J. Geophys. 46, 77–87, 1979

Journal of Geophysics

Overnight Statistical Variation of the North-South Movements of Radio Auroral Irregularities

C.I. Haldoupis* and G.J. Sofko

Institute of Space and Atmospheric Studies, Department of Physics, University of Saskatchewan, Saskatoon, Saskatchewan, S7N OWO, Canada

Abstract. The average overnight variation of the north-south mean movements of the auroral scatterers at 42 MHz has been determined by using mean Doppler shift chart recordings from 24 radio auroral events of different strength and duration. On the average, the scattering irregularities move equatorward before local magnetic midnight and poleward in the morning sector (after about 0200 CST). During the transition period when the motion reversal occurs, the mean Doppler shift values are less stable and can vary rapidly between positive and negative. For individual events the exact overnight variation and the time of motion reversal vary, possibly because of differences between events in the level of geomagnetic activity. It is argued that the overnight east-west component of the electric field variations in conjunction with both the meridional component of the electrojet current systems, in the evening and morning sectors, and in particular the Harang discontinuity, up until midnight, play the deciding role in determining the observed north-south movements of the irregularities.

Key words: Doppler shifts – Radio auroral motions – Auroral electrojets – Hall currents – Scatterers.

Introduction

Recent experimental studies using VHF backscatter radars and ground magnetograms from a number of stations beneath the scattering region show that there is good spatial correlation between the radio aurora and the auroral electrojets (Ecklund et al., 1977; Greenwald et al., 1973; McDiarmid et al., 1976). This observation is in agreement with growing evidence that the auroral irregularities which cause the scattering are closely associated with the auroral electrojets through either the plasma instabilities or turbulent mixing or particle precipita-

* *Present address*: Physics Department, University of Crete, Iraklion, Crete, Greece

0340-062X/79/0046/0077/$02.20

tion occurring in conjunction with the electrojets. According to Greenwald et al., 1975b, the irregularities causing the backscatter appear to be acting as tracers of the flowing currents. Other observations suggest that the radio aurora is closely associated with ambient DC electric fields which are believed to be of magnetospheric origin (Unwin and Knox, 1971; Tsunoda, 1975; Tsunoda and Presnell, 1976). The ambient DC electric field vector seems to be the main parameter which dictates both the particle velocity associated with the electrojets and the motion of the auroral irregularities (Holtet, 1973; Czechowsky, 1974; Ecklund et al., 1977).

A Doppler radio-wave system can measure the line-of-sight movements of the scattering irregularities and therefore may be used to deduce useful information about the auroral zone currents and ionospheric electric fields. A pulsed radar is better suited to the task than a continuous wave (CW) radio system, since the pulses provide information about both the echo intensity and the Doppler shift variations as a function of range. A CW Doppler system gives a Doppler spectrum which represents the average motions over the total, aspect sensitive, scattering volume.

During the last 20 years there have been several Doppler investigations of the radio auroral ionosphere which yielded considerable, although sometimes contradictory, information about the motions as well as the scattering mechanisms (for references before 1975 see Greenwald et al., 1975a; later references are: Tsunoda, 1975; Haldoupis and Sofko, 1976; Moorcroft and Tsunoda, 1978; Greenwald et al., 1978). Most of these studies were based on a limited number of events and limited sections of the auroral time sector. In the present paper, the systematic overnight behaviour of the drift motion of the auroral irregularities along the north-south direction is presented. According to Tsunoda and Fremouw (1976), poleward and equatorward movements are the most common characteristic observed in radar aurora. The results presented here are based on data from 24 auroral events of different strength and duration.

Experimental Details and Results

The observing system is a VHF bistatic radio Doppler system located near Saskatoon, Canada (geographic coordinates: 52° N, 106.5° W; geomagnetic coordinates: 60° N, 49° W). The transmitter, which generates a CW signal at 42.1 MHz, is separated by 35 km from the receiving site, roughly along the east-west direction. The transmitting and receiving 5-element Yagi antennas are fixed in position pointing northward along the geomagnetic meridian. Because of the low transmitted power ($\sim$40 W), the scatter observation period is limited to the period (usually from 2100 to 0800 CST or 0300 to 1400 UT) when the strongest radio auroral conditions are present. At the receiving site a weak ground wave received directly from the transmitter is passed through a VHF phase-locked-loop incorporating a stable 1562 Hz audio oscillator, thereby producing a stable reference signal shifted exactly 1,562 Hz from the transmitted wave. The reference signal is mixed with the backscatter to produce an audio output centered at 1,562 Hz. This output is recorded on an analog magnetic

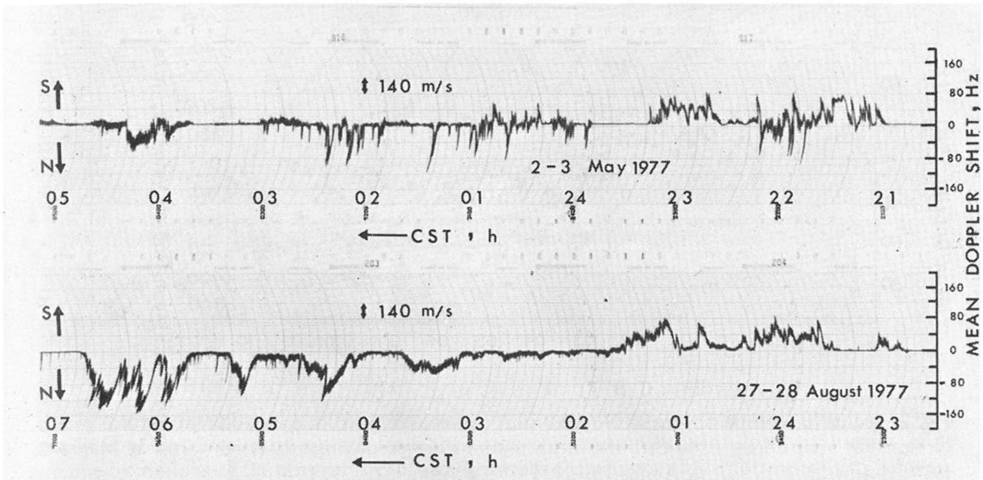

Fig. 1. Two typical examples of continuous chart recordings of mean Doppler shift variations of 42 MHz auroral backscatter due to the north-south movements of the scatterers. The horizontal axis represents local time (American Central Standard Time, CST)

tapedeck, and the tapes are analyzed using a Hewlett Packard Fourier Analyzer System.

The data used in this study was obtained by feeding the system output through a simple analog device, a frequency demodulator, to an Esterline Angus pen-recorder. This arrangement provided information on the mean Doppler shifts (or alternatively the mean radial motions) on a continuous 24-h basis. Tests of the demodulator performance, by comparison with independent spectral analysis of the simultaneously recorded tape data, have shown that this demodulator unit can provide a reliable estimate of the mean Doppler shift variations with time. More details about the experimental system and the characteristics of the frequency demodulator are given by Haldoupis et al. (1978).

The results presented in this paper are based on mean Doppler shift chart-recordings from 24 backscatter events of different strength and duration which occurred from April 15 to August 30, 1977. Two typical examples of mean Doppler shift pen-recordings corresponding to two different events are shown in Fig. 1. Since both the transmitting and receiving antennas were pointing towards geomagnetic north, the observed mean Doppler shifts in frequency reflect, approximately, the equatorward and poleward movements of the auroral ionization (notice that positive shifts in Fig. 1 are caused by southward motions). In sampling the records, a relatively large sampling interval, $\Delta t = 5$ min, was used throughout all recorded events. As a result, the 'fine structure' seen in the original pen-recordings (Fig. 1) and the strong short-lived spikes, usually due to the ion-acoustic type of echoes (Haldoupis and Sofko, 1978) lasting for about 1 to 3 min, are smoothed out in the results presented in Fig. 2.

Figure 2 illustrates the overnight variation of the mean frequency shift for four different events (the event of May 1–2, 1977 lasted for about 15 h and was the longest recorded in the present work). It can be seen from Fig. 2

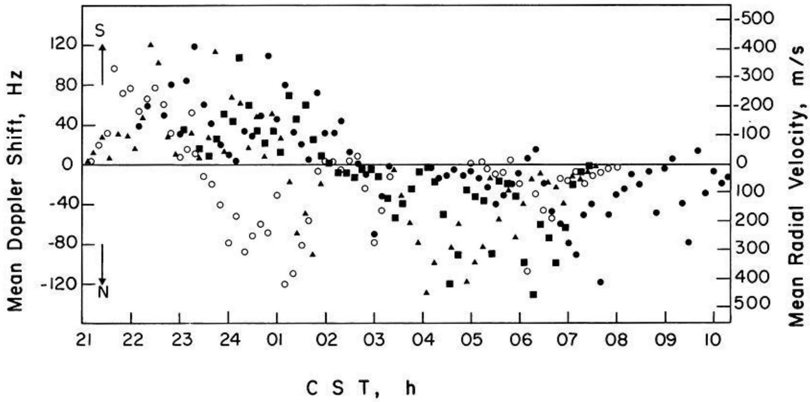

Fig. 2. Sequential samples of mean Doppler shift penrecordings from four different auroral events. Notice that after about 0200 CST the mean motions are predominantly northwards. ● May 1–2, 1977; ○ July 28–29, 1977; ▲ August 26–27, 1977; ■ August 28–29, 1977

that there is general agreement in the pattern of the overnight mean Doppler shift for all these events. It is clear that positive mean shifts (equatorward motions) are generally present before local midnight while negative shifts dominate the morning sector of the events. In addition to these two distinct periods, there is also a transition period (which can occur anywhere from about 2330 to 0330 CST) when the reversal of motion occurs. The exact time of reversal depends upon the particular auroral event (for example the reversal occurred at ~2330 CST for the July 28–29 event and at ~0230 CST for the May 1–2 event), but usually occurs between 0100 and 0300 CST. During the above transition period, the mean Doppler shift values are less stable and sometimes vary rapidly between positive and negative values. It has also been observed, by comparison with simultaneous signal strength chart recordings, that the echoes are weak, or disappear completely, during the transition of the mean Doppler shift from positive to negative values.

The morning sectors of the events are associated with radio echoes having, on the average, the most stable mean dynamic characteristics (e.g., mean Doppler shift and spectral width). Also it is during the morning period that the largest mean Doppler shifts (corresponding to about 700 m/s northward motions) are occasionally seen. From spectral analysis of the tape-recorded data (Haldoupis and Sofko, 1976; Haldoupis, 1978), it has been found that the spectral width is greater in the post-midnight period than before and around midnight. This is illustrated in Fig. 3 where samples of Doppler spectra received during the night of 4–5 August, 1975 are plotted in time sequence. From the increase in spectral breadth as the event proceeds in time, it can be inferred that the population of moving scatterers and the randomness in their motion increases especially after about local magnetic midnight (0200 CST). These observations, which agree with the result of Moorcroft and Tsunoda (1978), show that the parameters and dynamic characteristics of the auroral plasma are different in the morning sector than in the pre-midnight observation periods.

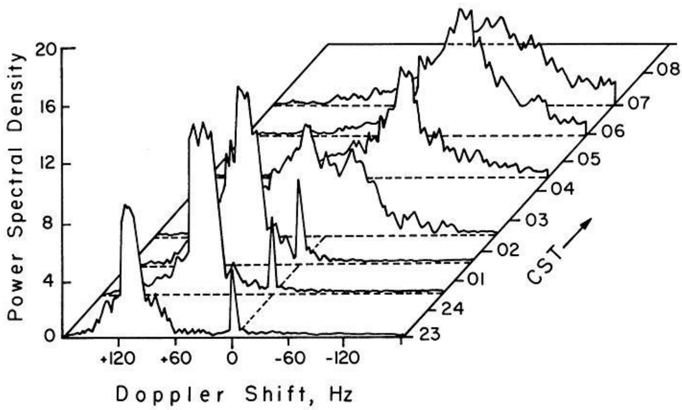

Fig. 3. A three dimensional plot (Doppler shift, local time, relative power spectral density) showing examples of typical auroral spectra from the night of 4–5 August 1975. Positive Doppler shifts are due to motions of the auroral irregularities towards the equator (1 Hz corresponds to 3.5 m/s). Notice that the character of the spectra changes drastically after about local magnetic midnight (~0200 CST)

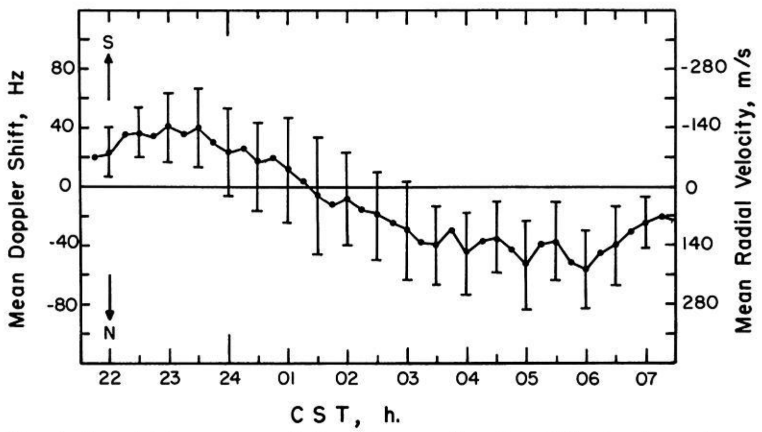

Fig. 4. Overnight average variation of mean Doppler shifts due to north-south movements of the auroral ionization. The bars denote the spread in the averaged values. This curve was based on 24 events of different strength and duration

The results of comprehensive statistical treatment of the data are presented in Figs. 4 and 5. Figure 4 illustrates the average overnight variation of the mean Doppler shifts based on data from all the events examined. The bars represent the standard deviation of the mean frequency shifts. This figure suggests that the time interval when the reversal of motion occurs extends from 00 to 03 h CST. Another interesting feature in Fig. 4 is the exact time when the reversal of the mean Doppler shifts occurs on the average; this is between 01 and 02 CST, close to the local magnetic midnight (~0140 CST at Saskatoon). Other points to notice in Fig. 4 are: (1) the relative spread is greater during the transition period (which means that the uncertainty of the mean Doppler

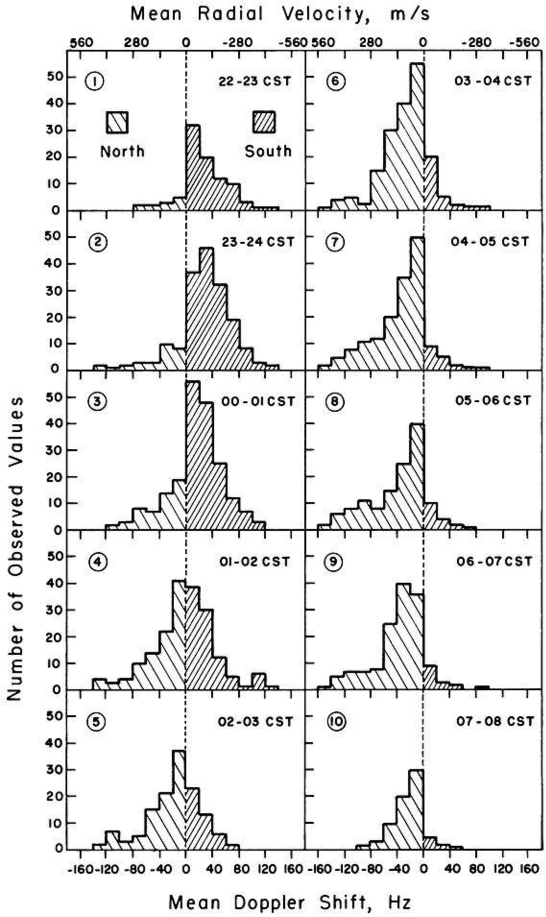

Fig. 5. Histograms (based on data from 24 events) showing the distribution of the mean Doppler shift in sequential one-hour intervals

shift position is larger), and (2) the mean frequency shifts are generally larger during the morning than the premidnight sector.

Figure 5 illustrates in a different form the statistical behavior of the mean frequency shift (or mean north-south motion of irregularities) for sequential one hour intervals of observation time. The radio scatter period (from 2200 to 0800 CST) is divided in 10 equal one-hour intervals and the mean Doppler shifts observed during these hour intervals, for all the events, are plotted in histogram form. Figure 5 shows clearly the increasing preference for negative shifts (northward motions) as the event proceeds in time from the premidnight to postmidnight sector. As can be seen from the histograms numbered 4 and 5, positive and negative shifts are equally probable during the transition time interval between 01 and 03 CST.

Interpretation and Discussion

The observed overnight variation of mean Doppler shifts due to the north-south motions of the auroral ionization cannot be explained from the present results alone. Simultaneous information about the auroral electrojet currents (which can be inferred from magnetometer records at auroral latitudes), the electric fields, as well as the range distribution of the received records is required. Unfortunately in the present experiment none of these are available. For this reason the following discussion relies on observations, reported by other workers, which demonstrate a close relationship between radio aurora, auroral electrojets and electric fields.

If we accept the premise that the auroral irregularities which cause the scattering of VHF waves are weak scatterers (associated with electron density fluctuations, $\Delta N/N$, of a few percent), then the theory developed by Kato (1963) about the drift motion of an assembly of weak irregularities may apply. According to Kato, the mean propagation velocity of weak electron density irregularities in the ionospheric plasma, where an electric field **E** is present perpendicular to the earth's magnetic field **B**, is given by

$$\mathbf{V} \simeq \frac{1}{1+\nu_{\mathrm{en}}\nu_{\mathrm{in}}/\omega_{B_e}\omega_{B_i}} \frac{\mathbf{E}\times\mathbf{B}}{B^2}, \tag{1}$$

where ν_{en}, ν_{in} are the electron and ion collision frequencies and, ω_{Be}, ω_{Bi} are the electron and ion gyrofrequencies. Thus, the mean drift motion observed in the present results could be an $\mathbf{E}\times\mathbf{B}$ Hall drift motion due to an electric field in the east-west direction (presumably the antenna orientation does not allow the observation of east-west motions). It is worth mentioning that **V** in Eq. (1) is the same as the phase velocity of plasma wave irregularities (two-stream or gradient-drift) predicted by the linearized theory [Sudan et al., 1973, their Eq. (12)], under the assumption that the electron-ion drift velocity $\mathbf{V}_{\mathrm{d}}$ is equal to $\mathbf{E}\times\mathbf{B}/\mathrm{B}^2$ Hall motion.

Recent results reported by Ecklund et al. (1977) (based on simultaneous observations of plasma drifts and associated electric fields) support strongly the $\mathbf{E}\times\mathbf{B}$ motion of auroral irregularities along the electron drift motion. Czechowsky (1974) has explained his overnight Doppler shift observations along the north-south direction, made in northern Germany and Scandinavia, by considering $\mathbf{E}\times\mathbf{B}$ drift motion of field-aligned electron inhomogeneities; he also concluded that the electric field is the most important factor in producing the irregularity drifts observed in auroral regions.

According to the above line of reasoning, the variations of the observed mean Doppler shifts should follow closely any variations of the east-west component of the electric field. In other words, the southward motions seen before magnetic midnight are due to a relatively strong westward component of the electric field. This field component weakens as the event proceeds in time and the mean Doppler shift decreases. Eventually the westward component reverses into an eastward oriented field responsible for the observed northward motions in the morning sector. Presumably, the exact variation of the field (strength and time of reversal) depends upon the magnetic activity for that particular auroral event and geomagnetic location. It should be mentioned that the term 'electric fields' is taken to mean large scale DC auroral electric fields presumably of magnetospheric origin (Holtet, 1973).

The above explanation, based on the $\mathbf{E} \times \mathbf{B}$ irregularity motion, is supported by the experimental results of Mozer and Lucht (1974). They have found average diurnal variations of auroral electric fields by using electric field data obtained by the flight of 32 balloons at auroral latitude locations in western Canada and Alaska. The overnight behavior of the east-west component of the electric field in heir results follows a consistent variation, being westward before midnight and changing into eastward later in the morning. It was also found that the strength increases as the geomagnetic activity increases.

Another observation which seems to be closely related to the existence of an eastward electric field at auroral zone latitudes in the morning sector was made by Rostoker and Hron (1975). By using a meridian line of magnetometers they have pointed out that in the dawn sector there exists an equatorward electrojet causing positive bias in the D component of the magnetometer due to northward electron motion. Hughes and Rostoker (1977) have investigated further this equatorward Hall current in the morning sector and suggested that it flows through the lower latitude ionosphere and into the postnoon auroral oval where it diverges up the field lines. The fact that the average eastward electric field (observed by Mozer and Lucht, 1974), the equatorward-flowing Hall current (observed by Rostoker and Hron, 1975) and the average poleward drift motions observed in the present results occur about the same time (morning sector) suggests strongly an interrelation between these phenomena.

Kamide et al. [1976a) have shown, by using the incoherent scatter radar in Chatanika, Alaska, that the auroral current system has a northward component in the evening sector and a southward component in the morning sector. Zmuda and Armstrong (1974) have established that the electrojets are associated with a pair of field-aligned sheet currents. In the evening, the flow is into the ionosphere on the equatorward side of the auroral oval and out of the ionosphere on the poleward side; the current directions are reversed in the morning pair, while either pair can appear in the transitional sector around midnight. Also Kamide et al. (1976b) have observed, by using ground and satellite data, that the horizontal auroral electrojet in the morning sector flows southwestward so that the 'westward electrojet' (a common term used for the auroral current regime in the morning sector) has in reality a large southward component. Now, taking into consideration that: (1) the electron drift motion is nearly opposite to the electrojet direction, assuming the Hall conductivity dominates, and (2) that the motion of the scattering irregularities as observed from the ground is the ionospheric Hall electron drift (Ecklund et al., 1977), it is clear that the mean motions presented in this paper are consistent with the above observations of the meridional motion components at the electrojet current system. This suggests that the electrojets play an important role in generating the scattering irregularities and controlling their motion. This is consistent with the basic assumptions of the various plasma instability mechanisms which have been proposed for the auroral plasma (Greenwald et al., 1975b).

A strong possibility exists that the premagnetic midnight echoes associated with southward motions originate from the Harang discontinuity (HD). This is the dynamic transition boundary between the eastward electrojet in the evening sector and the westward electrojet in the morning sector and may occur from 2000 MLT to magnetic midnight (Heppner, 1972) and may in fact 'jump" in longitude during a substorm (Horwitz et al., 1978). The HD, which is a highly turbulent region associated with a southward convective flow (Chen and Rostoker, 1974) may play an important role in the generation of southward moving scatterers. Another important observation which supports southward motions in this region is the westward orientation of the electric field (Maynard, 1974). Kamide et al. (1976b) suggest that the Hall conductivity is larger than the Pedersen conductivity at the HD, (as is true for the westward electrojet in general (Kamide and Brekke, 1977)) so that the northward ionospheric current (due to $\mathbf{E}\times\mathbf{B}$ southward electron drifts) prevails in the vicinity of the HD.

From the above, under the basic assumption that the dominant ionization movements are $\mathbf{E}\times\mathbf{B}$ Hall motions, it is clear that mean Doppler shift measurements of north-south auroral motions are useful in estimating the mean east-west component of the auroral electric field. Since the effect of neutral winds is negligible (Sudan et al., 1973) compared to the electric field motions, a simple equation for estimating the east-west mean electric field is given by

$$E_{my} \simeq 5.56\times10^{-2}\, V_{mx},\ (\mathrm{mV/m}), \tag{2}$$

where positive x and y are along the geomagnetic north and west respectively and V_{mx} is the north-south mean Doppler velocity [Eq. (2) is obtained from Eq. (1) by substituting $|B| \simeq 5.5\times10^4\ \mathrm{Wb/m^2}$ and $\nu_{en}\ \nu_{in}/\omega_{Be}\ \omega_{Bi} \simeq 10^{-2}$]. From Eq. (2) and Fig. 4 it can be shown that the average east-west component of the electric field takes values in the range of about ± 15 mV/m; this agrees with the agerage east-west electric field values observed by Mozer and Lucht (1974).

Conclusions

The results of this study show, on the average, a well-defined overnight variation of the mean motions of the auroral ionization along the north-south direction. Positive mean frequency shifts (due to equatorward motion) are generally present before local midnight while negative shifts (northward motions) dominate the morning sector of the events. The reversal of motion occurs during a transition period around local magnetic midnight. During this period, when the mean drift velocity along the line-of-sight goes to zero, the echoes are very weak or disappear completely; also the mean Doppler shift values are less stable and can vary rapidly between positive and negative.

Since there was not any direct information about other physical quantities (e.g., large scale electric fields, electrojet currents) which are believed to be related closely to radio auroral motions, interpretation of the above measurements was based on results reported by other investigations. The results suggest that the meridional motion components of the electrojet current system, in the evening and morning hours, and the Harang discontinuity, in the midnight-evening sector, play an important role in the generation and motion of the scattering irregularities. Based on the principle that the line-of-sight radio auroral Doppler velocities in the north-south direction are due to Hall drifts, such velocities are a continuous source of information about the average east-west auroral electric fields. The present results show that this mean east-west field component varies between ~15 mV/m eastward a few hours before magnetic midnight and ~15 mV/m westward a few hours after magnetic midnight.

Acknowledgement. This research work was made possible by grants to G. Sofko by the National Research Council of Canada.

References

Chen, A.J., Rostoker, G.: Auroral-polar currents during periods of moderate magnetospheric activity. Planet. Space Sci. **22**, 1101–1115, 1974

Czechowsky, P.: Movement processes of auroral structures. J. Atmos. Terr. Phys. **36**, 61–77, 1974

Ecklund, W.L., Balsley, B.B., Carter, D.A.: A preliminary comparison of F-region plasma drifts and E-region irregularity drifts in the auroral zone. J. Geophys. Res. **82**, 195–197, 1977

Greenwald, R.A., Ecklund, W.L., Balsley, B.B.: Auroral currents, irregularities, and luminosity. J. Geophys. Res. **78**, 8193–8203, 1973

Greenwald, R.A., Ecklund, W.L., Balsley, B.B.: Diffuse radar aurora: spectral observations of non-two-stream irregularities. J. Geophys. Res. **80**, 131–139, 1975a

Greenwald, R.A., Ecklund, W.L., Balsley, B.B.: Radar observations of auroral electrojet currents. J. Geophys. Res. **80**, 3635–3641, 1975b

Greenwald, R.A., Weiss, W., Nielsen, E., Thomson, N.R.: STARE: A new radar auroral backscatter in Northern Scandinavia. Radio Sci. **13**, 1021–1039, 1978

Haldoupis, C.: VHF Doppler investigations of the auroral ionosphere. Saskatoon, Canada: PhD Thesis, University of Saskatchewan, 1978

Haldoupis, C., Koehler, J.A., Sofko, G.J.: A VHF bistatic Doppler system for radio investigations of the auroral ionosphere. J. Phys. E: **11**, 135–138, 1978

Haldoupis, C., Sofko, G.: Doppler spectrum of 42 MHz CW aurora backscatter. Can. J. Phys. **54**, 1571–1584, 1976

Haldoupis, C., Sofko, G.: On ion-acoustic plasma waves in radio aurora and the two-stream instability. Can. J. Phys. **56**, 100–116, 1978

Heppner, J.P.: The Harang discontinuity in auroral belt ionospheric currents. Geofys. Publ. **29**, 105–114, 1972

Holtet, J.A.: Electric Field microstructures in the auroral E-Region. Geofys. Norv. **30**, No. 4, 1–88, 1973

Horwitz, J.L., Doupnik, J.R., Banks, P.M.: Chatanika radar observations of the latitudinal distributions of auroral zone electric fields, conductivities, and currents. J. Geophys. Res. **83**, 1463–1481, 1978

Hughes, T.J., Rostoker, G.: Current flow in the magnetosphere and ionosphere during periods of moderate activity. J. Geophys. Res. **82**, 2271–2282, 1977

Kamide, Y., Akasofu, S.I., Brekke, A.: Ionospheric currents obtained from the Chatanika radar and ground magnetic perturbations at the auroral latitude. Planet. Space Sci. **24**, 193–201, 1976a

Kamide, Y., Yasuhara, F., Akasofu, S.I.: A model current system for the magnetospheric substorm. Planet. Space Sci. **24**, 215–222, 1976b

Kamide, Y.R., Brekke, A.: Altitude of the eastward and westward auroral electrojet. J. Geophys. Res. **82**, 2851–2853, 1977

Kato, S.: Theory of movement of irregularities in the upper atmosphere. Planet. Space Sci. **11**, 823–830, 1963

Maynard, N.C.: Electric field measurements across the Harang discontinuity. J. Geophys. Res. **79**, 4620–4631, 1974

McDiarmid, D.R., Harris, F.R., McNamara, A.G.: Relationships between radio aurora, visual aurora and ionospheric currents during a sequence of magnetospheric substorms. Planet. Space Sci. **24**, 717–725, 1976

Moorcroft, D.R., Tsunoda, R.T.: Rapid-scan Doppler velocity maps of the UHF diffuse radar aurora. J. Geophys. Res. **83**, 1482–1492, 1978

Mozer, F.S., Lucht, P.: The average auroral zone electric field. J. Geophys. Res. **79**, 1001–1006, 1974

Rostoker, G., Hron, M.: The eastward electrojet in the dawn sector. Planet. Space Sci. **23**, 1377–1389, 1975

Sudan, R.N., Akinrimisi, J., Farley, D.T.: Generation of small scale irregularities in the equatorial electrojet. J. Geophys. Res. **78**, 240–248, 1973

Tsunoda, R.T.: Electric field measurements above a radar scattering volume producing 'diffuse' auroral echoes. J. Geophys. Res. **80**, 4297–4306, 1975

Tsunoda, R.T., Fremouw, E.J.: Radar auroral substorm signatures. 1. Expansive and recovery phases. J. Geophys. Res. **81**, 6148–6158, 1976

Tsunoda, R.T., Presnell, R.I.: On a threshold electric field associated with 398-MHz diffuse radar aurora. J. Geophys. Res. **81**, 88–96, 1976

Unwin, R.S., Knox, F.B.: Radio aurora and electric fields. Radio Sci. **6**, 1061–1077, 1971

Zmuda, A.J., Armstrong, J.C.: The diurnal flow pattern of field-aligned currents. J. Geophys. Res. **79**, 4611–4619, 1974

Received June 13, 1978; Accepted June 6, 1979