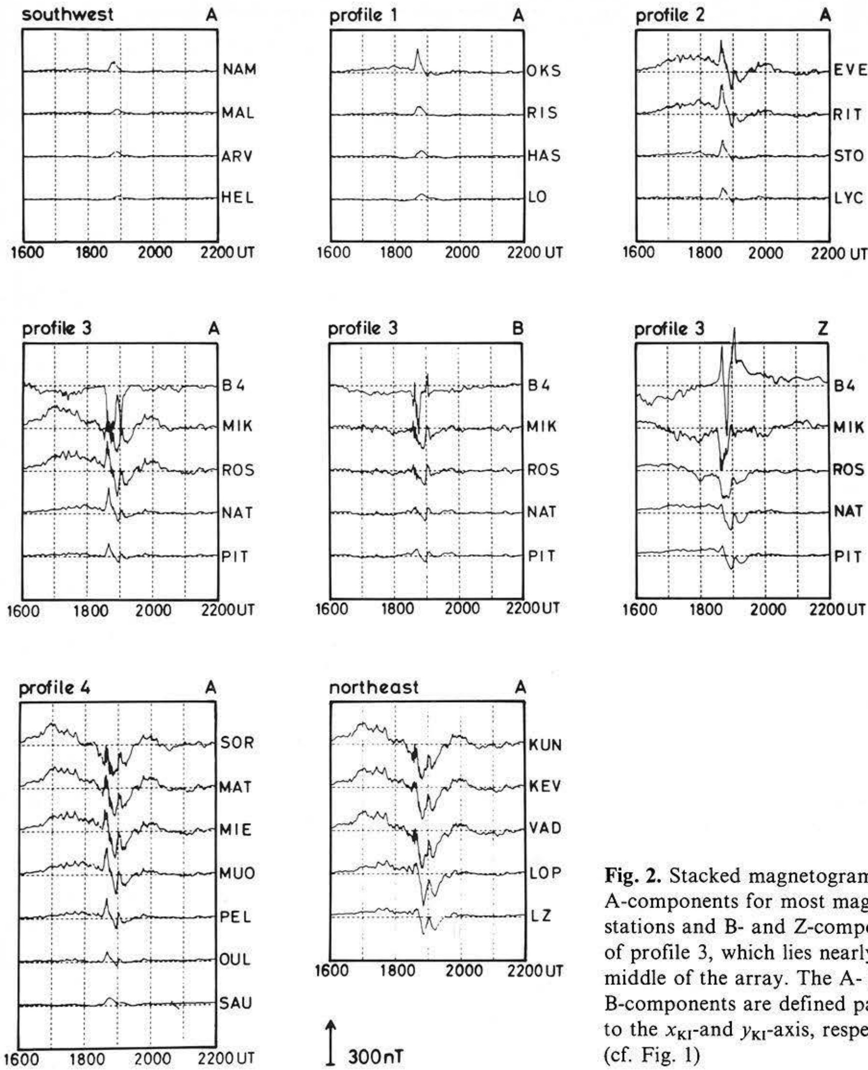

Fig. 2. Stacked magnetograms of A-components for most magnetic stations and B- and Z-components of profile 3, which lies nearly in the middle of the array. The A- and B-components are defined parallel to the x_{KI}-and y_{KI}-axis, respectively (cf. Fig. 1)

Overview of the 76-10-07 Substorm

On 7 October 1976, an isolated, weak substorm ($K_p = 3$) occurred between 1600 and 2200 UT (1830–0030 MLT). The magnetic effects observed in the Scandinavian sector in conjunction with this substorm are summarized in Figure 2. Here we show the A-components (magnetic deflection parallel to x_{KI}) for four profiles and the northeast and southwest stations. We also show the B-components (magnetic deflection parallel y_{KI}) and the vertical Z-components for profile 3. The components are obtained by conformal mapping of the spherical magnetic components.

One can see that, between 1600 and 1800 UT, the A-components of all stations except the northernmost (B4-Bear Island) were positive, thereby indicating an eastward electrojet over northern Scandinavia. Between 1800 and 1900 UT these features change dramatically. In particular the stations to the south continue to indicate positive disturbances for most of the hour, whereas the stations to the north begin to show negative disturbances indicative of a westward electrojet. The most dramatic changes take place shortly after 1830 UT. This current configuration with westward currents to the north and eastward currents to the sourth is a feature that occurs, on the average, shortly before magnetic midnight. It has become known as the Harang discontinuity (Harang, 1946).

The B and Z components on profile 3 also show dramatic variations after 1830 UT. The B-variations may be interpreted as north-south directed currents or the effects of field-aligned currents.

After 1900 UT, nearly all magnetometers have negative deflections indicative of a westward electrojet. This condition slowly weakens and eventually the current reverses. After 1930 UT most magnetometers again show a positive magnetic deflection suggesting an eastward electrojet.

On this day, the STARE radar near Trondheim recorded nearly continuous backscatter after 1430 UT. After 1600 UT, the region moved southward over northern Scandinavia. Until 1812 UT, only positive Doppler velocities were observed. These Doppler shifts could be interpreted as being due to westward moving irregularities. Hence, they are associated with an eastward electrojet.

After 1812 UT, negative Doppler velocities were, at times, observed in a second scattering region located well to the north of the eastward electrojet associated irregularities. These Doppler shifts could be interpreted as being associated with eastward moving irregularities (westward electrojet). During two periods, 1812–1912 and 2015–2045, the poleward scattering region underwent interesting Doppler variations, in which the Doppler velocity changed from positive to negative and then back to positive. These variations could be interpreted as rotations in the direction of the poleward current system. The equatorward scattering region either weakened or moved equatorward of the STARE viewing area during these periods.

Comparison of Magnetic and Radar Observations

In Figure 3 we present several comparisons of the magnetic and radar data during the period from 1700–2015 UT. The upper curve in this figure shows the variation in the ratio of the maximum horizontal magnetic disturbance ($H_{\max} = (\sqrt{A^2 + B^2})_{\max}$) to the maximum corrected backscatter amplitude ($R_{\max}$) observed in the common area of both measurements. The amplitude is simply the square root of the backscatter intensity. Both the radar and magnetic data represent 1 min averages taken every 5 min. The radar data are averaged over a 100×100 km^2 area. These areas were chosen as being more comparable with the spatial resolution of the magnetometers. The ratios have been normalized so that their average value over the entire period is unity.

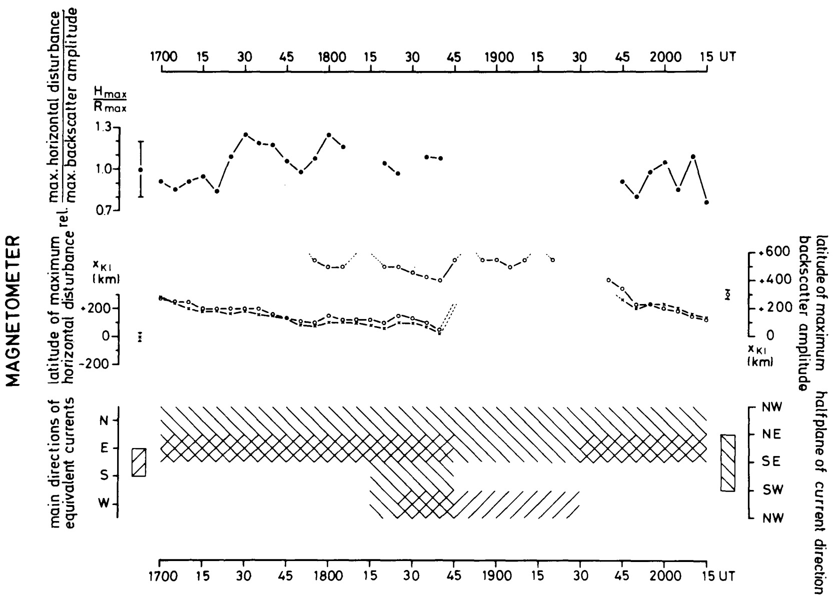

Fig. 3. Comparison of magnetic and radar data during the period from 1700–2015 UT. The upper curve shows the variation in the ratio of the maximum horizontal disturbance to the maximum corrected backscatter amplitude while the middle set of curves shows the latitudinal locations of these two maxima. The lower comparison relates the main direction of the magnetic equivalent current with the halfplane of allowable current direction consistent with the Doppler velocities

One can see that over the entire period of the measurement the ratio never varies outside of the range 0.7–1.3, even though there have been appreciable variations (up to a factor of 5) in both the horizontal magnetic disturbance and the backscatter intensity. This near constancy is more impressive when one considers that the probable errors in this comparison are of the order of $\pm 20\%$. They are due to uncertainties in interpolating the correct maximum amplitude between the observed values. Additionally, we have not considered the effects of field-aligned currents on the horizontal components or the effects of changes in the induced currents as the ionospheric current layer moves from being over water to being over land. For the radar measurements, variations in backscatter power could result from cross section changes produced by rotations of the current direction or changes in the height of the irregularity layer. None of the problems is, as yet, completely understood.

The middle set of curves in Figure 3 illustrates a comparison of the latitudinal locations of the maximum magnetic disturbance and the maximum backscatter amplitudes as a function of time. The magnetic data are represented by the small crosses and the radar data is denoted by circles. The latitudinal error for each set of measurements is shown by the error bars near each axis. One can see that between 1700 and 1840 UT the maxima of the magnetic disturbance and radar backscatter amplitude are at virtually the same latitudes. The same behaviour is true after 1945 UT when both techniques again observe maxima. Although the figure only displays a latitudinal comparison, we have found longitudinal variations of both maxima, but the spatial collocation was also observed. That is, the strongest backscatter is observed in the E-region above the magnetometer that observes the largest magnetic disturbance.

From the latitudinal comparison of disturbance maxima, we see that the radar observes a second maximum between 1755 UT and 1920 UT. However, as the current appears to be located well north of the Scandinavian coast, the magnetometers were unable to see the maximum.

Finally, the lower comparison in Figure 3 relates the main direction of the equivalent current derived from the magnetic A- and B-variations in the area of common observations with the halfplane of allowable current directions consistent with the observed Doppler velocities. The two measurements are differentiated by the direction of the hatching. We see that whenever the magnetometers observe an eastward current, the radar observes Doppler shifts implying this current direction (see also below). Furthermore, we see that it is an eastward current that yielded in the interesting relationships in the upper two curves of this figure. We also note that between 1825 UT and 1845 UT when the magnetometers observe the effects of a westward electrojet, the radar also observes westward electrojet associated irregularity drifts. A similar explanation can possibly hold for the period from 1815 UT to 1825 UT. It is possible that a westward electrojet was flowing in the north at this time, but it is too far north and was not strong enough to be observed by the magnetometers. The only time interval in which the magnetic and radar observed current directions are not consistent, extends from 1845 UT until 1930 UT. During this period the magnetometers indicate the presence of a westward current, whereas the radar would predict an eastward or northward current. One should note that during this period the disturbance maximum is well north of the northern coast of Scandinavia and only observable with the radar.

In order to examine the relationship between the current directions derived by both methods more carefully, we present in Figure 4 a more detailed comparison of equivalent currents obtained with the magnetometers and radial current direction component implied by the radar data. The current direction component implied by the radar data is opposite to the observed irregularity drift velocity component. Again, both data sets represent 1 min averages and the radar data is averaged over 100×100 km^2 areas.

The equivalent current vector analysis assumes that all current producing a disturbance on any given magnetometer flows horizontally above that magnetometer. The effects of field aligned currents or distant horizontal ionospheric currents are not considered. The equivalent current vector is obtained from the magnetic disturbance vector by rotating the vector 90° clockwise.

There are several important differences to keep in mind when looking at Figure 4. The length of the equivalent current vector is proportional to the horizontal magnetic disturbance and has its origin at the observing magnetometer's site whereas the length of the radar determined radial current direction arrow is equal and opposite to the radial irregularity velocity. The small box at the base of each radial current direction arrow has sides proportional to the intensity of the backscatter from that region.

In Figure 4a, we have compared the magnetic and radar data at 1700 UT.

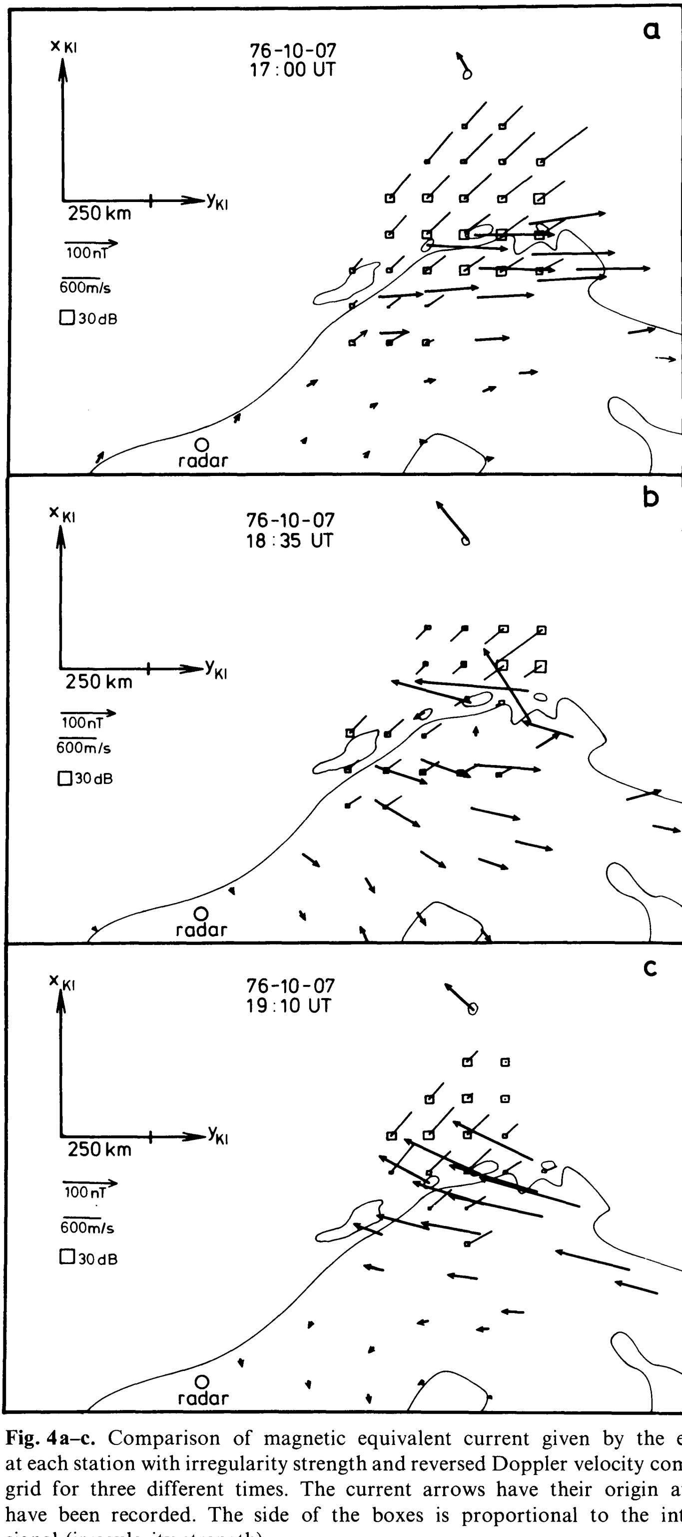

Fig. 4a–c. Comparison of magnetic equivalent current given by the equivalent current vectors at each station with irregularity strength and reversed Doppler velocity component on a 100 × 100 km grid for three different times. The current arrows have their origin at the station, where they have been recorded. The side of the boxes is proportional to the intensity of the backscatter signal (irregularity strength)

At this time the disturbance maxima in Figure 3 were collocated. One comes to the same conclusion by comparing the equivalent current vectors and box sizes in Figure 4a. Furthermore, all of the radar current direction components in Figure 4a are consistent with the eastward equivalent current vectors. Similar good agreement between the two data sets is observed at 1835 UT, shown in Figure 4b. At this time an eastward equivalent current was observed by the more southerly magnetometers and a westward equivalent current was observed by the magnetometers on the northern coast. Again the radar implied current directions are consistent with the equivalent current directions. One can also see that the radar shows the maximum westward-electrojet-associated irregularity intensity to occur just north of the Scandinavian coast and hence just beyond the latitude where the magnetometers could detect a disturbance maximum.

Finally, in Figure 4c, one can more clearly observe the disagreement in the data sets that occurred between 1845 UT and 1930 UT. Here, at 1910 UT, the radar locates the maximum disturbance about 200 km north of the coast and shows it to be associated with an eastward or northward current. The magnetometers show a westward equivalent current with a slight tendency for the vectors to turn northward on the coastal stations.

Discussion

As we have mentioned earlier in this paper, one would expect radar auroral irregularities to be located within the auroral electrojets and previous studies have shown this to be true. This study, however, has literally added another dimension to this association. The Scandinavian magnetometer array is the first closely packed two dimensional magnetometer network that has been set into operation at high latitudes for observations over several years. Used in conjunction with a multibeam backscatter radar, it has been possible to compare in both latitude and longitude the location of the most intense equivalent current with that of the most intense backscatter. This comparison has shown that the two are collocated to within the uncertainties of the analysis. Furthermore, the ratio of the equivalent current density to the backscatter amplitude, in the region where these two quantities maximize, remains approximately constant throughout the measurement.

The near constancy of the current density to backscatter amplitude ratio implies that the above mentioned possible reasons for non-constancy have either not occurred or had a weak influence. In particular, it appears that the equivalent current density was either dominated by horizontal currents or the ratio of field-aligned to horizontal currents remained constant during most of the comparison. Furthermore, it appears as if the height of the irregularity layer and the direction of the mean irregularity drift must have remained approximately constant, thereby not appreciably changing the irregularity cross-section.

Since the backscatter regions used for this comparison were associated with an eastward electrojet one can ask whether variations in the drift direction or height of the irregularities might have been expected to occur. From an examination of the variations in the direction of the eastward equivalent current, we have found that the current direction and, hence, the electron drift direction generally was within $\pm 10°$ of the y_{KI}-axis. An example of these current vector configurations can be seen in Figure 4a. Moreover, Kamide and Brekke (1977) have shown that the eastward auroral electrojet does not undergo large altitude variations and that it is enhanced primarily by intensifications of the northward electric field. Therefore, it would seem, that the irregularities are located in a relatively constant altitude range and that the variations in backscatter intensity are associated with variations of the northward ionospheric E-field. This conclusion was suggested earlier by Greenwald et al. (1975) on the grounds that modulation in the magnitude of the electric field would produce an associated modulation in the electron drift velocity and, hence, in the driving term of the plasma instability.

The relationship of mean radar auroral irregularity drift directions with ionospheric current directions is still a much debated topic. Recently, there has been an increasing amount of evidence that irregularity mean drift velocities can be used to determine the velocity of the Hall drifting electrons. For example, Ecklund et al. (1977) have shown that there is good agreement between the Hall drift of the F-region plasma as measured with the Chatanika incoherent scatter radar and the E-region irregularity drift. Also, Greenwald et al. (1977) have recently presented evidence that the mean irregularity drift direction is approximately that of the Hall-drifting electrons.

From the magnetic viewpoint, Fukushima (1976) has presented a theorem which states that no ground magnetic effect is produced by a combination of vertical currents into and out of the ionosphere and Pedersen closure currents within the ionosphere, if the height integrated ionospheric conductivity is uniform. Since field-aligned currents are nearly vertical in the auroral ionosphere, at times when the ionospheric conductivity is nearly uniform, ground magnetometers will see predominantly the effect of the ionospheric Hall current.

During the period of this comparison 30 MHz riometer data was available from Tromsø and Bear Island (Stauning and Christensen, 1977). This data indicates that prior to 1840 UT and after 1915 UT very little 20–40 keV electron precipitation was apparent. If we interpret the absence of energetic electron precipitation as indicative of a relatively uniform ionospheric conductivity, then we would expect the ground magnetic perturbations to be due to Hall currents. This would explain the good agreement between the current directions derived from the two techniques.

In contrast, between 1840 UT and 1915 UT, strong keV electron precipitation was observed at Bear Island while moderate precipitation was observed at Tromsø. It is during this period, that the uniform conductivity assumption is no longer valid and significant disagreements are noted between the two data sets. Presumably, the equivalent currents no longer represent only Hall currents, but are also due to field aligned currents and/or Pedersen currents. The analysis of the problem under these circumstances becomes extremely difficult. We plan in the future to use the completed STARE radar system, with which full electron drift velocity vectors can be estimated, in conjunction with the Scandinavian magnetometer array to make a more detailed analysis of this problem.

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