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Simultaneous Smoothed Variations of Signal Amplitude and Mean Doppler Shift in 42 MHz Auroral Backscatter

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. A recent detailed comparison of the amplitude of 50 MHz radio auroral backscatter at Anchorage with Chatanika incoherent radar data (Siren et al., 1977) has shown a good correlation between the echo amplitude and both the electrojet current and electric field strength. In this paper, smoothed backscatter data (the smoothing limits frequency variations to ≤ 0.1 Hz) from the 42 MHz CW Saskatoon Doppler system are used to make a detailed comparison between the amplitude and mean Doppler shift variations during selected portions of the strong April 18/19, 1977 event. A close relationship between these two variations is shown to exist, indicating that a common parameter (either the electrojet current or the electric field) 'modulates' both the mean drift velocity (related to the mean frequency shift) and the scattering cross section (related to the echo amplitude) of the echoing irregularities. However, the amplitude-mean Doppler shift relationship is more complicated than the linear current-amplitude relation in the Chatanika-Anchorage results, and is shown to change with the type of scattering mechanism present.

Key words: Auroral backscatter – Mean Doppler shift – Echo amplitude – Auroral electrojet.

Introduction

When radio waves of constant amplitude and frequency are transmitted towards the auroral ionosphere, often part of the signal is backscattered from the auroral medium if the frequency is in the appropriate range and certain geometric conditions are met (e.g., proper aspect sensitivity). The backscatter signal possesses, in general, both amplitude and frequency variations, because the temporal and spatial fluctuations in the auroral ionization act as 'natural modulators'.

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

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The variations in signal amplitude are presumably due to changes in both the population and strength of the scattering irregularities, while the fluctuations in frequency are primarily due to motions of the scattering ionization. The 'messages' contained in the amplitude (AM) and frequency (FM) modulation imposed by the scatterers are expected to contain important clues concerning the nature of the radio aurora.

Recent studies (Czechowsky and Lange-Hesse, 1970; Greenwald et al., 1973, 1975; Ecklund et al., 1974; McDiarmid et al., 1976; Siren et al., 1977) have shown that the radio aurora is closely associated with auroral electrojets. The spatial relationship between radio aurora and electrojet currents supports the idea that the scattering irregularities are generated through various current-associated plasma instabilities, and that the electrojet parameters play a major role in determining both the scattering cross-section and the motion of the scatterers.

Greenwald and Ecklund (1975), using a 50 MHz pulsed radar in Anchorage, Alaska, were the first to measure simultaneous range profiles of both the backscatter amplitude and mean Doppler shift in order to study the temporal and spatial structure of the radar aurora. The temporal variations in both amplitude and frequency of the received signal can also be obtained with a continuous wave (CW) Doppler system. Although a CW system does not give range information, it is useful in providing continuous information over the very short time intervals (5–200 ms) over which individual signal bursts occur (e.g., Haldoupis and Sofko, 1978a). In addition, through the use of smoothing, it is well suited to the study of long term variations of the mean signal characteristics which correspond to the changing average conditions in the total, aspect-sensitive, scattering volume.

In a previous paper (Haldoupis and Sofko, 1978a) digital demodulation techniques were applied to short (0.4 s) time sequences to extract concurrent time variations in amplitude and frequency in order to study the short term characteristics of ion-acoustic type echoes (these are the echoes whose Doppler spectrum exhibits a strong narrow peak at a frequency shift range which corresponds to the ion-acoustic velocity range in the auroral medium) for which the effect of interference between coexisting independent spectral components was not very serious. The purpose of the present investigation is to apply smoothing (only frequencies $\leqq 0.1$ Hz are considered) to auroral data recorded in analogue form from two linear demodulation units (an envelope and a frequency detector) in order to study simultaneous time sequences of mean Doppler shift (or mean signal frequency) and mean signal strength. Comparison of these sequences is found to be quite useful in studying the 'modulation' mechanism responsible for the observed fluctuations in both the signal strength (or scattering cross-section) and the mean line-of-sight motion of the scattering irregularities.

Experimental Details and Method of Analysis

The auroral backscatter data are obtained by means of a CW bistatic radio Doppler system located near Saskatoon, Canada (geographic coordinates: 52° N,

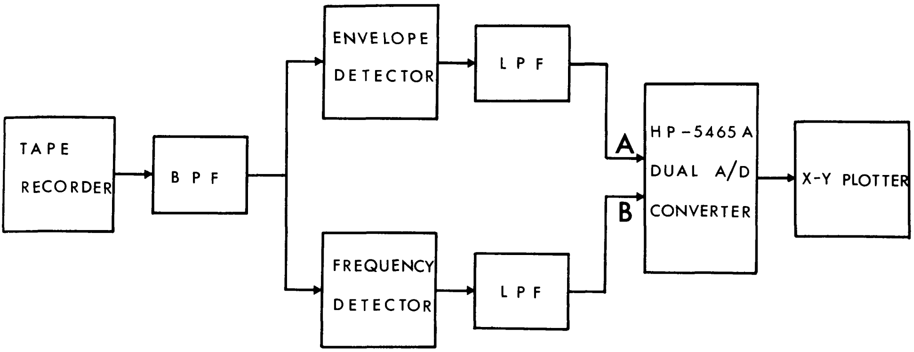

Fig. 1. Block diagram of the system used for studying simultaneous mean Doppler shift and signal strength variations. *BPF* Band-pass filter; *LPF* Low-pass filter

106° 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. 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 audio cassette recorder, and the tapes are analysed with a Hewlett-Packard Fourier Analyser System.

Two analogue demodulation units are employed to extract concurrent time variations in amplitude and frequency (or Doppler shift) from relatively long time intervals of tape-recorded data. Information about the signal strength is obtained with a portable linear envelope detector which is similar to those used for AM demodulation in heterodyne receivers and which consists of a full-wave precision rectifier and a low-pass filter. Continuous information about the instantaneous mean frequency (or mean Doppler shift) of the backscatter is obtained by means of a linear frequency demodulator employing a Signetics 565 phase-locked-loop. Tests of the demodulator performance, by comparison with independent spectral analysis of tape-recorded data, have shown that this simple unit provides a reliable estimate of the mean Doppler shift variations with time. More details about the experimental system and the characteristics of the above demodulation units are given by Haldoupis et al., 1978.

Figure 1 illustrates the technique used for studying concurrent mean Doppler shift and signal strength variations of the recorded echoes. The analogue output of the tape recorder passes through a band-pass filter (which removes any spurious frequencies below 1,000 Hz and above 2,000 Hz) and is then divided into two paths, one of which goes into the envelope detector and the other into the frequency demodulator. Both the frequency and amplitude demodulated outputs are lowpass filtered to attenuate high frequency variations of the incoming signal so that the sampled demodulated sequences are relatively smooth (the cutoff frequency was 0.1 Hz). The two sequences are sampled simultaneously by the HP-5465A dual A/D converter (on which the number of points, N, and the sampling interval, Δt, can be adjusted), stored in different memory blocks, and then plotted separately using an X-Y plotter. In the following, a few typical examples of relatively long period concurrent variations of mean Doppler shift and relative signal strength will be presented and discussed. All the examples presented below are from the same strong event of April 18–19, 1977. The average K_p index for the times treated in this paper was 6.

Experimental Results

Figure 2 shows an example of simultaneous mean amplitude and Doppler shift time sequences corresponding to ~17 min of continuous signal. A brief inspection shows that there is good correlation between the two records. The long term variations in amplitude are generally accompanied by similar variations in the mean frequency. Usually a sudden change in amplitude occurs simultaneously with a change in the frequency of the signal. The similarity between the mean signal strength and the frequency shift long term fluctuations is a general feature and leads to the important conclusion that the same cause is responsible for the long term modulation of both the amplitude and frequency of the scattered signal, i.e., a common mechanism influences both the velocity and the scattering cross-section of the irregularities. However, the detailed effects of this common modulating mechanism on the strength and frequency of the signal differ and are rather complicated. Comparison of the two sequences indicates that the larger Doppler shifts do not necessarily correspond to the stronger signal. For example, the strongest signal in Fig. 2 is observed in the 900–1,000 s time interval but the largest Doppler shift occurs between 300 and 450 s; also the signal strength in this 300–450 s time interval is as strong as that in the 650–850 s interval but the corresponding frequency shift in the latter is close to zero. Greenwald and Ecklund (1975) reported similar results when comparing simultaneous range profiles of the backscatter amplitude and mean Doppler shift velocity obtained by using a 50 MHz radar pointing towards geomagnetic north.

In an attempt to gain more information about the above 'modulation' process, sequential power spectra (averages of 10 individual 0.41 s spectra sampled evenly over ~55 s intervals of data) were computed by using the fast Fourier transform technique. Samples of the computed averaged spectra are shown in Fig. 3; each is marked with a capital letter and corresponds to a 55 s segment of mean amplitude and frequency shift designated with the same letter in Fig. 2. Examination of the power spectra shows that most of the long (~17 min) data sequence under discussion is associated with diffuse broad spectra centered close to zero shift position (e.g. Fig. 3A, D and E). However for the interval from about 300–450 s (spectra *B* and *C* in Fig. 3) a strong group of spectral peaks, confined to a relatively narrow frequency band of about 40 Hz and centered at about 125 Hz (450 m/s radial speed), dominates the spectrum. The

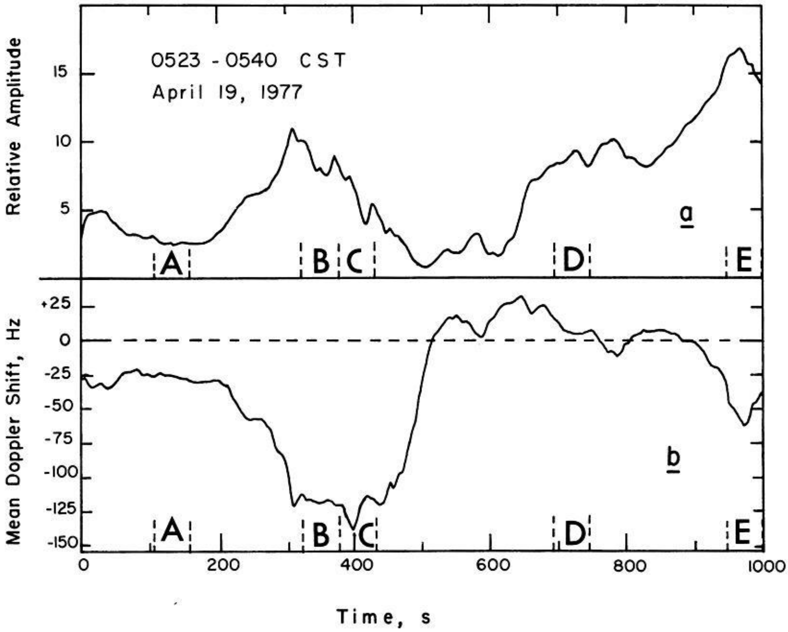

Fig. 2a and b. Concurrent long term variations of the relative amplitude and mean Doppler shift of 42 MHz auroral backscatter. The capital letters *A, B, C, D,* and *E* designate time segments whose power spectra are shown in Fig. 3. Note that Central Standard Time (*CST*) is 6 h behind UT, so the time interval is 1123–1140 UT

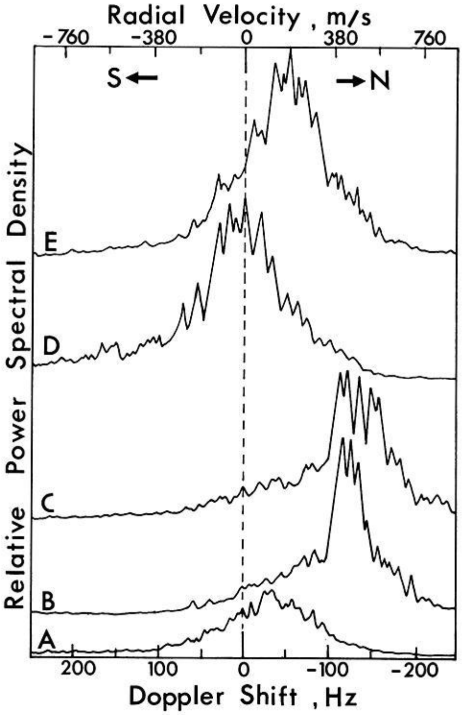

Fig. 3. Samples of Doppler power spectra from the data whose amplitude and Doppler shift are shown in Fig. 2. Each spectrum is marked with a capital letter and corresponds to the time interval designated by the same letter in Fig. 2

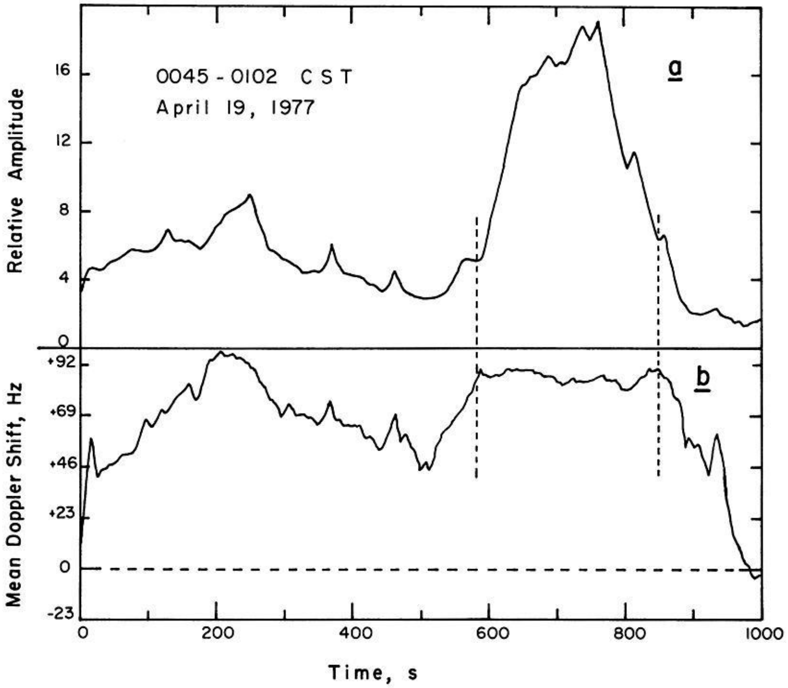

Fig. 4a and b. Plot of simultaneous amplitude and mean Doppler shift variations, showing good correlation from 0–600 s, then 'saturation' of the mean Doppler shift from 600–800 s

latter may well be due to a type of irregularity, such as primary ion acoustic plasma density waves (Haldoupis and Sofko, 1976; 1978b), differing from the irregularities corresponding to the rest of the data sequence. Presumably, ion acoustic plasma wave scatterers cause the almost constant Doppler shift observed in Fig. 2b during the 300–450 s time interval.

Figure 4 shows another example of concurrent amplitude and frequency sequences of 1,000 s duration. The two sequences are in good correlation between 0 and 600 s but this correlation breaks down completely for the time interval (enclosed in dashed lines in Fig. 4) from 600 to 850 s in which the frequency remains fairly constant but the amplitude varies. Detailed fading and spectral analysis of this event (Haldoupis, 1978) show: (1) that the signal during the latter time interval is dominated by strong specular components and exhibits slow and quasi-periodic fading as compared to the rapid fading observed for the former, and (2) the power spectrum associated with the 600–800 s part of the sequence is fairly narrow, with a small number of equally strong peaks grouped together in a narrow frequency band centered at about 85 Hz (300 m/s radial speed), in contrast to the broad type of spectrum corresponding to the initial time interval from 0 to 600 s. The above evidence suggests that a different type of irregularity may be responsible for the scattering in each time interval.

Usually, occurrences of constant frequency shift are observed only for relatively short intervals of time ($\leqq 5$ min) associated with the ion-acoustic type

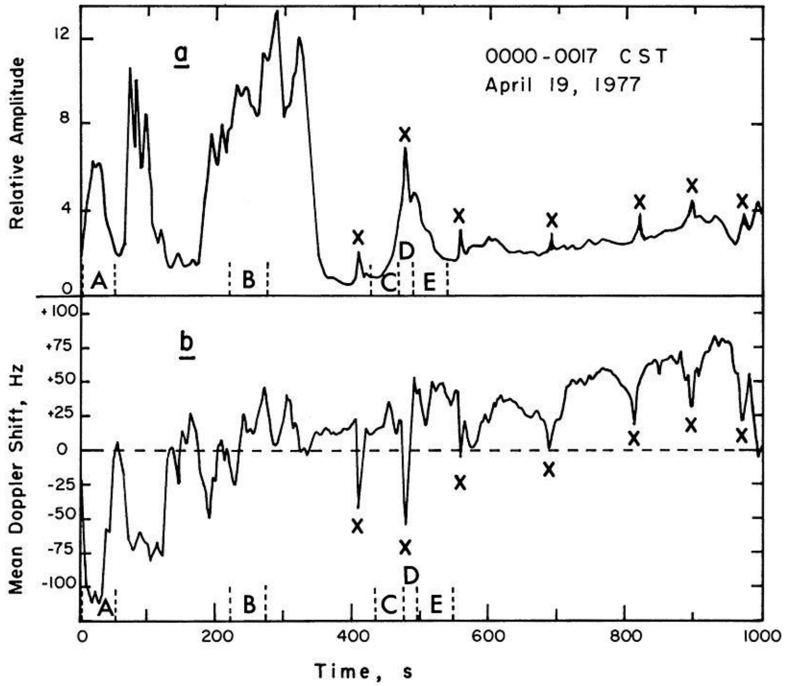

Fig. 5a and b. Another example of concurrent amplitude and frequency records. The peaks marked by 'X' are due to the growth of short-lived bursts of spectral power in the frequency range corresponding to northward-moving ion acoustic waves, as shown in Fig. 6D

of echoes. At such times, the Doppler shift remains almost constant (never exceeding ~140 Hz for the transmitted frequency of 42 MHz) even when the amplitude shows appreciable changes (Haldoupis and Sofko, 1978b). Reports of the occurrence of an almost constant velocity associated with ion-acoustic echoes, which are believed to be caused by longitudinal plasma density waves generated by the two-stream instability mechanism (Farley, 1963), have been made for both the auroral (Hofstee and Forsyth, 1969; Balsley and Ecklund, 1972; Haldoupis and Sofko, 1978b; Moorcroft and Tsunoda, 1978) and the equatorial (Farley and Balsley, 1973) ionospheres. Since this constant velocity is not predicted by the linearized theory, various non-linear theories have been developed (Sato, 1976 and references therein) to explain this saturation effect. The evidence presented in this paper suggests that the mechanism which imposes an upper limit to the velocity of this type of irregularities does not necessarily impose a similar limitation on the scattering cross-section.

A last example is presented in Fig. 5. The first third of the amplitude record consists of three sequential, relatively strong signal bursts of different strength and duration. These backscatter bursts presumably are due to the development of three different irregularity structures, as can be seen by comparing the amplitude and mean frequency variations. For example, the first burst (the weakest and shortest in duration) displays the largest Doppler shift and is due to scattering from irregularities moving northwards with speeds near the ion-acoustic

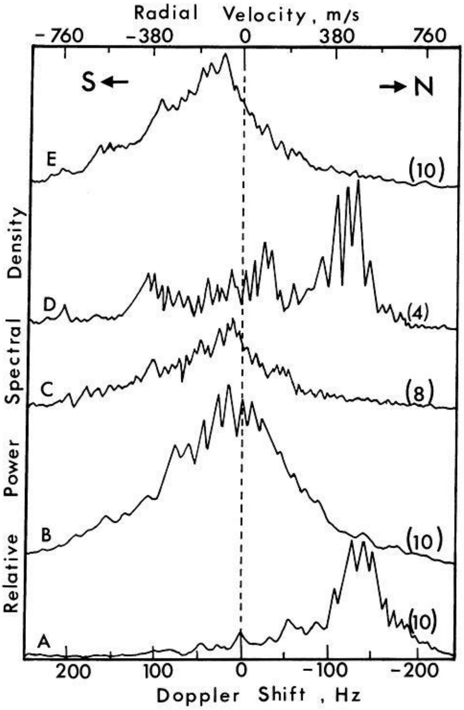

Fig. 6. Five spectra corresponding to the intervals labelled *A* to *E* in Fig. 5. The spectra *C*, *D*, and *E* illustrate the development of the spectral power in the ion-acoustic range, corresponding to the '*X*' peaks in Fig. 5. The bracketed numbers indicate the number of individual spectra averaged

speed in the medium. On the other hand, the third burst (the strongest and longest lived) displays relatively small deviations in frequency about zero shift level. It should be noted that, in all these bursts, sudden changes in amplitude are always accompanied by variations in the mean frequency shift.

The last two-thirds (from 380–1,000 s) of the sequence shown in Fig. 5a would represent a continuous smooth amplitude variation if the superimposed short lived narrow peaks (marked with 'X' in Fig. 5) were not present. Inspection of the corresponding Doppler shift sequence in Fig. 5b shows that the mean frequency shift changes slowly with time (presumably due to a slowly increasing southward drift) except when the short lived echoes dominate the scatter. These echoes are associated with sudden northward relative motions likely caused by a different type of irregularity.

Examination of averaged Doppler spectra associated with different portions of the time sequences in Fig. 5 reveals several different Doppler spectral types. Samples of these Doppler spectra are plotted in Fig. 6; each averaged spectrum is marked with the same capital letter that corresponds to a segment of mean amplitude and frequency shift in Fig. 5. Spectrum A in Fig. 6 shows that the first signal burst in Fig. 5a has a relatively narrow spectrum confined to a frequency shift range which corresponds to the ion-acoustic velocity range in the auroral plasma; on the other hand, the Doppler spectrum B in Fig. 6 associated with part of the strongest signal burst in Fig. 5a is very broad and centered close to zero shift. Comparison of the sequential spectra C, D and

E in Fig. 6 with Fig. 5 reinforces the suggestion, stated in the previous paragraph, that the shortlived peaks (marked with 'X') are caused by a type of scattering irregularity which differs from the one before and after these peaks. Figure 6D indicates clearly that for a short period of time (~20–30 s) a northward-moving group of irregularities develops with velocities confined to a narrow range (~350–500 m/s) near the ion-acoustic velocity range in the medium. These irregularities cause the sudden increase observed in the signal strength as well as the abrupt change in the mean Doppler shift; in Fig. 6C and D the broad spectral background centered close to zero shift position likely is caused by a different type of scatterers.

Discussion

The radio aurora is closely related to the magnetic substorms and in particular to the auroral electrojet current system (Tsunoda et al., 1976). Good spatial relationship between the radio aurora and the electrojet currents has been verified by experimental results, based on simultaneous radar scatter and ground magnetograms, obtained by various researchers (Greenwald et al., 1973; Ecklund et al., 1974; McDiarmid et al., 1976). This is in agreement with growing evidence that the auroral electrojet current represents the primary source of energy which sustains, through turbulent mixing and/or plasma instability mechanisms, the auroral scatterers. Studies by Gray and Ecklund (1974), Greenwald et al. (1975), and Czechowsky and Lange-Hesse (1970) have shown that at times the scatter amplitude is linearly related to the electrojet current intensity as deduced from ground-based magnetometers. A rough comparison between the chart-recorded signal strength records of our backscatter system and Saskatoon magnetograms shows that the radio backscatter is always accompanied by geomagnetic activity and that usually, but not always, there is a direct relationship between the strength and duration of the received echoes and those of the magnetic perturbations.

The most decisive recent experiment relating radio aurora to ionospheric parameters was the comparison by Siren et al. (1977) of the 50 MHz Anchorage coherent backscatter amplitude with electric fields and height-integrated current flow inferred from Chatanika incoherent scatter measurements of electron density and ion drift. The results indicate a linear relationship between the electrojet current magnitude and backscatter amplitude, the slope remaining constant whether the current is eastward or westward. A linear relationship was also found to hold between the north-south electric field strength and the echo amplitude, although threshold values of 25 mV/m northward and 10 mV/m southward had to be exceeded before the onset of instabilities in the eastward and westward electrojets respectively. Assuming that these results apply also to the 42 MHz Saskatoon Doppler system (which receives echoes from the L-value range 5.6–6.5 whereas Chatanika is at $L \sim 5.7$), the present results indicating a close relationship between amplitude and mean Doppler shift imply that the mean drift motion of the scatterers is determined by the electrojet current and/or the electric field.

At the present time it is believed that most of the radio auroral irregularities are generated by plasma instability mechanisms (basically the two-stream and the gradient-drift instabilities) which are current-associated since they require a certain relative electron-ion drift to exist in order for the plasma density waves to develop. The existing instability theories predict that the generated primary plasma waves propagate in the direction of the electron drift with a phase velocity close to the electron drift velocity, which itself is associated with the existing current system presumably present in the scattering region. Sudan et al. (1973a) used a nonlinear approach to show that when primary plasma wave irregularities (predicted by linear theory) are generated along the main electron drift, smaller scale secondary plasma waves may become unstable and propagate in directions centered about the perpendicular to the primary plasma waves. The phase velocity of the secondary waves depends again on the electron-ion drift velocity and the amplitude $A (A = \Delta N/N)$ of the primary wave. The plasma wave scatterers are strongly anisotropic spatially periodic structures of ionization, and cause coherent weak scattering of the incident radio waves if the plasma waves propagating along the radio wave line-of-sight have a wavelength equal to half the radio wavelength (Flood, 1967). Generally, for the case of plasma wave scatterers, it is believed that the relative electron-ion drift velocity is an important factor in determining not only the Doppler shift in frequency but also the strength of the scatterers as well (Farley, 1963; Unwin and Knox, 1971).

Very clear evidence of ion-acoustic waves has been presented in this paper. The results of Figs. 2 and 3 in the 300–500 s period (~0530 CST) labelled 'B' and 'C', and the 0–55 s interval labelled 'A' in Figs. 5 and 6 (~0000 CST) clearly show evidence of ion-acoustic echoes associated with northward motions, while the 600–800 s interval in Fig. 4 (~0056 CST) shows an ion-acoustic event associated with southward motion. The latter case is interesting since it suggests that the mean Doppler shift exhibits saturation but the amplitude does not. This agrees well with the observations by Siren et al. (1977) that no saturation is observed in echo amplitude with current or electric field strength, whereas many measurements (e.g., Hofstee and Forsyth, 1969; Haldoupis and Sofko, 1978b) have shown that the ion-acoustic velocity forms a limit to the two-stream instability echoes observed. The development of a brief northward moving ion-acoustic scatterer group in conjunction with a longer-lived broad spectrum is illustrated in the sections of Figs. 5 and 6 labelled C, D, and E.

Finally we mention briefly that some of the results presented suggest the possibility of irregularities other than those having a well defined wavelike structure (e.g., a random assembly of field-aligned short-lived blobs of ionization). In particular, the broad spectra of Fig. 3 associated with northward mean motions in the intervals A, D, and E in Fig. 2, and the broad spectra of Fig. 6 associated with southward mean motions in the intervals C, D, and E in Fig. 5, would seem to fall into this category. The possibility exists that a turbulent electrojet subject to inhomogeneous particle precipitation and rapidly changing electric fields may play an important role in generating and sustaining such an assembly of irregular scatterers. According to Sato (1968) the irregularities in a highly turbulent electrojet cannot be recognized as having the form of plasma waves. For the above case a theoretical relationship between the electrojet intensity and the mean frequency and amplitude of the backscattered signal is not known (if there is such a relationship, it must be rather complicated). According to Holtet (1973), the mean drift velocity (mean Doppler shift) of an assembly of weak irregularities is determined mainly by the existing large scale DC electric field present; this mean drift is in the same direction as the electrojet current under the assumption that the Hall conductivity dominates over the Pedersen conductivity (which is a well observed fact for the auroral regions, particularly for the westward electrojet, e.g., Kamide and Brekke, 1977; Horwitz et al., 1978). Egeland (1973), in explaining the variation of mean Doppler shift with azimuth angle (for a steerable antenna) or time of occurrence (for a fixed antenna), suggested that the echoes are the result of irregular ionization blobs drifting along the electrojet so that the mean Doppler shift would be the drift velocity of the irregularities times the cosine of the angle between the radio beam and the direction of the electrojet. If this is the case the direction of the electrojet relative to the radio beam is very important in determining the observed Doppler shift of the received echoes.

The electrojet dimensions (or spatial extent) may well have a direct effect on the population of scatterers and the degree of spatial uniformity in their motion. Also, the location of the electrojet with respect to the radio beam and the earth's magnetic field lines is very important for the strength of the radio scatter since it may affect drastically the aspect sensitivity of the echoes. For example, it is a common observation of our system that the early evening period is characterized by few, if any, echoes and that these echoes are weak. Maximum echo occurrence frequency takes place in the early morning hours when also the strongest signals are received. This may well be because of the position of the electrojet with respect to the optimum aspect sensitivity location for our system. At a scatterer height of 110 km, the aspect angle varies from about 97° to 93.5° as the echo range goes from 400 to 700 km. At a scatterer height of 90 km, however, the aspect angle is somewhat improved, going from 94° to 92° over the range 400 to 750 km. A characteristic difference in ionospheric altitude between the eastward electrojet in the evening sector and the westward electrojet in the morning sector was measured by Kamide and Brekke (1977); using the Chatanika incoherent scatter facility, they found that the eastward electrojet in the evening sector and the predominantly westward current system in the morning sector are located at approximately 120 and 100 km respectively, with the latter system showing much more variability. Thus, morning echoes from lower heights are optimal for our system if the scatterers are aspect sensitive.

According to the above discussion one may argue that the auroral electrojet plays a basic role in the creation, strength and the motion of the scattering irregularities. Presumably changes in the intensity of the current system (mainly due to the fluctuations in electron density and/or local electric fields) and in its dimensions and location cause the modulation observed in the mean amplitude and frequency of the radio echoes. In addition to the electrojet, the type of scatterer (e.g. a random assembly of numerous field aligned inhomogeneities or spatially periodic plasma wave scatterers) has an important effect on the amplitude-frequency relationship.

Conclusions

By using two linear demodulation units (an envelope and a frequency detector), simultaneous long period variations of the mean amplitude and frequency of the scattered signal have been investigated. The experimental evidence suggests that a common mechanism modulates both the average velocity (related to the mean Doppler shift) and the scattering cross-section (related to the signal strength) of the scattering irregularities. Although it was found that sudden changes in the signal strength are accompanied by well-defined changes in the mean Doppler shift, the overall relationship between the two variations is not a straightforward one. It was shown that the nature of the irregularities (i.e., the type of scattering mechanism) plays an important role in dictating the observed amplitude and frequency variations. For example, the evidence suggested that occasionally a physical process operates in the auroral plasma to impose an upper limit to the speed (and therefore the Doppler shift) of certain scatterers without limiting their scattering cross-section. Examination of concurrent averaged Doppler spectra indicated that this situation is observed usually with narrow ion-acoustic-type spectra. By assuming that the results of Siren et al. (1977) which show a linear relationship between 50 MHz backscatter amplitude and both the electrojet current and electric field (beyond the threshold values) over Chatanika ($L \sim 5.7$) are applicable to the Saskatoon 42 MHz Doppler system (echoes from $L = 5.6$ to 6.5), the close relationship between amplitude and mean Doppler shift for the (42 MHz) backscatter implies the common mechanism which 'modulates' both these quantities is either the electrojet current or the electric field or both. It was argued that changes in the strength, direction, dimensions and location of the flowing electrojet current system could be causing the long term variations observed in the amplitude and frequency of the auroral scatter.

Acknowledgements. The present research work was supported by the National Research Council of Canada.

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