A review on radio studies of auroral *E*-region ionospheric irregularities

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ABSTRACT. During the last few years, high latitude *E*-region ionospheric irregularities have been studied extensively with ground-based coherent VHF and UHF radar systems. Research in this field has been influenced greatly by the work done in the equatorial *E*-region because both phenomena have a good deal of common ground. The basic common property is that in both these regions of the ionosphere strong horizontal currents, carried by $\mathbf{E} \times \mathbf{B}$ drifting electrons, do exist and are believed to constitute the main source of energy that sustains through plasma instability mechanisms the small scale electrostatic turbulence in the media. Recent auroral observations, however, which include new echo types (e.g. types 3 and 4), large magnetic aspect angle effects, short-lived and spacially coherent localized scattering regions, have reenforced the conviction that, contrary to equatorial electrojet, there is a number of important different physical processes taking place in the auroral plasma. As a result, it is now becoming clear that equatorial *E*-region irregularity theories, which have been applied directly to aurora (i.e. to a medium that undergoes much more dynamic variations subject to geomagnetic substorms, field aligned currents and very intense electrojet systems), need further modification to account for these high latitude backscatter observations. In this paper, we review recent radar studies of auroral irregularities at different frequency bands in the VHF and UHF range, compare their findings and evaluate their physical significance. Emphasis is placed on Doppler spectral studies, because the Doppler spectrum signatures and properties of the echoes emerged through the years as the main diagnostic tool in the identification and study of instability méchanisms in the plasma. An objective of the paper is also to update some remaining questions/problems that need to be further studied and understood.

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1. INTRODUCTION

The most pronounced ionospheric backscatter phenomena occur in the magnetic equatorial and high latitude (auroral) *E*-regions, where it is known from magnetometer measurements that quite strong electrojets are present. This is because of the unique properties of ionospheric plasma at *E*-layer's maximum near 105 km, where ion motion is controlled by collisions with neutrals because $\nu_i \gg \Omega_i$ and electrons are entirely magnetized because $\nu_e \ll \Omega_e$. That leads to strong $\mathbf{E} \times \mathbf{B}$ Hall currents to set up in the presence of an appreciable ambient electric field. This picture applies in both the equatorial and auroral *E*-regions, although the field geometry, magnitude and dynamics, are quite different. At present, it is widely accepted that the electrojets play an active role as energy suppliers in generating and sustaining the electrostatic turbulence in both regions. It is this electrostatic turbulence that causes coherent scattering of radio waves at VHF frequencies or higher.

Short scale inhomogeneities in electron density have been studied extensively, in both the equatorial and auroral plasmas. It is fair to say, however, that our present interpretation and understanding of radio wave scattering phenomena from meter scale ionospheric irregularities has been based on the first radar studies of equatorial backscatter at the Jicamarca Radio Observatory in Peru (Bowles *et al.*, 1960 ; 1963) and the theoretical work of Farley (1963), as well as on subsequent important contributions originated mainly at Cornell University. Radio auroral research has benefited a lot from equatorial progress, a fact that came as a natural consequence. On the other hand, direct application of equatorial knowledge to radar aurora, which is a much more complex and dynamic phenomenon of direct magnetospheric control, constitutes in some ways a simplification of the problem. Therefore, it is not surprising that there is now an increasing list of observational facts in radar aurora not explained in the framework of equatorial reasoning.

There are several comprehensive reviews on the subject of ionospheric irregularities which examine several aspects of the radar auroral phenomenon (Fejer, 1979 ; Fejer and Kelley, 1980 ; Hanuise, 1983 ; Fejer, 1985 ; Fejer and Providakes, 1987). In the present paper we review mainly recent radar results related to *E*-region auroral irregularities with spatial scale sizes less than 3 m, i.e. detectable with radar systems operating at frequencies $f_r \geqslant 50$ MHz.

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The objective is to make an integrated survey of recent observations and compare them to existing theoretical predictions. We make an effort to assess the current situation by placing the emphasis on observations that have no equatorial counterpart, which at present are not adequately understood and need further work, both experimental and theoretical.

2. SOME BASICS ON SCATTERING FROM IRREGULARITIES

Figure 1 is to define, in a general conceptual manner, the experimental problem. In figure 1, the unmodulated transmitted signal is incident upon the auroral medium which acts as a « natural modulator » returning to the receiver a complex signal that is modulated in both amplitude and phase angle. In principle, the amplitude variations reflect changes of an effective irregularity scattering cross section, whereas changes in phase angle are due to line-of-sight irregularity movements. Of course, in treating the received echoes as a time varying bandpass signal, one should be aware of limitations due to spatial effects, because of separate backscatter subregions whose signals may cause strong interference at the receiver. Ultimately, it has been the task of radio auroral experimentalists, in the past 30 years of active research, to improve the resolving power of their observing equipment and apply effective techniques in the analysis of data in order to extract the returned information and determine its physical significance.

As mentioned, in this paper we are concerned with radio wave scattering at frequencies near, or higher than 50 MHz, which are well above the critical frequencies reflected from the earth's ionosphere. Scattering in this case is caused by field aligned electron density inhomogeneities generated by plasma instability mechanisms. The basic physical understanding originates in the theory of single scattering from a diffused ionized medium (e.g. see Farley, 1971). In this theory, for a plane wave incident upon a scattering volume V_s, which is large compared to the radio wavelength but small enough to ensure statistical uniformity, there is a scattered wave whose electric field is

$$E_s(t) \propto \int_{V_s} \Delta n(\mathbf{r}, t) \exp(-\mathrm{j}(\mathbf{k}_r - \mathbf{k}_s) \cdot \mathbf{r}) \, \mathrm{d}^3\mathbf{r} , \quad (1)$$

where $\Delta n(\mathbf{r}, t)$ represents the electron density fluctuations from the mean ambient value n_0 and $\mathbf{k}_r$, $\mathbf{k}_s$ are the wavevectors of the incident radio signal and received scattered wave, respectively. Equation (1) shows the scattered signal to depend on the spatial spectrum of electron density fluctuations evaluated at a particular Fourier component with wavevector $\mathbf{k}_r - \mathbf{k}_s$, which for backscatter in a literal sense, i.e. for a monostatic radar with $\mathbf{k}_r = -\mathbf{k}_s$, equals two times the radio wavevector. This comes as a result of constructive interference between wavelets originating at various phase fronts and adding coherently. Therefore, as Farley (1971) points out, the radio scattering measurements involve a spatial Fourier analysis of the scattering volume with the radar being sensitive only to one specific spacing and orientation of several plane wave fronts imbedded in an apparently random medium. This picture is visualized in figure 2. Notice that the sketched geometry is for the more general case of a bistatic system, for which the irregularity spacing depends also on the scattering angle Θ (i.e. $\lambda_{ir} = \lambda_r/(2 \sin(\Theta/2))$). The angle Θ is defined as $\Theta = \arccos(\hat{k}_r \cdot \hat{k}_s)$, and is equal to 180° for a monostatic radar.

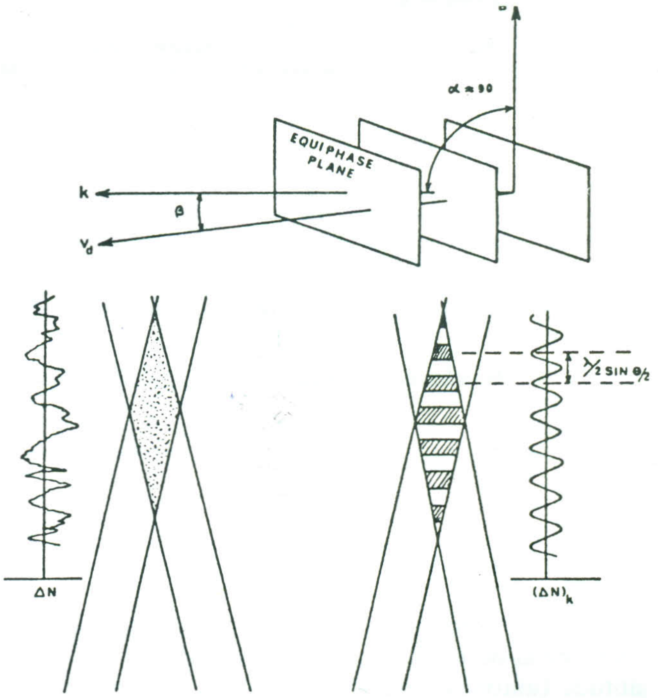

Figure 2

The radar is sensitive only to one spacing in the scattering volume defined by the radio wavelength and the scattering angle (from McNamara, 1971).

The plasma irregularities are magnetic field aligned, i.e. have their phase fronts nearly parallel to **B**. This is because in directions departing from perpendicularity, the plasma waves cannot be easily sustained due to strong damping by diffusion. This magnetic aspect sensitivity condition imposes certain restrictions on the experiment's location and design in general. For

Figure 1

The incident wave is both amplitude and phase angle « modulated » by the auroral scattering medium.

strong and frequent auroral echo reception, the radio system must be located well south of the scattering zone in order for the magnetic perpendicularity condition to be met. A typical monostatic auroral radar geometry, i.e. having the transmitter and receiver in the same site, is depicted in figure 3. In the present report, we dot not review the radar experiments and techniques used by various research groups. Such information can be found elsewhere in summarized form (e.g. see Fejer and Kelley, 1980 ; Hanuise, 1983).

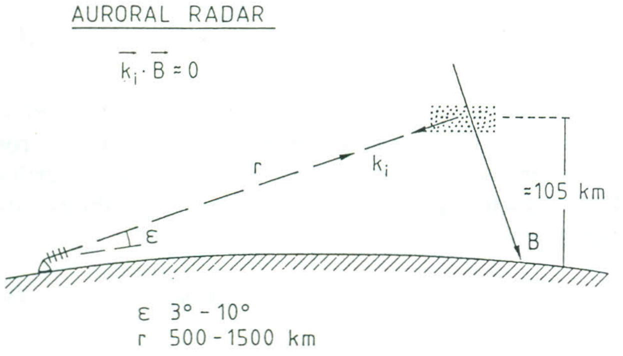

Figure 3

Radar location relative to auroral scattering zone. Figure was provided by K. Schlegel.

3. ELECTROJET PLASMA INSTABILITIES

Since the modern era in the study of electrojet plasma instabilities, that started with the independent works of Farley (1963) and Buneman (1963), there have been a large number of papers on both linear and nonlinear theories. It is not our scope to examine here all these theories and the interested reader should consult comprehensive reviews by Fejer and Kelley (1980) and Farley (1985). In this section we concentrate only on the basic material which is pertinent to the completeness of the present paper.

In the existing linear theories of electrojet instabilities the ambient electric field and electron density gradient are the primary driving terms in the generation of electrostatic plasma density waves. Both terms can be included in the same dispersion relation, representing the modified two stream and gradient drift instabilities respectively, but their significance differs depending upon the irregularity wavelength being considered. Following Rogister and D'Angelo (1970), who used a two-fluid collisional model for the electrojet plasma and assumed full magnetization for electrons and collision control for ions, one obtains the following expressions for the oscillation frequency

$$\omega_k = k V_d \cos\theta / (1 + \Psi) , \qquad (2)$$

and growth rate

$$\gamma_k = \frac{\Psi}{(1+\Psi)} \left[\frac{\omega_k^2 - k^2 C_s^2}{\nu_i} + \frac{\Omega_e \, \omega_k}{\nu_e k L} \right] , \qquad (3)$$

of electrostatic plasma waves. The term Ψ is defined as

$$\Psi = \frac{\nu_e \, \nu_i}{\Omega_e \, \Omega_i} \left(1 + \frac{\Omega_e^2}{\nu_e^2} \sin^2 \alpha \right) . \qquad (4)$$

A similar dispersion relation which in addition includes recombination effects, which are of significance for large wavelengths, is given by Fejer *et al.* (1975).

In the above equations ν_e, ν_i are the electron and ion collision frequencies with the neutrals, Ω_e, Ω_i are the gyrofrequencies, k is the plasma wavenumber, $C_s = \sqrt[2]{K(T_e + T_i)/\langle m_i \rangle}$ is the ion acoustic speed, $L = n_0/(\mathrm{d}n_0/\mathrm{d}x)$ is the electron density gradient scale length along the ambient electric field, V_d is the relative electron-ion drift speed ($\mathbf{V}_d = \mathbf{V}_e - \mathbf{V}_i$) which often is taken approximately equal to the electron Hall drift $\mathbf{E} \times \mathbf{B}/B^2$. The linear theory expressions in (2), (3) and (4) include two important directional dependences, one represented by the « flow angle », $\theta = \arccos\ (\hat{k} \cdot \hat{V}_d)$, and the other by the « magnetic aspect angle » α defined as the angle between the propagation vector **k** and the direction perpendicular to **B**. It turns out that the magnetic aspect angle control is indeed quite strong because the driving terms must take unrealistically high values in order for the instability to set up and be maintained at angles α higher than a fraction of a degree (e.g. see Farley, 1963 ; Wang and Tsunoda, 1975 ; Haldoupis and Sofko, 1978*a* ; Schlegel and St-Maurice, 1982 ; Fejer *et al.*, 1984*a*). This is equivalent to saying that the resulting plasma wave propagation is restricted in the plane perpendicular to the magnetic field.

Although the fluid approximation leads to comprehensive, closed form analytical expressions, it does not apply for short wavelengths down to ion gyroradius sizes (i.e. near 1 m at electrojet heights). On the other hand, kinetic theories are suitable for shorter wavelengths down to few centimeters. There are several kinetic theories developed for *E*-region electrojet instabilities (e.g. Farley, 1963 ; Lee and Kennel, 1973 ; Ossakow *et al.*, 1975 ; Schlegel and St-Maurice, 1982 ; Schlegel, 1983) which arrive in comparable results with fluid theory, even at scale sizes as short as 1 m. This means that for the majority of radar observations, i.e. at frequencies less than 150 MHz, fluid theory is adequate. For shorter wavelengths, however, one has to take corrections into consideration (e.g. see Moorcroft, 1979).

In the absence of density gradients (i.e. $L \to \infty$) the equations reduce to the Farley-Buneman instability which requires for the plasma to become unstable that $V_d \cos\theta \geqslant C_s(1 + \Psi)$. This mechanism can account for direct generation of short scale plasma waves inside a sector where $V_d \cos\theta \geqslant C_s(1 + \Psi)$ in directions close to perpendicular to **B**, and explain some properties of type 1 echoes. These echoes have narrow Doppler spectra with mean frequency shifts corresponding to wave phase speeds at, or slightly above, the ion acoustic speed in the plasma (e.g. see Cohen and Bowles, 1967 ; Balsley and Ecklund, 1972 ; Haldoupis and Sofko, 1976 ; Moorcroft and Tsunoda, 1978 among others). The role of density gradient term in the two stream instability has been examined for the equatorial case by Farley and Fejer (1975), and for the aurora by Fejer *et al.* (1984*a*), and found to be important for longer wavelength waves i.e. with $\lambda_{ir} \geqslant 20$ m.

When $V_d \cos\theta < C_s(1+\Psi)$, the unified two stream and gradient drift theory fails to account even for the excitation of meter scale irregularities with phase velocities less than C_s. These are known to be associated with the second distinct category of equatorial and auroral echoes, named type 2, which are observed at large flow angles, in directions nearly perpendicular to the electrojets. The difficulty of generating meter scale type 2 irregularities was resolved by a two-step mechanism proposed by Sudan *et al.* (1973). In this mechanism, wave energy cascades from longer wavelength primary waves to secondary short wavelength ones by the combined action of electric fields and density gradients of the primary waves. In essence, Sudan *et al.* (1973) applied the linearized fluid theory for indirect generation of secondary short wavelength irregularities by taking simply a sinusoidal variation for the electron density gradients of long wavelength primaries and replacing V_d in eq. (2) by

$$V_{ds} = \frac{\nu_i}{\Omega_i} \frac{V_d}{(1+\Psi)} A \sin\phi \,, \tag{5}$$

where V_{ds} is the relative electron-ion drift velocity caused by the polarization electric fields set up within the primary wave, A is the maximum wave amplitude (i.e. $\delta n/n_0 = A \sin\phi$) and ϕ is the phase angle in the frame of reference of the wave.

A better physical insight of eq. (5) can be obtained if we consider the local polarization fields and currents associated with a primary wave (e.g. see Sato, 1973). Figure 4 illustrates these quantities within a primary sinusoidal wave (of two stream and/or gradient drift type) propagating along the *x*-direction. In region *A* of the wave crest, the conductivity in the plasma would be somewhat higher than in neighboring region *B* of electron density trough. This, under the action of the primary *E*-field will cause alternating polarization fields to set up as shown in figure 4. In turn, these secondary fields will drive Pedersen currents along the *x*-direction and stronger Hall currents parallel and anti-parallel to the primary destabilizing terms. All currents will be stronger in region *A* than *B*, due to higher conductivity but the normal current component at the interface between the two regions must be continuous. This requires that

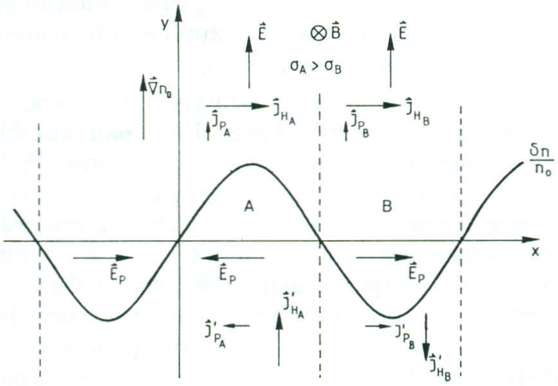

Figure 4

Secondary fields and currents within a long wavelength primary electron density wave generated by the two stream/gradient drift instability.

$$\mathbf{J}_{H_A} - \mathbf{J}'_{P_A} = \mathbf{J}_{H_B} + \mathbf{J}'_{P_B} \,, \tag{6}$$

where primed symbols refer to polarization field currents. By taking $n_A \simeq n_0 + \delta n$ and $n_B \simeq n_0 - \delta n$ and using eq. (6), we arrive in the following expression for the polarization fields

$$E_p = \pm E \frac{\sigma_H}{\sigma_P} \frac{\delta n}{n_0} \,, \tag{7}$$

where σ_H/σ_P is the local Hall to Pedersen conductivity ratio. Under the assumption that $\mathbf{E} \times \mathbf{B}$ electron drifts prevail in the region, the polarization drifts, V_{ds}, which drive the secondary instabilities are expressed by

$$V_{ds} = \pm V_d \frac{\sigma_H}{\sigma_P} A \sin\phi \,. \tag{8}$$

The last equation reduces to eq. (6) of Sudan *et al.* (1973), after substituting for the conductivity ratio $\sigma_H/\sigma_P \simeq (\nu_i/\Omega_i)/(1+\Psi)$.

By substituting V_d by V_{ds} and L^{-1} by $k_p A \cos\phi$ in eqs. (2) and (3), one obtains the corresponding equations for the oscillation frequency

$$\omega_{ks} = k_s \frac{\nu_i}{\Omega_i} \frac{V_d \cos\theta}{(1+\Psi)^2} A \sin\phi \,, \tag{9}$$

and growth rate

$$\gamma_{ks} = \frac{\Psi}{(1+\Psi)} \times \\ \times \left[\frac{1}{\nu_i} (\omega_{ks}^2 - k_s^2 C_s^2) + \frac{\Omega_e}{k_s \nu_e} \omega_{ks} k_p A \cos\phi \right] , \tag{10}$$

of secondary waves. The subscripts *p* and *s* stand for primary and secondary, respectively. If the secondary polarization fields and density gradients are strong enough (their strength depending on the ambient destabilizing terms and the primary wavelength), secondary meter scale irregularities can be generated in the crests and troughs of the primary wave and propagate in opposite directions.

The instability conditions resulting from the above equations have been exploited with success in both equatorial (e.g. Farley and Balsley, 1973 ; Fejer *et al.*, 1975) and auroral (Greenwald, 1974 ; Tsunoda, 1975 ; Moorcroft, 1979) backscatter studies to explain mainly the generation of type 2 echoes. On the other hand, this theory fails to explain important observations such as the Doppler spectrum and the existence of waves with phase velocities close to zero which are responsible for most of backscatter power of type 2 echoes. Obviously, the above model is only suggestive on the form of wave energy cascade but it cannot account for the isotropic turbulence as type 2 observations strongly suggest.

In the last few years there have been important theoretical developments on the subject of electrojet turbulence presented in a series of papers by Sudan's group at Cornell University (Sudan and Keskinen, 1979 ; Keskinen *et al.*, 1979 ; Kulsrud and Sudan, 1982 ; Sudan, 1983*a*). The basic process that leads to turbulence is wave-wave coupling through the nonlinear interaction of a triad of waves having comparable wavenumbers, i.e. waves with $k_1 \sim k_2$ are mixing to give $\mathbf{k}_3 = \mathbf{k}_1 + \mathbf{k}_2$ and this continues indefinitely leading to isotropization of waves. Numerical simulation studies (McDonald *et al.*, 1975 ; Ferch and Sudan, 1977 ; Keskinen *et al.*, 1979) seem to have confirmed the continuous cascade process, just described above, as capable of producing fairly isotropic turbulence at meter scale sizes. This theory, which predicts the irregularity spatial spectrum and explains several characteristics of equatorial type 2 echoes (e.g. see Farley, 1985), is certainly applicable to the auroral electrojet as well. In the following section we apply the predictions of this theory in the interpretation of existing results for type 2 auroral echoes.

The linearized two stream/gradient drift theory for type 1 echoes, can provide some but not all the answers. For example, it can predict the irregularity generation and what the growth rates and phase velocities are at the initial stage. The final state of the process can only be described by nonlinear mechanisms that determine the saturation of wave amplitude and the propagation characteristics of irregularities. In the seventies, a fair number of nonlinear theories have been developed, mostly for the equatorial electrojet, which tried to account for observational facts not explained by linear theory (for relevant references see Fejer and Kelley, 1980). The problem is that the assumptions used in these theories cannot be easily tested.

Recently, there have been more theories on the subject of nonlinear saturation of type 1 waves, published by Sudan (1983*b*), Robinson (1986), and St-Maurice (1987). In all these theories, the nonlinear interaction of electrostatic waves with the electrons in the ambient plasma is recognised as the most important process in understanding the physics of electrojet irregularities. By exploiting the concept of « orbit diffusion », discussed first by Dupree (1968), Sudan (1983*b*) developed a model which explained the stabilization of the Farley-Buneman instability spectrum and the long standing problem of constant phase velocity of type 1 echoes. This results from enhanced diffusion due to an anomalous increase of effective electron collision frequency caused by the wave electric fields which interact with the electrons and perturb their orbit in a random manner. For a detailed review and exposition of Sudan's theory, as it is applied to equatorial electrojet studies, see Farley (1985).

Robinson (1986) extended the wave-enhanced diffusion ideas and using them to electron wave heating phenomena in the auroral plasma he found the phase speeds of Farley-Buneman waves as a function of electron drift velocity. More recently, St-Maurice (1987) provided a unified view of the work that has been done to date on the subject of anomalous resistivity and wave heating effects in the unstable electrojet region, and presented several improvements. At present, researchers in the field are in the process of assessing the implications of these theoretical ideas and use them to the interpretation of the observations. We shall refer to these theories again, later in the paper.

4. OBSERVATIONS OF TYPE 1 AND TYPE 2 IRREGULARITIES

The terms « type 1 » and « type 2 » were originally used only in equatorial studies to identify two distinct irregularity types defined by the radar observing geometry and their Doppler spectrum characteristics. During the last few years, the same terms have also been applied in auroral backscatter studies with the same meaning as at the equator. In both cases, type 1 and type 2 irregularities are believed to be associated with primary and secondary plasma density waves, respectively, generated by the plasma instability mechanisms described in the previous section.

Besides the spectral observations, there is also a number of other observations that favor the two stream and gradient drift instability mechanisms. These include : 1) The observation of a threshold electric field corresponding to an electron drift near the ion acoustic speed in the plasma (Tsunoda and Presnell, 1976 ; Moorcroft, 1979 ; Cahill *et al.*, 1978). 2) The close association of backscatter properties to the electrojet strength and location (e.g. Greenwald *et al.*, 1973, 1975 ; Siren *et al.*, 1977 ; Haldoupis *et al.*, 1982). 3) Some positive evidence on the destabilizing role of horizontal electron density gradients, obtained *in situ* from rocket measurements (Pfaff *et al.*, 1984), ground-based 50 MHz interferometric and all sky camera observations (Providakes *et al.*, 1985), and STARE spectral measurements (Haldoupis *et al.*, 1985*a*). It should be noted, however, that the density gradient role has not yet been fully investigated.

In the following we review only certain prominent observational characteristics related to type 1 and type 2 irregularities and compare them to theory.

4.1. Doppler spectral signatures

Compared to the equator, there is a great deal more complexity and variability in auroral spectra. This reflects simply the dynamic nature of high latitude phenomena as well as the greater magnitude of the electric fields, the greater intensity of the currents and possibly also the greater degree of spatial structure to the field and current systems. The two main auroral spectral types are sketched in figure 5. The dashed line spectra indicate that they can be observed with either positive or negative Doppler shift polarity. Often, as a result of temporal and spatial averaging, a fair percentage of the observed spectra can be a mixture of the two elementary types. Notice that types 1 are narrower with peaks at a preferred frequency shift band near the ion acoustic speed, whereas types 2 are peaked at sub-ion acoustic speeds and are much broader suggesting the existence of strong plasma turbulence.

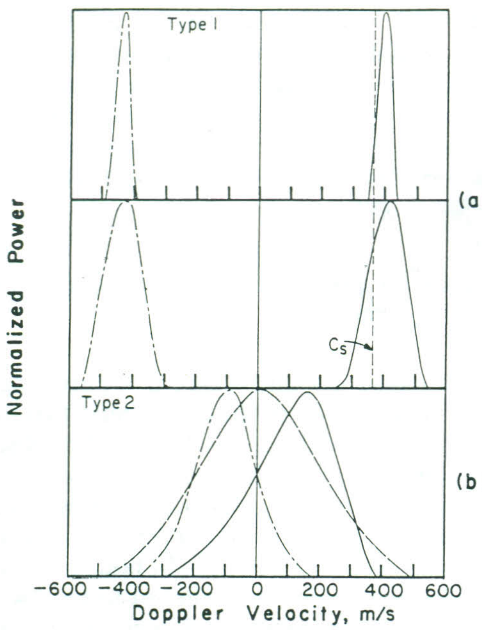

Figure 5

Drawings of typical power spectral signatures of type 1 and type 2 radio auroral electrojet echoes. Type 1 spectra are narrow with their peaks located at or slightly above the ion acoustic speed in the E-region plasma.

These spectral types have been reported by a number of researchers over a wide range of frequencies, i.e. in the 50 MHz band (Balsley and Ecklund, 1972 ; Greenwald and Ecklund, 1975 ; Haldoupis and Sofko, 1976 ; 1978*a* ; Reed, 1980 ; Providakes, 1985), in 150 MHz band (Nielsen *et al.*, 1984 ; Haldoupis *et al.*, 1984 ; Schlegel *et al.*, 1986), and in UHF band (Abel and Newell, 1969 ; Tsunoda, 1976 ; Moorcroft and Tsunoda, 1978). Typical examples of these spectral types observed at 50 MHz, 140 MHz and 400 MHz are shown in figure 6.

In general, the spectrum observations confirmed that the plasma instability mechanisms which operate at the equatorial *E*-region are also present in the auroral electrojets as well. A direct verification was provided by the recent results of Nielsen *et al.* (1984) and Haldoupis *et al.* (1984) obtained with STARE, a twin radar system which allowed concurrent observation of the same electrojet volume at small and large flow angles. Although the spectral resolution was poor, the STARE results proved the simultaneous existence of both irregularity types (primary and secondary) in the same volume and verified the pronounced azimuthal anisotropy of Doppler spectrum properties.

4.2. Electron drift velocity and irregularity phase velocity

The radar estimates the phase velocity (or angular frequency) of plasma waves. For type 1 echoes, linear theory predicts that phase velocity follows closely variations in electron-ion drift velocity which, to a first approximation, equals the electron drift velocity $\mathbf{E} \times \mathbf{B}/B^2$ in the electrojet. This theoretical prediction and preliminary experimental evidence led several people to believe that auroral radars could be used to deduce *E*-region drifts and, consequently, estimate electric fields quite accurately. This assumption seemed to work well for STARE (Greenwald *et al.*, 1978) and it has been used to estimate high latitude electric fields on a routine basis (Nielsen and Whitehead, 1983).

On the other hand, equatorial evidence on the invariability of type 1 echo phase velocity with elevation angle and its limitation to values equal the ion

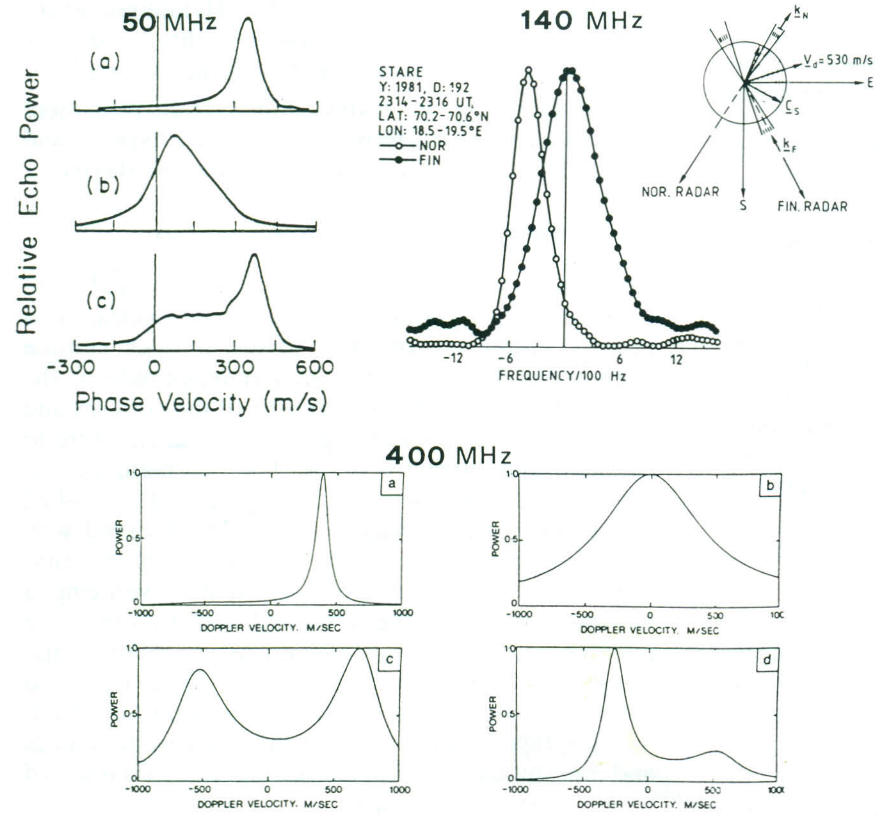

Figure 6

Typical examples of type 1 and type 2 Doppler spectra observed at different irregularity wavelengths or radar frequencies. 50 MHz : *from Reed* (1980) ; 140 MHz : *from Haldoupis* et al. (1984) ; 398 MHz : *from Moorcroft and Tsunoda* (1978).

acoustic speed, as well as several auroral Doppler results (e.g. Moorcroft and Tsunoda, 1978 ; Haldoupis and Sofko, 1978), suggested that the so-called « cosine law » relationship between phase velocity and electron drift velocity may not be valid. The first direct evidence in favor of this suggestion came recently from comparisons of STARE and EISCAT measurements. Nielsen and Schlegel (1985), examined simultaneous observations of wave phase velocities (STARE) and electron drift velocities (EISCAT) on a common flux tube in the *E*- and *F*-regions. Their findings are summarized in figure 7. From these results it has been confirmed that phase velocities of meter scale type 1 electrojet irregularities are limited to values near the ion acoustic speed, generally, in line with equatorial observations. The authors explained the variability of type 1 phase velocities as being due to alterations in ion acoustic speed caused by wave heating of electron gas.

A possible interpretation seems to come from Sudan's (1983*b*) theory. In this theory, the nonlinear dispersion relation results by substituting ν_e by $\nu_e + \nu_e^*$ in the linearized eqs. (2) and (3). Here, ν_e^* represents an anomalous electron collision frequency due to momentum transfer between electrons and plasma waves. The theory predicts that type 1 waves stabilized in this way would have phase velocities equal to the ion acoustic speed, i.e.

$$V_{\mathrm{ph}} = \frac{\omega_k}{k} = \frac{V_d \cos\theta}{1 + \Psi + \Psi^*} \simeq C_s\,, \qquad (11)$$

where $\Psi^* = \nu_e^* \, \nu_i / \Omega_e \, \Omega_i$. It is important to mention that eq. (11) applies strictly to propagation perpendicular to the magnetic field and the appropriate expression for Ψ here is that given in eq. (4) but with α set equal to zero. Notice that ν_e^* is anisotropic in the plane perpendicular to **B** depending on the wave amplitudes $\delta\mathbf{E}$ which maximize along $\mathbf{V}_d$ and drop to zero at the angle $\theta_c = \arccos\,[C_s(1 + \Psi)/V_d]$. In this theory, all type 1 waves inside the unstable sector defined by θ_c, would propagate at the ion acoustic speed, as it is apparently observed.

Robinson (1986) extended Sudan's theory to include anomalous wave heating effects due to electron-plasmon (i.e. plasma wave) collisions, which would dominate over electron-neutral collisions when Farley-Buneman waves are strongly excited. Robinson solved numerically the equations to find that C_s increases monotonically with V_d, this dependence being stronger at higher than lower altitudes. The altitude variations are due to changes with height of ambient plasma parameters. In figure 7, we took the liberty to superimpose Robinson's theoretical curves on the observations of Nielsen and Schlegel (1985) for comparison purposes. Obviously, there is an excellent agreement if we assume that scattering comes, on the average, from heights near 103 to 105 km.

To get a feeling for the magnitude of ν_e^*, let us consider the results shown in figure 7, and apply eq. (11). If we take $V_d = 1000$ m/s (i.e. $E \sim 50$ mV/m), we find from the best fit curve of Nielsen and Schlegel (1985) that $C_s = 410$ m/s. Next, if we assume that scattering comes on the average from 104 km and use CIRA (1972) model atmosphere to get $T_e = T_i = 212$ K and $\nu_i = 2.3 \times 10^3\ \mathrm{s}^{-1}$, an electron temperature $T_e = 410$ K is inferred from the above value of C_s and consequently, an electron-neutral collision frequency $\nu_e = 4.6 \times 10^4\ \mathrm{s}^{-1}$. To compute ν_e we used the equations proposed by Schunk and Nagy (1978) and the CIRA (1972) model atmosphere. Finally, after substituting the above numbers for ν_e, ν_i and C_s to eq. (11), we get $\nu_e^* = 25\ \nu_e = 1.1 \times 10^6\ \mathrm{s}^{-1}$. In the same way, if we use the height of 112 km ($T_e = T_i = 260$ K, $\nu_i = 0.7 \times 10^3\ \mathrm{s}^{-1}$) we obtain for the same C_s a value for $\nu_e = 1.1 \times 10^4\ \mathrm{s}^{-1}$, and finally $\nu_e^* = 280\ \nu_e = 0.9 \times 10^6\ \mathrm{s}^{-1}$.

Indirect evidence on the magnitude of ν_e^* has been provided by Primdahl and Bansen (1985) and Primdhal (1986), who were able to explain *in situ* measurements of electrostatic wave potential fluctuations by using Sudan's theory and taking values for ν_e^* in the range between 0.8×10^6 to $2.5 \times 10^6\ \mathrm{s}^{-1}$. Recently, Igarashi and Schlegel (1987), who measured with EISCAT considerable electron temperature enhancements in auroral *E*-region, found an excellent agreement with theoretical estimates of electron gas heating by assuming an average density perturbation of 3.5 percent (heating theory of St-Maurice *et al.*, 1981), or an anomalous electron collision frequency ν_e^* of 1.0 to $2.0 \times 10^6\ \mathrm{s}^{-1}$ (theory of Robinson, 1986). The quoted values for ν^* are all in the range from a few

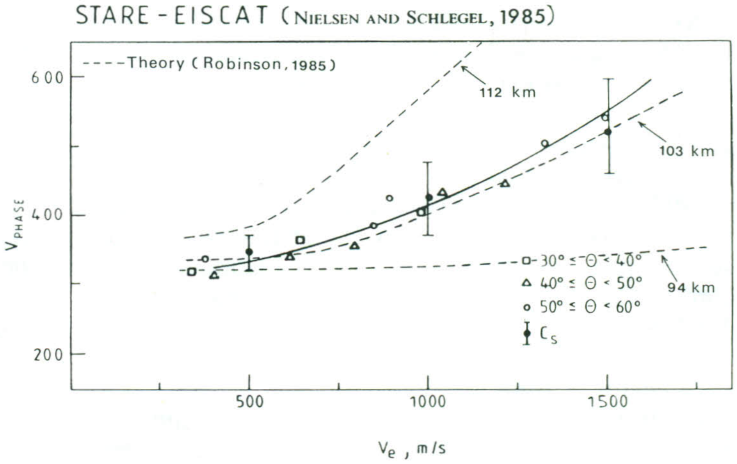

Figure 7

Experimental results of Nielsen and Schlegel (1985) *and theoretical predictions (adapted from Robinson,* 1986) *on the dependence of irregularity phase velocity on electron drift velocity.*

percent to 25 percent of the electron gyrofrequency ($\Omega_e = 10^7\ \mathrm{s}^{-1}$). Can ν_e^* take such large values without violating the basic assumption that electrons are strongly magnetized ? This question is addressed by St-Maurice (1987) who estimated the upper limit for ν_e^* to be less than about 10 percent of Ω_e, by using known estimates of full turbulence limits. He concluded that if this is indeed true, then ν_e^* may in fact be overestimated by a Sudan-type theory.

4.3. Irregularity scattering cross sections

In the radar equation (e.g. see Moorcroft, 1987*a*), the received signal strength is directly proportional to the scattering cross section (SCS) of the irregularities. The latter is a measure of absolute mean level of electron density fluctuations along the radar line of sight and only at the specific spacing which equals half the radar wavelength, i.e.

$$\sigma_k \propto \langle |\Delta n(2\,k_r)|^2 \rangle \,, \tag{12}$$

where k_r is the radar vector wavenumber and $\langle |\Delta n(2\,k_r)|^2 \rangle$ is the mean spatial Fourier component, at the specific wavelength π/k_r, of electron density fluctuations in the scattering volume. In principle, one can measure the absolute radar scattering cross section and derive information about the rms level of fluctuations in the medium. In practice, however, the difficulty in determining the various quantities entering the radar equation makes measuring σ_k a very tricky problem. On the other hand, the relative scattering cross section can easily be estimated if one adopts some arbitrary normalization.

Accumulated experimental evidence shows that σ_k depends upon a number of parameters such as drift velocity V_d, ambient electron density n_0, flow angle θ, and magnetic aspect angle α. In other words, σ_k becomes a complicated function, $\sigma_k = f(V_d, n_0, \theta, \alpha)$, whose form is not known. At present, the existing observations provide only simple empirical relationships, whereas a unified theoretical treatment of the subject is far from complete.

Magnetic aspect angle

The dependence of σ_k on α is a well known phenomenon observed since the beginning of radio auroral research. The decrease of backscatter intensity with magnetic aspect angle, known as aspect sensitivity (AS), is expressed in dB/degree. The overall picture on AS remains unclear and somewhat contradictory, because various experiments yielded widely different results. From the existing publications, one may in general conclude that echoes at 50 MHz are less aspect sensitive than those at 150 or 400 MHz. At 50 MHz the echo intensity decreases at an average rate of 1 to 3 dB/deg while at higher frequencies the rate is near 8 to 10 dB/deg (e.g. Leadabrand *et al.*, 1965 ; Chesnut *et al.*, 1968 ; McDiarmid, 1972 ; Ecklund *et al.*, 1975 ; Koehler *et al.*, 1985 ; Haldoupis *et al.*, 1986 ; Nielsen, 1988). Apparently, this difference emanates from the fact that longer scale electrostatic turbulence is more easily generated compared to shorter scale. In order to explain the aspect sensitivity, Moorcroft (1985) introduced a scattering model consisting of an assembly of wave-like irregularities, each with a gaussoidal envelope, that added up having an effective scattering coefficient as a function of aspect angle. Although Moorcroft had taken into consideration all possible contributions to aspect sensitivity (e.g. magnetic field line distortion and ionospheric refraction), he concluded that the experimental observations required scattering models consisting of irregularities elongated along the magnetic field by only a few plasma wavelengths which is physically unreasonable.

Flow angle and drift velocity effects

Naturally, the well known Doppler spectrum anisotropy in the observing plane, caused by the presence of two distinct irregularity types that dominate entirely different azimuthal sectors relative to the destabilizing drift, is expected to apply to SCS as well. The first systematic study of auroral SCS in the azimuthal plane was carried out by André (1983) at 140 MHz with the STARE dual radars. André's results confirmed an anisotropy in the signal strength with flow angle, with a density fluctuation minimum at $\theta = 90^\circ$ and an increase towards $\theta = 0^\circ$ over the drift velocity range up to 1000 m/s.

Haldoupis and Nielsen (1984) studied the relative SCS angular dependence of 140 MHz backscatter using Doppler spectra to identify the irregularity types. In their results, type 1 primary irregularities have highly anisotropic SCS as compared to secondary 1 m waves. The strength of primaries is strongly dependent on flow angle with the intensity decreasing from 0.3 to 0.6 dB/deg as θ increases ; on the other hand, the strength of secondaries is rather weak and insensitive to angular variations, in line with the concept of isotropic turbulence. These findings agree with similar results reported by Ierkic *et al.* (1980) for 50 MHz equatorial backscatter. Recently, Mattin and Jones (1987) reported a detailed study on flow angle dependence of 1 m irregularities based on dual radar SABRE measurements, which show that the problem is more complex. They found that, although for small drift velocities there is isotropic behaviour, at higher drifts there are anisotropies developing in the observing plane which are not symmetric showing unexpected subsidiary minima at directions along the drift, i.e. at directions where one would have expected the signal to maximize.

As pointed out by Fejer and Providakes (1987), Sudan's (1983*b*) theory predicts for type 1 waves at electrojet altitudes with $k_\parallel = 0$, that

$$\sigma_k \propto [(V_d \cos\theta - C_s)/C_s]^2 \,. \tag{13}$$

Notice, that according to the theory C_s is also depending on $V_d \cos\theta$ due to anomalous electron gas heating as it has been discussed in Section 4.2. Equation (13) implies that wave saturation amplitudes increase in a nonlinear manner with radial drift $V_r = V_d \cos\theta$, in general agreement with the observed flow angle anisotropy. The only semi-quantitative experimental study on the dependence of relative SCS on $V_d \cos\theta$ has been reported by

Haldoupis *et al.* (1984) for 1 m waves with $k_\parallel \sim 0$, using STARE spectral data. In the analysis, they used a large data base from different events and assumed the effect on σ_k from other parameters to average out, to a large extent. In addition, they have dealt with electric fields less than 40 mV/m (i.e. electron drifts less than 800 m/s) which are believed to be estimated fairly accurately by STARE (Nielsen and Schlegel, 1985). From figure 8*a*, showing the results of Haldoupis *et al.* (1984), one sees that $\sigma_{1m} \propto (V_d \cos\theta)^{3.5}$. To compare with theory, we plot in the same figure the result of eq. (13) using some appropriate arbitrary normalization. The comparison shows not very good agreement for radial velocities below 500 m/s, i.e. in the range where most of type 1 echoes are observed.

For secondary irregularities, the strong turbulence theory of Sudan (1983*a*) shows the saturation amplitudes to depend on both ambient destabilizing terms V_d and L in the following way (e.g. see Farley, 1985)

$$\sigma_k \propto L^{-4/3} V_d^{2/3} . \qquad (14)$$

The STARE data study of Haldoupis *et al.* (1984), seen in figure 8*b*, shows that $\sigma_{1m} \propto V_d^{2/3}$, a result that is in good agreement with a similar dependence found at 50 MHz in the equator (Balsley, 1969 ; Farley and Balsley, 1973) and from numerical simulations of Keskinen *et al.* (1979). As Farley (1985) has also pointed out, the agreement between theory and experiment is rather poor. This is shown in figure 8*b* where we superimposed the result of eq. (14) assuming L = const. For a detailed discussion on this point see Farley (1985).

Ambient electron density

We have just seen that a strong dependence of σ_k on V_d, or ambient E field, does exist. On the other hand, there is a number of studies both at 50 MHz (Greenwald *et al.*, 1975 ; Siren *et al.*, 1977) and at higher frequencies (e.g. Haldoupis *et al.*, 1982 ; Uspensky *et al.*, 1983, 1986 ; Starkov *et al.*, 1983) suggesting that $\sigma_k \propto n_0^2$. Apparently, the backscatter strength under some circumstances is governed by the ambient E field and under some other circumstances by the ambient electron density. The n_0 control seems to be dominant at drift velocities well above the required ion acoustic speed threshold for type 1 irregularities. The reasons for σ_k to be at times proportional to n_0^2 and the competing roles of n_0 and E field, are not clear. It is interesting to point out that the existing theories do not include the ambient electron density in the calculations of wave saturation amplitudes. Certainly, the role of n_0 in the backscatter process is not well understood.

Absolute scattering cross sections

Oksman *et al.* (1986), were the first to attempt some specific calculations of absolute SCS of radar aurora, utilizing data from several radars, to calculate mean fractional electron density fluctuation amplitudes. Recently, Moorcroft (1987*a*) conducted a thorough study on absolute SCS by exploiting published material on calibrated backscatter measurements to estimate absolute scattering coefficients per unit volume in over a range of frequencies from 30 to 1210 MHz. In his calculations Moorcroft used a 10 km width for the scattering layer and selected data where the aspect angles were close to zero, so as to minimize magnetic aspect angle effects ; the estimated SCS are illustrated in figure 9*a*. Notice that the scattering coefficients vary over 3 orders of magnitude at any frequency, and that there is a definite trend for cross sections to decrease with frequency.

By using a number of arguments based on experimental evidence, Moorcroft (1987*a*) concluded that the strongest events in each distribution of figure 9*a* are due to primary (type 1) irregularities and produced figure 9*b* which shows estimates of maximum SCS as function of radar frequency or irregularity wavelength. The straight line is a least squares fit to all points except for 30 and 1210 MHz data which were excluded for a number of reasons discussed in detail by Moorcroft (1987*a*). In the range between 50 and 800 MHz, i.e. λ_{ir} between 3 m and 0.2 m, the frequency dependence for waves propagating along the destabilizing flow and perpendicular to **B** can be described well by an absolute scattering cross section per unit volume given by

$$\sigma_v = 3 \times 10^{-7} k^{-2.25} , \quad \mathrm{m}^{-1} . \qquad (15)$$

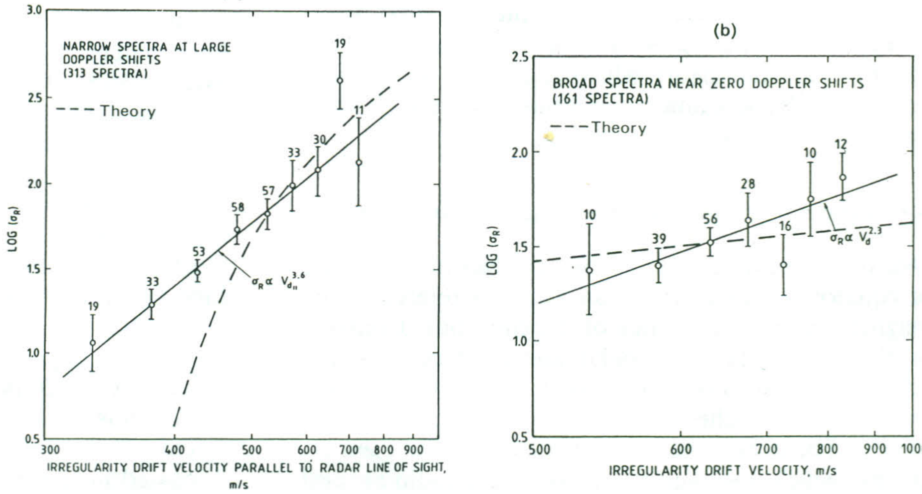

Figure 8
Relative scattering cross section dependence on drift velocity for type 1 *(fig. 8a) and type* 2 *(fig. 8b) of* 140 MHz *auroral echoes* (STARE). *The dashed lines were based on theoretical predictions (Sudan,* 1983*a ;* 1983*b) using arbitrary normalization.*

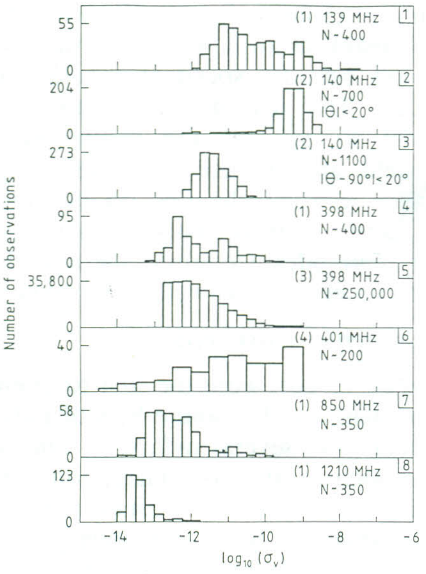

Figure 9*a*

Occurrence distributions of absolute scattering coefficients of radar auroral irregularities observed at different frequencies (from Moorcroft, 1987a).

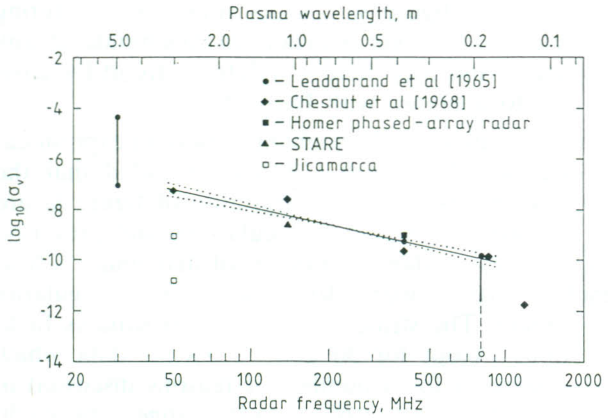

Figure 9*b*

Estimates of maximum absolute scattering coefficients of radio auroral echoes (presumably of type 1) as a function of radar frequency or irregularity wavelength. In the same figure available results from the equator (Jicamarca) are included for comparison purposes (from Moorcroft, 1987a).

The dotted lines in figure 9*b* indicate a range uncertainty of 0.35 for the power of 2.25 in the above equation. It is interesting to point out that these results are in fair agreement with Sudan's (1983*a* ; 1983*b*) nonlinear theory which suggests a k^{-2} dependence for the saturation amplitudes of type 1 short wavelength irregularities.

4.4. Echo occurrence at large magnetic aspect angles

One of the most important discrepancies in the nature of equatorial and auroral backscatter is related to the magnetic aspect properties of irregularities. Contrary to the equatorial case, radio auroral type 1 and 2 echoes do exist, although weaker, at magnetic aspect angles much higher than one degree allowed by theory. There have been several radar auroral experiments, which observed routinely strong radio auroral echoes coming from aspect angles in the range between 1° to more than 15° (e.g. Leadabrand *et al.*, 1965 ; McDiarmid and McNamara, 1967 ; McNamara, 1971 ; Hofstee and Forsyth, 1972 ; Ecklund *et al.*, 1975 ; Mitchell and Brown, 1976 ; Sofko *et al.*, 1983 ; Koehler *et al.*, 1985 ; Providakes, 1985 ; Haldoupis *et al.*, 1986 ; André *et al.*, 1988).

Recently, coherent radio auroral echoes were reported to have been observed at large magnetic aspect angles with incoherent radar systems operating at UHF. St-Maurice *et al.* (1989) observed auroral echoes, received by the Millstone Hill radar (440 MHz) that is located south of the auroral zone, at aspect angles as large as 11°. Also, Moorcroft and Schlegel (1988) have reported coherent auroral echoes detected by EISCAT (933 MHz), the large European incoherent facility located near the center of the auroral zone in northern Scandinavia. Contrary to theoretical predictions, Moorcroft and Schlegel (1988) observed weak coherent *E*-region echoes at aspect angles as large as 6 degrees, when the EISCAT antennas were directed north at low elevation angles.

Haldoupis *et al.* (1987) analysed a large data base compiled from several experiments at 50 MHz, carried out in Central Canada by the University of Saskatchewan. The measurements were made with high resolution CW Doppler systems at 10 different aspect angles ranging between 1° and 14°. Their evidence suggested that 3 m primary and secondary plasma waves with $k_\parallel / k_\perp$ wavenumber ratios perhaps larger than 0.25 do exist in the auroral plasma on a continuous basis. Figure 10 shows several examples of both type 1 and type 2 echoes observed simultaneously from two different azimuths at fairly large aspect angles, 9.5° and 13.5°. The aspect angle statistics of type 1 and 2 echoes, presented by Haldoupis *et al.* (1987), are summarized in figure 11. Notice, the basic spectral properties of 50 MHz echoes follow only minor changes with aspect angle in the 1° to 15° range. On the other hand, Ogawa *et al.* (1980) reported a significant decrease of type 1 phase velocity with aspect angle in the 1° to 5° range, for 50 MHz echoes. This result, however was based on a limited data and it is not clear if they dealt with type 1 irregularities only.

The linearized theories of both primary and secondary electrojet instabilities fail to explain generation of irregularities at angles higher than a degree or so, because the driving terms must take unrealistically high values. A mechanism, which possibly could extend electrostatic turbulence at higher aspect angles, is some kind of anomalous resistivity which could introduce electron collision frequency enhancements in the dispersion relation. The destabilizing role of electron collisions is well recognized in current driven instabilities (e.g. see D'Angelo, 1973). Such a mechanism was proposed by Volocevich and Liperovskiy (1975). Haldoupis *et al.* (1986), have shown that, in order to explain their results, one needs very large electron collision frequencies of the order of 10 to 20 percent of the electron gyrofrequency. There seems to be no theory to justify such large electron collision frequencies. A Sudan-type theory, discussed in the previous section, was developed only

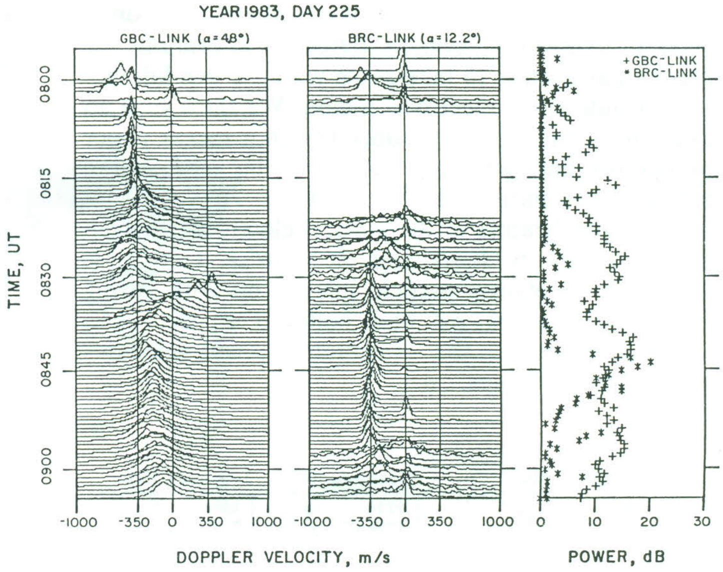

Figure 10

Simultaneous sequential Doppler spectra from two widely different azimuths show that type 1 and type 2 echoes are observed at quite large magnetic aspect angles (here aspect angles are 5° and 12° ; from Haldoupis et al., 1986*).*

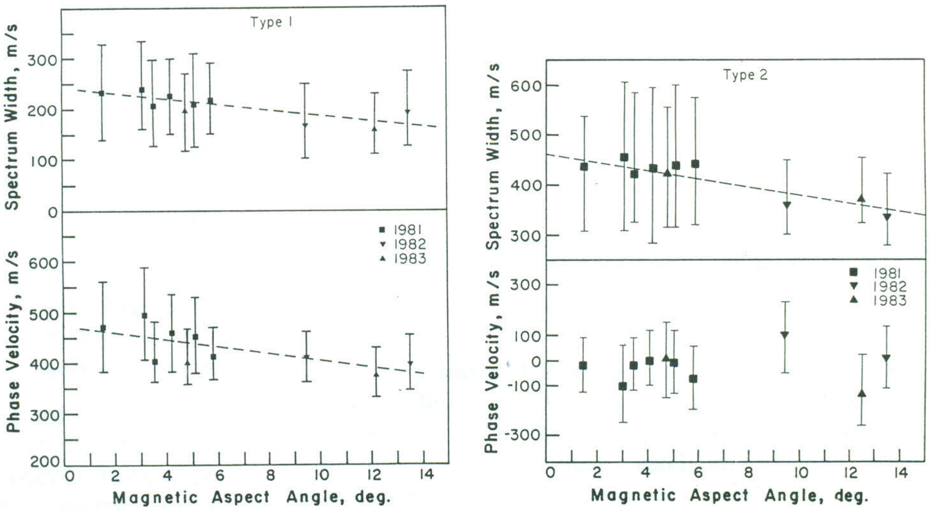

Figure 11

Variation of type 1 and type 2 mean spectral properties with magnetic aspect angle, based on different experiments at 50 MHz (from Haldoupis et al., 1987*).*

for $k_\parallel \sim 0$ and cannot be applied to large aspect angles. Therefore, the concept of anomalous ν_e enhancements may be suitable for explaining effects at small aspect angles, (Nielsen (1986) has demonstrated that STARE 140 MHz results are consistent with a six-fold enhancement in ν_e), but is inadequate for backscatter at aspect angles larger than a couple of degrees. At present, we have not yet a convincing theoretical interpretation of auroral backscatter properties at large magnetic aspect angles.

5. ALTITUDE CHARACTERISTICS OF AURORAL BACKSCATTER

First, we should point out that most radar experiments could not provide adequate height information to be used in the interpretation of data, because of broad antenna beamwidth in elevation. This was an important disadvantage because there are several reasons to believe that height effects do exist and must play a crucial role in the physics of the phenomena. Ambient plasma parameters (e.g. temperatures, collision frequencies, electron density and density gradients) that affect the instability mechanisms and the magnitude and direction of electrojet, do change appreciably with altitude. For example, figure 12 shows important height differences in the theoretical dependence of threshold electric field for two stream waves at

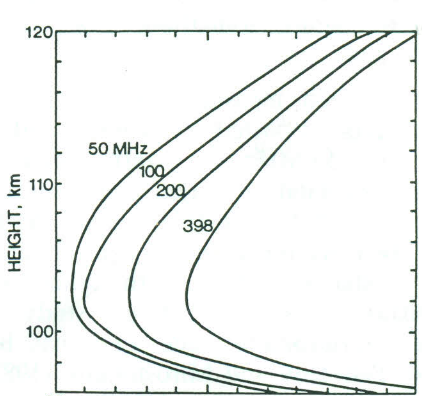

Figure 12

Height dependence of threshold electric field of two stream generated waves at various frequencies (from Moorcroft, 1979).

various frequencies. Furthermore, there is enough evidence showing sizeable dynamic alterations of plasma parameters to take place within a few kilometers altitude in the electrojet region. We show such an example in figure 13 reproduced from a recent paper by Igarashi and Schlegel (1987) referring to *E*-region temperatures measured with EISCAT. The anomalous electron heating in the auroral electrojet, discovered first by Schlegel and St-Maurice (1981), is attributed to plasma particle interaction with strong Farley-Buneman waves and believed to act as a feedback element in the saturation of phase velocities of two stream waves.

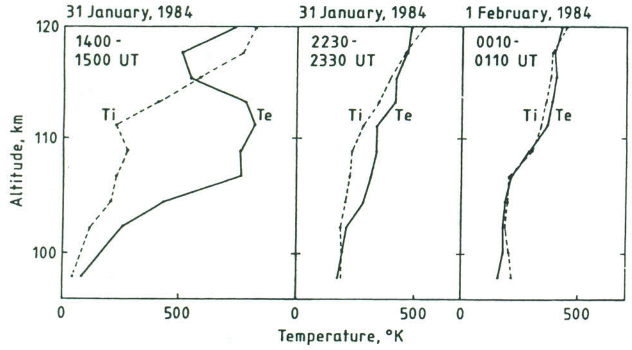

Figure 13

Example of an anomalous electron heating event in the E-region as measured by EISCAT *(from Igarashi and Schlegel,* 1987*).*

The auroral echoes are believed to come from an *E*-region layer centered near 107 km and having a variable thickness from less than 2.5 km to possibly more than 20 km. These numbers came from radar backscatter altitude estimates (e.g. see Unwin, 1972). Also rocket measurements detected, with ac electron density and *E*-field probes, a layer of strong electrostatic turbulence located between 95 and 120 km (e.g. see Kelley and Mozer, 1973 ; Bahnsen *et al.*, 1978 ; Ogawa *et al.*, 1976 ; Pfaff *et al.*, 1974). However, it is important to keep in mind that rocket measurements are biased towards long wavelengths, longer than those observed with radars, so they are not looking in the same part of the irregularity spectrum. Often we simply infer that rocket observations are valid to shorter wavelengths, something which may not be necessarily true.

The first detailed measurements of radar auroral altitude effects, reported by Unwin and Johnston (1981) with a 53 MHz sea interferometer radar in South New Zealand, revealed considerable altitude structuring within the electrojet layer. At time they observed two scattering layers, at about 106 and 112 km, producing echoes with different spectral characteristics. A second detailed study using the same sea interferometer technique, has been conducted by Timofeev and Miroshnikov (1982) with a 90 MHz radar in Karelia, USSR. Their findings include, 1) much more altitude variability and layering in the westward than eastward electrojet, 2) a pronounced east-west altitude asymmetry in both electrojet time sectors and, 3) short-lived and localized double scattering layers with a thickness of about 2 km and an altitude separation of less than 10 km. They have attributed these effects to a mechanism of collective interaction of energetic auroral electron fluxes with the *E*-region plasma. In general, we do not know at present in what way this altitude structuring affects the scattering mechanisms of radar aurora.

Uspensky (1985) presented a model for a quantitative estimation of backscatter altitude profiles. This was based on the radar beam geometry, the variation of magnetic aspect angle with height and the dependence of scattering cross section on electron density. He found that for radar frequencies smaller than about 70 MHz and moderate to high *E*-layer electron densities, the altitudinal profiles of auroral backscatter show double maxima structures due to radio wave ionospheric refraction. For frequencies higher than 70 MHz, for which refraction becomes unimportant, only single peaked profiles are predicted. Uspensky (1985) had shown that his model is capable in explaining the observations of Unwin and Johnston (1981). On the other hand, it does not explain the double layer structures observed by Timofeev and Miroshnikov (1982) at 90 MHz. In a more recent paper Uspensky *et al.* (1986) have discussed the possibility of the formation of a double hump profile in auroral backscatter altitude profiles for higher frequency radio waves. In this case the decisive parameter is the vertical electron density gradient which must become larger than some threshold value. Obviously, these ideas are certainly useful but their validity can only be established by adequate experimental testing.

Important information on height effects for 398 MHz backscatter have been obtained by Ruohoniemi and Moorcroft (1985) by utilising the narrow beam elevation scanning capability of the Hommer radar in Alaska. In their technique, they exploited the different echo intensities from successive elevation positions at a given range to calculate the elevation angle, and therefore the altitude, of the scattering layer. They found important differences in the echo altitudes for premidnight and postmidnight backscatter periods, i.e. in the eastward and westward jets, respectively. For the east jet the echo altitudes were confined between 97 and 117 km whereas for the postmidnight period (westjet) the scattering layer was much narrower centered at lower altitudes near 103 km. The lower heights for westward electrojet could be explained, considering the role of electron density in scattering cross section, as described by Uspensky (1985), and that the westward jet is usually centered at altitudes considerably lower than the eastward electrojet (Kamide and Brekke, 1977). Further work by Moorcroft and Ruohoniemi (1987) on Doppler velocity altitude variations at 398 MHz, revealed, among other things, that low velocity echoes, presumably due to secondary waves, are more restricted in height range than echoes with ion acoustic velocities which are believed to come from primary, Farley-Buneman waves. This interesting result of Moorcroft and Ruohoniemi (1987), which is shown in figure 14, is difficult to be explained and understood without supportive observational evidence.

At present, the existing theories are not adequate in explaining altitude observations of the type shown in figure 14. As Moorcroft and Ruohoniemi (1987) pointed out, it is now clear that height information is essential for the physical understanding of auroral backscatter observations. Furthermore, detailed height measurements might be useful in testing existing theoretical predictions on plasma wave propagation within the unstable layer, both upward and downward along the magnetic field lines (Moorcroft, 1984 ; St-Maurice, 1985 ; Moorcroft, 1987*b*). For example, the waves grow as they propagate and if growth rates are larger compared to propagation times, then one would expect to observe the strongest echoes coming from the top and bottom of the unstable layer.

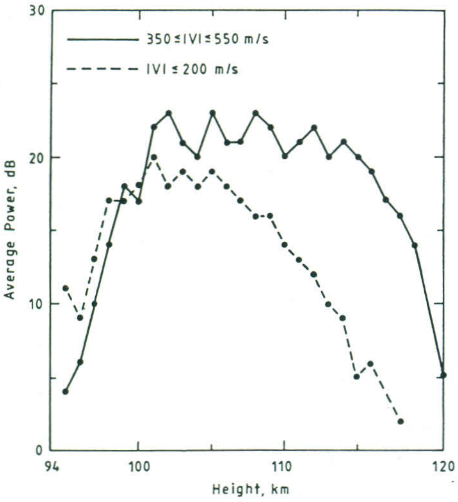

Figure 14

Average echo power in dB versus *altitude for type* 1 *and type* 2 *echoes at* 398 MHz *(from Moorcroft and Ruhoniemi,* 1987*).*

6. NEW ECHO TYPES AT 50 MHz AURORAL BACKSCATTER

In the previous sections we reviewed type 1 and type 2 irregularity characteristics detectable in the entire VHF and UHF range. These we interpreted in the framework of two stream, gradient drift, and secondary instabilities. In this section we examine in brief two newly discovered categories of auroral radar echoes observed so far only at 50 MHz, i.e. with 3 m irregularities. The terms used to identify these echoes are « type 3 » and « type 4 », in contrast to the familiar type 1 and 2.

6.1. Type 3 echoes and ion cyclotron instabilities

Type 3 echoes (Reed, 1980 ; Fejer *et al.*, 1984*b* ; Providakes *et al.*, 1985 ; Haldoupis *et al.*, 1985*b* ; Prikryl *et al.*, 1987) are identified by their Doppler spectrum signature sketched in figure 15. On the average, type 3 echoes are related to strong intensity signals having very narrow spectra peaked below ion acoustic Doppler speeds and preferentially either in the 50 to 70 Hz shift band (150 to 220 m/s) or less often in the 20 to 40 Hz shift range (60 to 120 m/s).

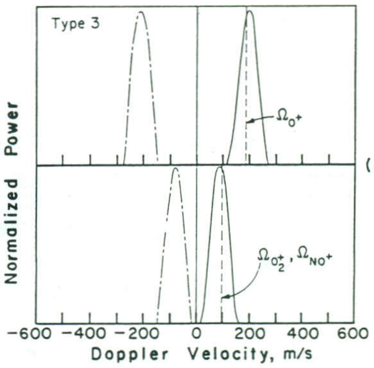

Figure 15

Drawings of typical type 3 *radio auroral spectra observed at* 50 MHz.

These frequency bands are centered on values corresponding approximately to the cyclotron frequencies, or their harmonics, of the main ionic species in the plasma (i.e. O_2^+, NO^+, O^+). Figure 16, is an example of type 3 spectra centered near 30 and 60 Hz, observed simultaneously from two different azimuths and at aspect angles ~ 5° and 12°, respectively. It is interesting to note that all the reported observations were made so far with high resolution 50 MHz radars whose beams were several degrees from perpendicularity with the magnetic field, i.e. type 3 echoes seem to require less favorable aspect sensitivity conditions than type 1 and 2 echoes. According to Haldoupis *et al.* (1987), type 3 echoes were seen frequently in the entire aspect angle range between 1° and 14°, i.e. with $k_\parallel / k_\perp$ ratios may be larger than 0.25. Also, type 3 echoes are observed during more disturbed rather than more quiet geomagnetic conditions.

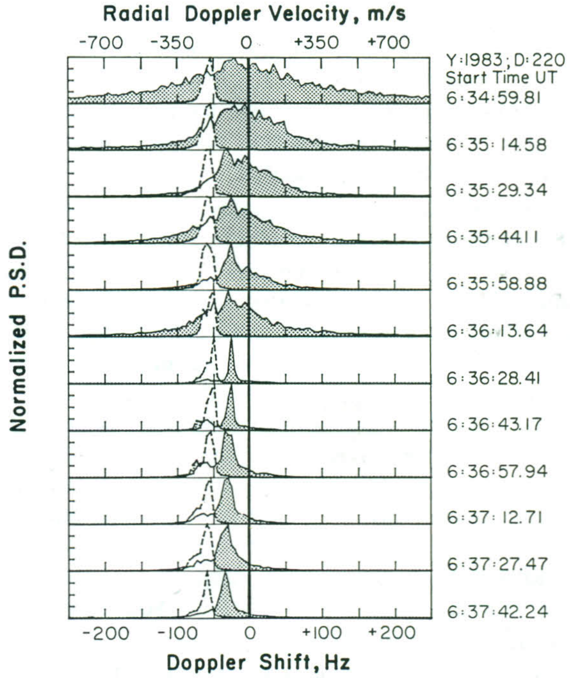

Figure 16

Sequential type 3 *spectral peaks at* 60 *and* 30 Hz *Doppler shift, observed simultaneously from two different azimuths at* 5° *(dashed lines) and* 12° *(shaded spectra) magnetic aspect angles respectively. Presumably, the broad part is of type* 2 *(from Haldoupis* et al.*,* 1985*b).*

These characteristics, and in particular the fixed Doppler shift near the ionic gyrofrequencies, led Fejer *et al.* (1984*b*) to propose that these echoes are due to electrostatic ion cyclotron (EIC) plasma waves generated by strong field aligned currents (FAC) in the upper *E*-region (i.e. well above the electrojet). Besides the Doppler spectrum evidence, there is indirect evidence based on concurrent optical data, reported by Providakes *et al.* (1985) and by Prikryl *et al.* (1987), in favor of strong FAC involvement in the generation of type 3 echoes. Also, there are measurements made *in situ* with rocket probes which detected ion cyclotron electrostatic oscillations in the upper *E*-region (e.g. Ogawa *et al.*, 1981 ; Bering, 1983).

In a recent paper, Prikryl *et al.* (1988) presented evidence (based on high resolution Fourier analysis of short time sequencies of 50 MHz CW backscatter), that EIC harmonics are possibly always present in the Doppler spectra. They went further to suggest that the so-called « ion acoustic » peaks (i.e. those related to type 1 echoes) may in fact be « ion cyclotron » peaks at an appropriate gyrofrequency harmonic of the main ionic species. To support their proposition, Prikryl *et al.* (1988) assumed that these echoes come from limited regions of intense FAC in the upper *E*-region and presented numerical results showing EIC harmonic generation, obtained from the ion cyclotron dispersion equation of Kindel and Kennel (1971). The problem with these ideas is, however, to reconcile ion cyclotron harmonics with the bulk of auroral echoes which are known to occur at electrojet heights in the 100 to 115 km range. Also, as it would be discussed shortly, the theory applied by the authors may not be valid for upper *E*-region heights at wavelengths for which electrons are strongly collisional.

At present the existing experimental evidence, although it strongly favors the existence of EIC waves in the auroral plasma, should be considered only as necessary but not sufficient to prove the electrostatic ion cyclotron source mechanism for auroral backscatter, and further experimental results, especially altitude information, are needed.

The first to discuss theoretically the importance of FACs in the generation of electrostatic ion cyclotron waves were Kindel and Kennel (1971). Their theory applied to the weakly collisional upper *E*-region and lower *F*-region ionospheric plasma (i.e. for $\nu_i \ll \Omega_i$ and $\nu_e < k_\| V_e$, where V_e is the electron thermal speed). According to the kinetic theory of Kindel and Kennel, once the threshold drift velocity is exceeded, short wavelength waves near the ion cyclotron frequency (i.e. $\omega_k \sim \Omega_i$) become unstable and propagate outward from a current beam in directions such that $k_\perp \gg k_\|$. This theory however shows that ion neutral collisions have a strong stabilizing effect (even when $\nu_i/\Omega_i \simeq 0.02$), thus immense FACs would be needed to sustain EIC waves below ~ 170 km.

On the other hand, D'Angelo (1973) and Chaturvedi (1976), who used fluid theory, considered the destabilizing role of electron neutral collisions and argued that EIC waves could be generated even at 120 km, where ν_i and Ω_i become comparable. Fejer *et al.* (1984*a*) generalized the fluid theory of electrojet instabilities to include ion magnetization effects and FAC generation of EIC waves at higher altitudes. Fluid theory, however, predicts direct generation of EIC waves with $\lambda_{ir} \geqslant 15$ m to 20 m and frequencies $\omega_k = (\Omega_i^2 + k^2 C_s^2)$, i.e. phase velocities above the ion acoustic velocity C_s. Obviously this theory neither explains the generation of 3 m waves nor predicts the observed Doppler shifts so near the ionic gyrofrequencies.

At this point it is interesting to mention that recently Villain *et al.* (1987), using the APL HF radar facility in Labrador, which scans in frequency from 8 to 20 MHz, reported observations of *E*-region irregularities with λ_{ir} near 15 m which are associated with either low (i.e. sub-ion acoustic) or high velocity echoes. Among the high velocity signals, two distinct types were identified, with velocities near 445 m/s and 580 m/s respectively, which can be present simultaneously. They assumed the lower of the high velocity signals to be ion acoustic echoes whereas the high velocity ones were interpreted in terms of EIC waves produced by NO$^+$ ions, in good agreement with the above dispersion relation of fluid theory. Furthermore, their evidence suggested that magnetic field aligned drifts combined with sub-critical perpendicular electron drifts might be responsible for the production of both the EIC and the ion acoustic echoes.

Kinetic studies of collisional EIC waves ($\nu_e > k_\| V_e$) in the upper *E*-region, which took into consideration the destabilizing effect of electron neutral collisions, was reported by Providakes *et al.* (1985) and Satyanarayana *et al.* (1985). As seen in figure 17, reproduced from Providakes *et al.* (1985), the theory predicts that 3 m EIC waves can have angular frequencies near the ion gyrofrequencies but for direct excitation unreasonably high electron drift velocities along the field lines are required, even higher than the electron thermal speed (~ 130 km/s). It should be pointed out that for the most easily excited 3 m EIC waves (at 0.5° aspect angle) the required parallel

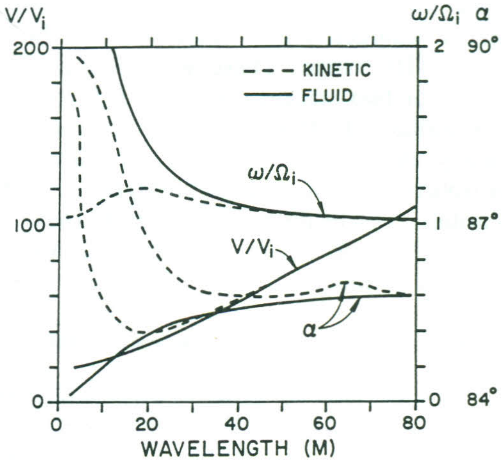

Figure 17

Theoretical results for electrostatic ion cyclotron waves at instability threshold in the upper E-region (150 km). *V/V_i is the ratio of field aligned electron drift to ion thermal speed. This figure compares both fluid and kinetic theory results. Kinetic theory can explain the observed Doppler frequencies but not the direct generation of type* 3 *echoes (from Providakes* et al., 1985*).*

electron drift velocities at threshold are unrealistically high and become much higher at larger aspect angles. Recently, numerical simulation results of resistive current driven EIC instabilities published by Seyler and Providakes (1987), show that 50 MHz type 3 echoes can be caused by the direct excitation of kinetic collisional EIC waves driven unstable by intense FACs at altitudes were $\nu_i \sim 0.02\,\Omega_i$. This would imply that type 3 echoes can hardly be generated and sustained at altitudes below ~ 170 km.

In summary, collisional fluid or kinetic theories of FACs ion cyclotron instabilities cannot provide adequate explanations for the type 3 observations at 50 MHz. Yet the frequent observation of these waves at large aspect angles shows that the theories must be modified so as to relax the threshold conditions for instability in both small and large aspect angles and to allow for phase velocities near the ion gyrofrequencies. Also careful experimental studies are needed to determine the altitude at which these echoes originate. Based on the observation that type 3 phase velocities remain very stable, as it is the case for type 1 echoes, one could argue that the echoes may come from within, or near the top, of the electrojet because if they were to come from above the electrojet then their Doppler shift would have been subject to $\mathbf{E} \times \mathbf{B}$ plasma motions. On the other hand, if type 3 echoes come even from upper electrojet layers, can we define electrostatic ion cyclotron waves in regions where the ions are hardly magnetized ?

6.2. Type 4 echoes

A few years ago, Haldoupis and Sofko (1979) reported a new spectral signature observed with a CW bistatic Doppler system at 42 MHz, during exceptionally disturbed conditions in the postmidnight sector. An example of their observations is shown in figure 18. The spectrum consisted of two components, a broad one centered near 500 m/s and a narrower one near 1100 m/s. The overall duration of such events was fairly short, from tens of seconds to less than about 4 min. The more strongly shifted component is composed of echoes caused by fast moving irregularities with lifetimes less than 50 ms and appears weaker because of considerable spatial averaging. The evidence of Haldoupis and Sofko (1979) suggested that the fast moving irregularities must have originated from very localized scattering regions during unusual plasma conditions.

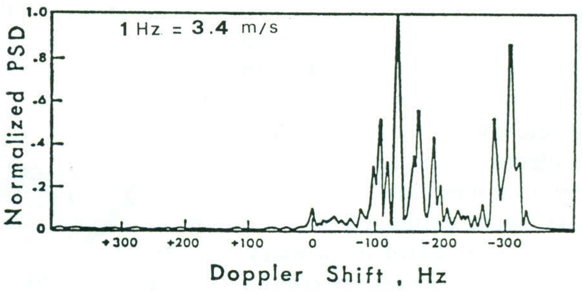

Figure 18
A typical example of the type 4 spectral signature observed at 42 MHz. *This spectrum corresponds to a short data sample of* 0.2 s *duration (from Haldoupis and Sofko,* 1979*).*

This observation has been identified as a distinctly different echo type of 50 MHz radar aurora by Providakes (1985) and Fejer *et al.* (1986) who observed several type 4 events with the high resolution Cornell University Portable Interferometer Radar System (CUPRI), during disturbed conditions in the postmidnight sector. On these occasions, short-lived narrow spectral peaks with very large phase velocities approaching 1 km/s are observed to dominate over a broad, type 2-like component, but with considerably higher average Doppler velocities and spectral widths. The auroral backscatter echo is often strong and highly variable in range and time and the same dynamic behaviour is also true for the Doppler spectrum (e.g. see fig. 19). They also found the type 4 component to be more aspect sensitive than the broad type 2 like.

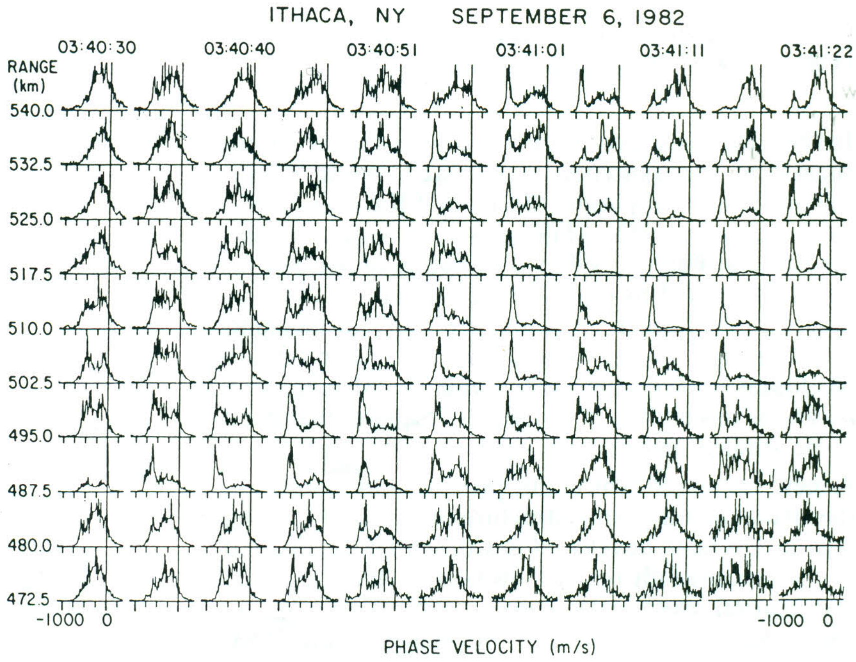

Figure 19
Temporal and spatial dynamics of type 4 *spectra observed with the* CUPRI *radar at* 50 MHz. *It is interesting to point out the rapid temporal and spatial variations of type* 4 *peak phase velocity (from Fejer* et al., 1986*).*

In their interpretation, Fejer *et al.* (1986) relied on the shape of the peaks and their time evolution to suggest that type 4 events represent a true two stream instability case, implying that at these times the ion acoustic speed is extremely enhanced due to anomalous electron heating conditions. The rare occurrence, short lifetimes, and highly variable nature of type 4 peaks, were explained as a consequence of an extremely narrow sector of primary two stream irregularities, so type 1 waves are confined along the destabilizing drift and observed only when cos $(\hat{k}\cdot\hat{V}_d)\simeq 1$. This interpretation implies very large electron temperatures in the range between 2000 K and may be more than 3000 K. As we have mentioned, *E*-region electron temperature enhancements are known from incoherent scatter measurements to occur during periods of large electric fields, but very rarely we have such large values being reported in the literature.

We believe that the proposed interpretation for type 4 echoes is feasible but it needs more experimental testing. One may find it difficult to conceive that type 4 echoes are only due to a narrow, highly directional, cone of primary irregularities, when we know from STARE that the primary cone is always very broad (for example the Norway radar sees almost always narrow type 1 spectra). Also, from the published type 4 spectra, e.g. those of Haldoupis and Sofko (1979) and Fejer *et al.* (1976), there seems to be a preferred frequency band close to 300 Hz for type 4 spectral peaks, something that may be incompatible with the proposed interpretation. Very recently, however, there has been a study, by Providakes *et al.* (1988), on joint measurements of auroral *E*-region irregularities made with the CUPRI radar interferometer, and *E*-region electron heating made with EISCAT. In one case they found good correlation between a type 4 echo and an intense short-lived electron heating event during which the electron temperature increased by a factor of 2-4 times near 108 km. This is the first direct evidence that comes out in favor of the interpretation proposed by Fejer *et al.* (1986) for type 4 echoes.

7. INTERFEROMETRY STUDIES OF LOCALIZED SCATTER REGIONS

In the past, there have been a number of observations suggesting the existence of localized strong scatter regions in auroral plasma (Sofko and Kavadas, 1969 ; 1971 ; Unwin, 1972 ; Haldoupis and Sofko, 1978*b* ; Sinclair and Forsyth, 1980). The notion of backscatter being dominated by echoes from a point-like dynamic source, imbedded in an apparently random medium, is intriguing, hinting that under some appropriate conditions occurring at limited volumes of space, the plasma is susceptible to instability processes that need to be studied and understood.

A new technique which can provide information on the spatial and temporal structure of localized echoing regions has been developed at Cornell University and applied successfully the last few years to the equatorial and auroral electrojets (Ierkic, 1980 ; Farley *et al.*, 1981 ; Kudeki *et al.*, 1981 ; Providakes *et al.*, 1983, 1985 ; Riggin *et al.*, 1986 ; Fejer *et al.*, 1986). The first auroral interferometer results, reported by Providakes *et al.* (1983) using a monostatic 50 MHz coherent radar with antenna separation of 50 m, verified the existence of localized scatter sources in the auroral plasma with dimensions of less than few kilometers. Recently, Haldoupis *et al.* (1988) described the conversion of a bistatic 50 MHz CW Doppler system to an auroral interferometer, designed to investigate short term dynamics of highly localized regions of backscatter with mean transverse sizes in the range from 0.5 to 5 km.

Figure 20 illustrates the basic geometry of horizontal interferometry. If within the large viewing region there is a localized scatter source then the principal difference between the waves at the two spaced receivers A and B are in their phase. If we assume the received signals to result from the superposition of many wavelets originating from a random assembly of source elements having their phases $\Phi_{\omega i}$ normally distributed, it can be shown (Farley *et al.*, 1981) that the complex cross spectrum is

$$S_{AB}(\omega) = \exp(\mathrm{j}k_r\, d\langle\Phi_\omega\rangle)\times \\ \times\exp(-k_r^2 d^2\sigma_\omega^2/2)\,, \quad (16)$$

where k_r is the radar wavelength, d is the antenna separation distance, and σ_ω, $\langle\Phi_\omega\rangle$ are the angular spread and the mean azimuthal position of the localized source which is identified in the spectrum by its mean Doppler shift ω. In principle, one can estimate the source mean size and its mean angular position by computing the normalized cross spectrum, known as coherency, and the phase cross spectrum and also measure source movements transverse to the viewing directions. For details see Farley *et al.* (1981) and Providakes (1985).

The Cornell interferometer results for radar aurora revealed a number of interesting features. Providakes

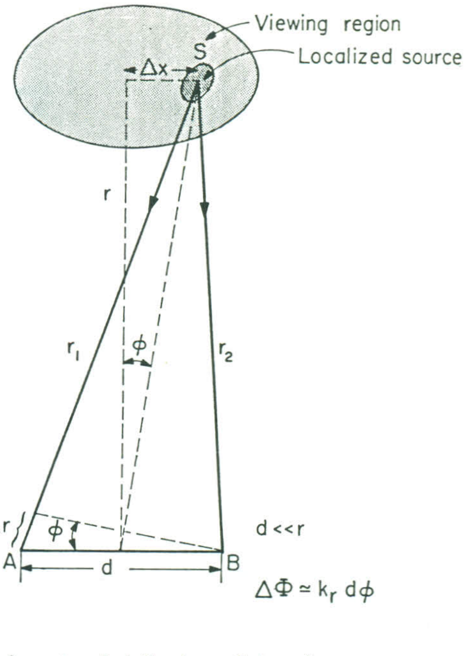

Figure 20
Geometry for azimuthal (horizontal) interferometry.

et al. (1983) reported measurements showing that type 1 and type 2 echoes may originate from different regions in the scattering volume. Other observations by Providakes *et al.* (1985) showed that type 3 echoes are associated with horizontal shears in the cross field plasma flow, and with highly localized and irregular structures within the scattering volume. Also it was found that type 4 echoes are extremely localized in space, which led Fejer *et al.* (1986) to propose the existence of spatially confined regions of elevated electron temperatures. Haldoupis *et al.* (1988) reported with the University of Saskatchewan CW interferometer that at times, high coherence echoes of type 1 or type 3 originate from strongly unstable regions related to dynamic source regions of transient nature with azimuthal sizes possibly less than 1 km. An example of high resolution CW interferometry, related to a type 3 echo, is shown in figure 21. This is from a short-lived impulsive event whose growth took place during a fraction of a second and whose duration was about 40 s. Figure 21 shows averaged normalized Doppler spectra from both east and west antennas and the corresponding cross spectral estimates. Notice that high coherencies and relatively steady phases appear only for the narrow dominant peak of type 3 near 70 Hz. The coherence values in figure 21 suggest a scattering region with an rms cross sectional area of 2 km, or less, transverse to the observing direction.

The existing observations demonstrate that interferometry is a promising technique for investigating dynamics of localized regions of backscatter, and that carefully designed experiments can provide unique altitude information and rapid height movements of spatially coherent structures in the auroral plasma. The first results of 50 MHz interferometric altitude measurements were discussed briefly in a recent paper by Providakes *et al.* (1988). They observed that scatterers exhibit an apparent large spread in altitude during periods of weak signals whereas for strong signals the scattering layer becomes narrow and it is located in the altitude range between 100 and 120 km. Certainly, we expect to see more of interferometer studies in the near future.

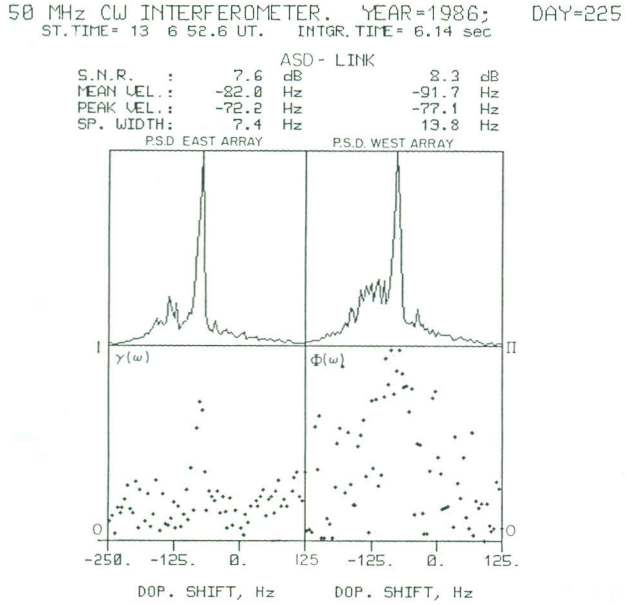

Figure 21

Normalized Doppler spectra (upper panels) from east and west antenna arrays, and the corresponding cross spectral estimates, i.e. the coherency (low left panel) and cross phase spectrum (low right panel), for an impulsive short-lived type 3 echo (from the 50 MHz *interferometer of the radio auroral group, University of Saskatchewan, Canada ; also Haldoupis* et al., 1988*).*

8. CONCLUDING COMMENTS

In this report, we have reviewed several observations of high latitude auroral *E*-region irregularities and considered their interpretation in the framework of the existing linear and nonlinear theories. We conclude that, at present, there is a substantial amount of knowledge accumulated through intensive research efforts over the last few years, which has improved the physical picture considerably. On the other hand, our understanding is not yet complete because there are important points that need further study, both theoretical and experimental. Most of the unresolved problems seem to have only auroral identity, i.e. they have no equatorial counterpart. For example, there is now enough evidence to substantiate the claim that there are important differences between 50 MHz equatorial and auroral backscatter processes. These differences focus mainly on the magnetic aspect properties of type 1 and 2 echoes and on new echo types observed only in the auroral plasma. Also, the role of altitude and of electron density in the generation and saturation of instabilities, seem to be much more important in auroral than the equatorial *E*-region. Furthermore, it is possible to have in the auroral plasma large amplitude, nearly monochromatic, electron density waves originating from very localized point-like regions associated with dynamic sources of transient nature.

The evidence discussed in this paper, emphasize the need for a general unified theory of radio aurora which would incorporate additional energy sources, beyond those applied in the equator, new (or modified) nonlinear saturation mechanisms and wave energy propagation characteristics. There is now more attention directed to Field Aligned Currents as an important source of energy which can destabilize the plasma. It is not unreasonable to assume that FACs is may be the missing element to be included in the equatorial models when applied to aurora. However, Chaturvedi *et al.* (1987) who considered parallel current effects on the *E*-region instabilities, found that FACs are not enough, when applied in the framework of a linearized theory, and some nonlinearity is necessary to account for results such as backscatter at large magnetic aspect angles.

Besides the necessity for auroral-oriented theoretical models, we also need more carefully designed experiments to measure with good azimuthal and vertical resolution sheared flow and altitude effects. In particular, the need for precise altitude and calibrated scattering cross section measurements is urgent because there is very little information available on these two important parameters. Also high resolution

Doppler spectrum measurements are needed at radar frequencies higher than 50 MHz in order to search for the existence of type 3 and type 4 irregularities at shorter wavelengths. Finally, for more conclusive results it is important to conduct joint experiments (e.g. using concurrently auroral radars, rocket and/or incoherent scatter measurements) to carry out correlative studies. These studies would possibly resolve questions concerning the roles of important parameters in the instability processes, such as electron density, electron density gradients and electron temperatures, and provide useful hints to theorists.

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