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J. D. Sahr
Bela G. Fejer, *Utah State University*

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Auroral electrojet plasma irregularity theory and experiment: A critical review of present understanding and future directions

John D. Sahr

Department of Electrical Engineering University of Washington, Seattle

Bela G. Fejer

Center for Atmospheric and Space Sciences, Utah State University, Logan

Abstract. We review the experimental observations of meter scale plasma irregularities in the auroral E region and the status of their theoretical understanding. Most of the experimental data is derived from VHF radar scatter experiments, but sounding rockets also provide crucial information not obtainable from radars. Linear theories correctly predict the altitude of occurence, strong magnetic aspect sensitivity, marginal instability, and typical phase velocities. Subsequent nonlinear theories have been developed to account for other observed features but with less satisfying application. Further understanding of auroral electrojet irregularities is impeded by precision limitations of existing instruments, by radar data which may seem incompatible, by the usually poor knowledge of the ambient conditions during these experiments, and by some confusion in the nomenclature (e.g. "type 2") used to describe the irregularities. We hope to clarify some of these experimental and theoretical issues. We will discuss observational "facts" that need to be refined and point out weaknesses of existing theories or their common interpretations. Finally, we will outline some avenues for future experimental and theoretical pursuit.

Introduction

In a remarkably modern experiment, *Eckersley* [1937] detected and correctly interpreted strong 9-MHz radar returns as scatter from the upper atmosphere. By transmitting a double pulse with varying lag, he was able to estimate the echo correlation time (a few milliseconds); by comparing the phase of scattered signals arriving on two antennas, Eckersley deduced that the echoes originated at an altitude above 100 km and below 300 km; this is a description of the main functionality of the Scandinavian Twin Auroral Radar Experiment (STARE) VHF radar. By the late 1950s and early 1960s this scattering was understood in terms of large amplitude ion sound waves at E region heights excited by electron drift through nearly stationary ions. These early theories and experiments account for most of what we know about "auroral electrojet irregularities."

Nevertheless, the last 30 years' efforts have not been wasted. Many useful and clever radar experiments have been performed during this period, and incoherent scatter and sounding rocket studies belong entirely to these 3 decades. Phenomena which are coincident with electrojet irregularities, such as auroral arcs, airglow, radio emissions, and radio absorption in the lower ionosphere, attract considerable attention in their own right. The gradual acquisition of a database suitable for statistical analysis offers great hope for the future; as natural examples of almost-two-dimensional turbulence, the auroral and equatorial electrojets are extremely interesting. Ionospheric irregularities cause scintillation (fading) of radio communication and radio navigation signals, so refined understanding of this natural turbulence has great practical importance. Finally, incremental progress in a difficult field is, after all, progress.

Our goal is to clarify the state of observational and theoretical knowledge of meter-scale plasma irregularities found in the auroral E region. We hope this summary will provoke an effort to rationalize nomenclature used by experts in the field while also introducing the phenomenon, experiments, and theories to those less familiar with the field. We will begin by outlining purely experimental observations, and commenting on the capabilities and limitations of radar and sounding rocket instrumentation. Because the majority of work revolves around radar studies, we will emphasize radar results in this report. After adding a summary of linear and nonlinear theory we'll conclude with a critique of common interpretation and suggest some experiments for the future.

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A Brief History of Experimental Observations

After the early radar experiments of Eckerslev and others [*Harang and Landmark*, 1938], there was a lull in activity during and immediately after the Second World War. Many radar experiments that probed the ionosphere during the 1950s, primarily at high latitudes (see references within *Leadabrand et al.* [1965]), J established many important parameters of ionospheric irregularities. Particularly strong echoes were observed in the vicinity of the northern and southern auroræ, so the high-latitude scatter is sometimes called the "radar aurora" or "radio aurora."

Leadabrand et al. [1965] performed multifrequency observations of the northern radar aurora, establishing their altitude and field-aligned character quite precisely. *Unwin* [1967] used a 50-MHz Lloyds Mirror interferometer to establish the altitude and thickness of the scattering layer in the sourthern auroral zone (see also work by *Greenwald et al.* [1973], and *Ogawa et al.* [1982]). In the early 1970s, auroral VHF radar measurements from Alaska provided new information on the Doppler characteristics of auroral echoes and their relationship to auroral visual forms and current systems [e.g., *Greenwald et al.*, 1973, 1975a, b]. STARE [*Greenwald et al.*, 1978] produced maps of 1-m irregularities over much of the Scandinavian peninsula. *Ruohoniemi and Moorcroft* [1985] used the Homer Radar (Alaska) to investigate the altitude of 35-cm irregularities. A wide variety of radar observations have been made over Canada with a 50-MHz radar [*Haldoupis and Sofko*, 1979, *Koehler et al.*, 1990, *Haldoupis et al.*, 1995]. In the mid-1980s the Cornell group began a series of studies with a 50-MHz pulse-mode radar interferometer which produces power spectra and some "imaging" within the relatively narrow radar beam [*Providakes et al.*, 1985, *Sahr et al.*, 1992].

Radar observations over the Canadian prairie have been performed by a unique multistatic coherent radar, permitting a number of observations at different aspect angles, latitudes, oblique scattering geometries, and even dual frequencies [*Watermann et al.*, 1989, *Koehler et al.*, 1990, *Kustov et al.*, 1994]. Very recently, STARE gained a vertical interferometric capability [*Ierkic et al.*, 1992]. *Hanuise et al.* [1993] have used the Système HF d'Etudes Radar Polaires et Aurorales (SHERPA) to perform detailed studies of the power spectrum and autocorrelation function of high-latitude decameter-scale ionospheric irregularities. Recently, the Millstone Hill, Sondrestrøm Fjord, and EISCAT incoherent scatter facilities have made some measurements of decimeter-scale irregularities, establishing the scattering cross-section and aspect angle sensitivity from perpendicularity to the incoherent scatter signal floor [*St.-Maurice et al.*, 1989; *del Pozo et al.*, 1993; *Moorcroft and Schlegel.*, 1990].

Beginning in the mid-1960s, sounding rockets were flown with auroral *E* region-specific missions (see Table 1). Sounding rockets provide direct in situ measurements of electric fields, background densities, and fluctuation densities. To this day there is no robust theory for the amplitude of density fluctuations associated with radar backscatter, so all knowledge of the absolute level of fluctuations is derived from sounding rockets; this information is quite distinct from the scattering cross-section measurements mentioned above.

Coherent and incoherent scatter radars have been teamed to simultaneously study the plasma parameters while also studying turbulence [*Providakes et al.*, 1988]. More recently, sounding rockets have been flown through the common volume observed by coherent and incoherent scatter radars [*Pfaff et al.*, 1992, *Rose et al.*, 1992]. Excellent reviews of coherent radar observations and capabilities are provided by *Haldoupis* [1989] and *Hanuise* [1983].

Table 1. A Partial List of Sounding Rockets Which Have Probed the Auroral *E* Region

year	project	citation
1964	AD-II-52	*McNamara* [1969]
1970	VB-31	*Kelley and Mozer* [1973]
1970	S70/1, S70/2	*Ungstrup* [1973]
1972	S-210JA 8–10	*Ogawa et al.* [1976]
1973	S-210JA 16–18	*Ogawa et al.* [1976]
1974	SEC 1	*Pécseli et al.* [1989]
1977	Porcupine II	*Mallinckrodt* [1980], *Mallinckrodt and Carlson* [1985]
1978	F-47, F-48	*Thrane and Grandal* [1981]
1979	Porcupine III	*Pfaff* [1986]
1979	Porcupine IV	*Pfaff* [1986]
1981	Auroral E (A19.903)	*Pfaff* [1986]
1982	34.008	*Labelle et al.* [1986]
1984	38.001	*Pfaff* [1986]
1988	21.097	*Pfaff et al.* [1992]
1989	21.100,21.096	*Pfaff et al.* [1992]
1989	ROSE	*Rose et al.* [1992]

Some of these data are from *Pfaff* [1986]. We concentrate on those flights designed to study the *E* region specifically; many more flights have passed through the *E* region on the way to higher altitudes.

Several other radio remote sensing techniques, principally riometers, ionosondes, are useful in studying irregularities in the ionosphere (cf. a book by *Hunsucker* [1991] and an appendix to the book by *Kelley* [1989]). These tools detect particle precipitation, overall density structure, and perturbations of the magnetic field due to ionospheric currents. We are concerned with direct observation of the meter-scale irregularities, so we will concentrate on rocket and coherent scatter radar data.

Knowledge Derived From Experiments

We now briefly describe the experimental foundation upon which our understanding of auroral electrojet irregularities rests. We distinguish between radar- and spacecraft-derived information, concentrating on observations which are "fundamental" in that they tell us something about the irregularities without relying upon any theory of the irregularities. In a subsequent section we will describe some of the experimental challenges that limit the precision of measurements.

Knowledge Derived From Radar

Most of our experimental measurements of auroral electrojet irregularities arises from "coherent" radar observations simply because there have been many more radio studies than in situ experiments. The term "coherent scatter" is used to distinguish these observations from "incoherent" or "Thomson scatter"; the primary difference is that auroral electrojet irregularities have an enormous scattering cross section compared to thermal fluctuations. Many of the results below have been described in a large number of papers. Here we specifically mention only some of the most recent studies. It may be helpful to refer to Figure 1 to see the experimental geometry for backscatter radars.

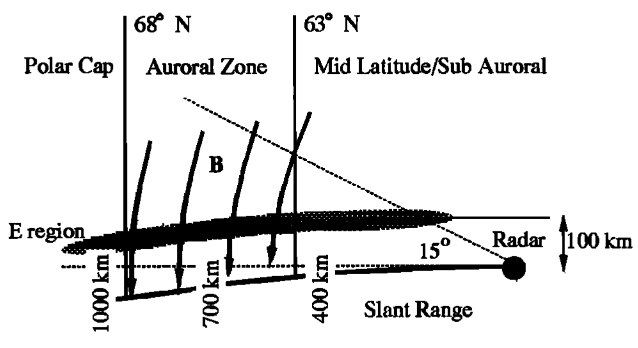

Figure 1. Typical coherent scatter radar geometry for northern high latitude backscatter. The radio waves must encounter the irregularities while propagating nearly perpendicular ($\sim \pm 2°$) to the magnetic field, or very little scatter occurs. For VHF and UHF frequencies (for which there is little refraction) the scatter may occur as close as 400 km or as distant as 1200 km. The location of the auroral zone can vary widely, of course.

1. E region altitude: Radar experiments have established the echo source in the lower E region (95-125 km). This information is derived in two ways: from a "conventional" narrow antenna beam [*Leadabrand et al.*, 1965, *Ruohoniemi and Moorcroft*, 1985] and from interferometry [*Unwin*, 1967, *Sahr et al.*, 1991].

2. Meter scale plasma density irregularity: Above 100 km altitude the tenuous neutral atmosphere cannot scatter detectable amounts of radio wave energy. Furthermore, Thomson (incoherent) scatter from ionospheric plasma is quite weak, so Bragg-like scatter from large perturbations or irregularities in the plasma density must be the source of the coherent echoes. For VHF radars this implies the existence of meter-scale irregularities; more precisely, the spatial Fourier transform of the plasma density has significant amplitude in wave number $k \sim 1\ \mathrm{m}^{-1}$.

3. Latitude distribution: The strongest E region echoes occur at latitudes near 65° north and south; during magnetically disturbed conditions, the scattering region extends equatorward. A very similar phenomenon occurs at the magnetic equator [*Fejer and Kelley*, 1980].

4. Local time occurence: High-latitude radar echoes are detected at any time of day but are most pronounced near local magnetic midnight.

5. Correlation with auroral phenomena: Backscatter is frequently observed in conjunction with observations of the visual Aurora and ionospheric electric currents [*Greenwals et al.*, 1973; *Providakes et al.,*, 1985].

6. Nonstationarity: The timescale for statistical stationarity may be as little as a few seconds, but a few minutes is typical (see Figure 3 [*Providakes*, 1985; *Sahr*, 1990].

7. Threshold electric field: Meter-scale auroral E region irregularities are observed only when there is sufficiently large ambient perpendicular electric field ≥ 20 mV/m [*Haldoupis et al.*, 1990; *Fejer and Kelley,*, 1980].

8. Characteristic Doppler velocity: Although the data are highly variable, the observed Doppler shifts are roughly proportional to the radar operating frequency [*Greenwald et al.*, 1975c; *Watermann et al.*, 1989]. Thus the spectra are better characterized by velocity (meters per second) than by frequency (hertz). Apparent phase velocities lie primarily from 0 to 500 m/s, although examples approaching 1500 m/s are known [*Providakes et al.*, 1988; *Haldoupis and Nielsen*, 1989b; *Sahr et al.*, 1989].

9. Flow angle effects: The average Doppler shift is zero when the radar wave vector is perpendicular to the plasma drift velocity and increases as the angle (flow angle) between $\mathbf{k}$ and $\mathbf{V}_d$ decreases. Type 1 echoes (described below) are seen when the radar wave vector has an appreciable component parallel to $\mathbf{V}_d$. At VHF (but not at UHF) frequencies the power also increases as the flow angle decreases. Note that this observation requires independently knowing the direction of the electron drift, which can be provided from measurements

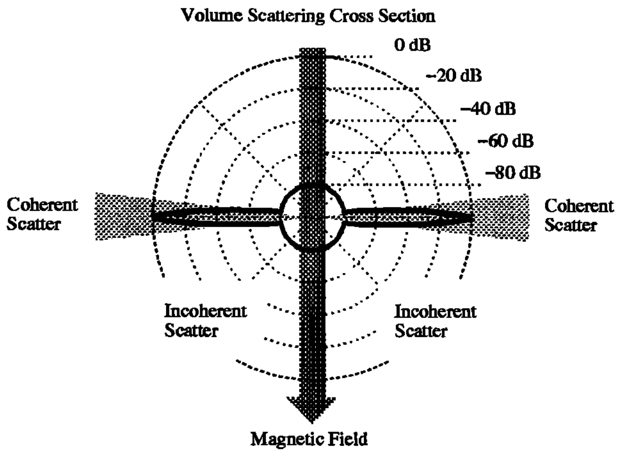

Figure 2. A schematic illustrating the enormous difference in scattering cross section between Thomson scatter and electrojet irregularities. Only a thin disk perpendicular to **B** provides strong scatter. It is remarkable that incoherent scatter radars can perform conventional incoherent scatter measurements while coherent scatter radars see enormous scatter at a similar wavelength and in the same volume [*Providakes et al.*, 1988].

of electric field (satellite, sounding rocket, or incoherent scatter; see *Eglitis et al.* [1996]).

10. Correlation time: VHF irregularities have correlation times ranging from 0.5 to 20 ms, corresponding to spectral widths that may be as large as 1000 m/s.

11. High aspect sensitivity: The strongest scatter is observed when the bisector of the incident and scattered radio wave is perpendicular to the magnetic field. Scatterers with this property are said to be "highly field aligned" with respect to the magnetic field, just as a surface water waves are highly field aligned with respect to gravity. Roughly speaking, the echoes are observed within about 2° of the plane perpendicular to **B**. Several radar experiments have established the rapid decrease of echo strength as the aspect angle increases. *Kustov et al.* [1994] and *Foster et al.* [1992] have also studied the variation of Doppler velocity with aspect angle.

12. Total scattering cross section: Radars which are amplitude calibrated can measure the absolute scattering cross section [*Foster et al.*, 1992; *Kustov et al.*, 1994]. These measurements show the scattering cross section to be 50—80 dB stronger than incoherent scatter (illustrated in Figure 2). Strong echoes at 50 MHz have a total volume scattering cross section of roughly 10 m^2/km^3, consistent with incoherent scatter measurements (J. D. Sahr, private communication, 1991). These scattering cross sections are best interpreted as a lower bound, since it is not clear that the scatterers fill the beam.

13. Large scale turbulence: VHF radar interferometer measurements indicate that the meter-scale waves usually come from highly localized regions with high time variability [*Fejer and Providakes*, 1987]. Very high range resolution has been achieved in the equatorial electrojet, and the scatter is structured on scales as fine as 100 m [*Swartz and Farley*, 1994]. While such fine structure is quite likely in the auroral zone, the finest range resolution at high latitudes is approximately 5 km (cf. *Providakes et al.*, 1988). The very large scattering cross section suggests that multiple scatter may play an important role in interpreting the radar data [*Donovan and Moorcroft*, 1992]. This has an implication in precisely stating item 2, above.

Many modern radar experiments provide estimates of the power spectrum of the scatter, not merely the power and mean Doppler velocity. A nomenclature of "types" has been adopted which characterizes the first and second moments (mean Doppler and Doppler width) of the spectra. Examples of several power spectra are shown in Figure 3, and a classification template developed by *Sahr* [1990] for determining echo "type" is shown in Figure 4. Another figure illustrating the high range and time variability of the spectra is shown in Figure 5. Theoretical investigations have been devoted to explaining the features of the spectra; we review the highlights

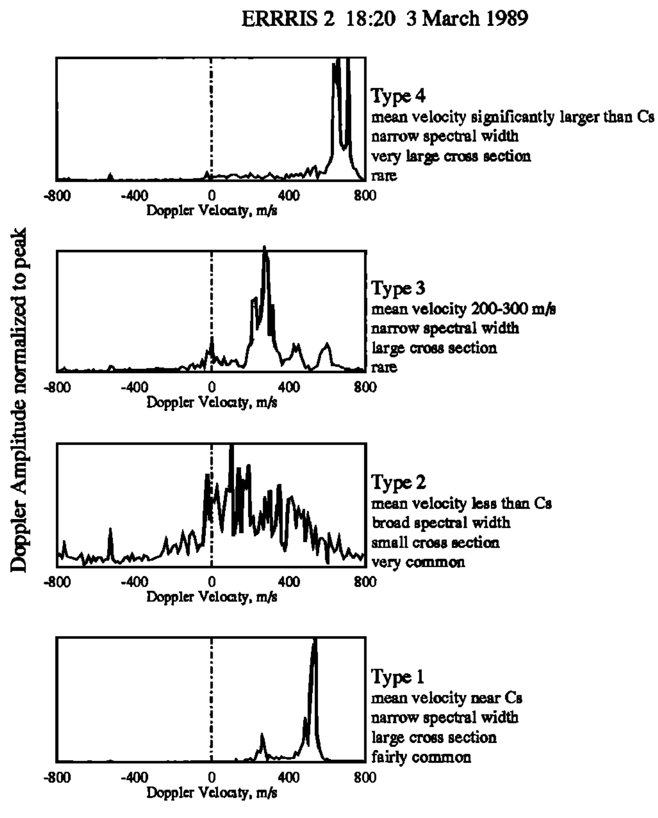

Figure 3. Examples of four different echo types. The most common nomenclature lists four "types" based upon the mean Doppler velocity and the spectral width. These examples are "typical" in that they are not particularly clean. All occurred in one 20-s window. The data are drawn from a 50-MHz radar (CUPRI) as part of the E Region Rocket Radar Incoherent Scatter (ERRRIS) experiment described by *Pfaff et al.* [1992]).

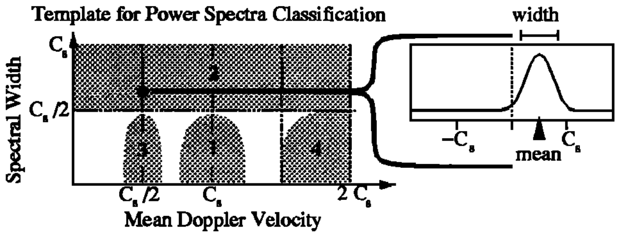

Figure 4. Template for determining electrojet echo "type" based upon the Doppler width and the mean Doppler velocity. This template, representing empirical practice, should be interpreted quite loosely.

below. For the moment we merely state that at high latitudes there is no firm justification for the template of Figure 4, and there will be considerable disagreement about the template we present.

Knowledge Derived From Spacecraft

The E region is not directly accessible by satellites because orbits rapidly decay at such low altitudes. Spaceborne and ground-based optical instruments readily observe airglow associated with Auroral emissions in the E region, however, the optical auroræ and the radar aurora are not directly coupled.

Numerous sounding rockets have penetrated the E region, and superb knowledge of the structure of the turbulent E region has been obtained for very brief periods of time. A partial list of auroral sounding rocket flights is given in Table 1, and some fundamental observations are summarized below. A schematic of a sounding rocket payload with E field booms and plasma density probe is shown in Figure 6.

1. Density fluctuations: The auroral E region is remarkably turbulent; the density fluctuations $\langle \delta N \rangle$ approach 1/10 of the ambient density [*Primidahl*, 1989; *Pfaff et al.*, 1992; *Rose et al.*, 1992]!

2. Threshhold electric field: Sounding rockets with electric field probes provide precise measurements of the large and small scale vector electric fields, and observe irregularities when the ambient electric field exceeds about 20 mV/m.

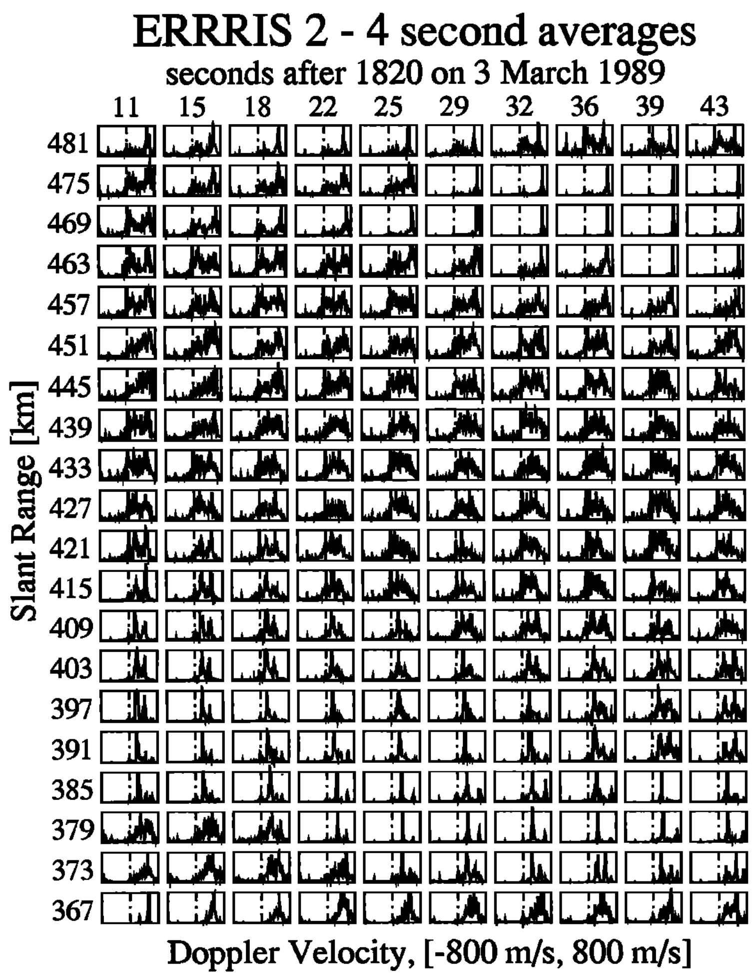

Figure 5. Some high-resolution power spectra over northern Scandinavia derived from a 50-MHz radar. The spectra are computed every 4 s (incoherent averages of 8) every 6 km in range. All of the various spectral "types" are represented, and the nonstationarity is evident even on this short timescale. The data are drawn from a CUPRI experiment (after *Sahr* [1990, Figure 6.9]; the experiment is described by *Pfaff et al.* [1992]).

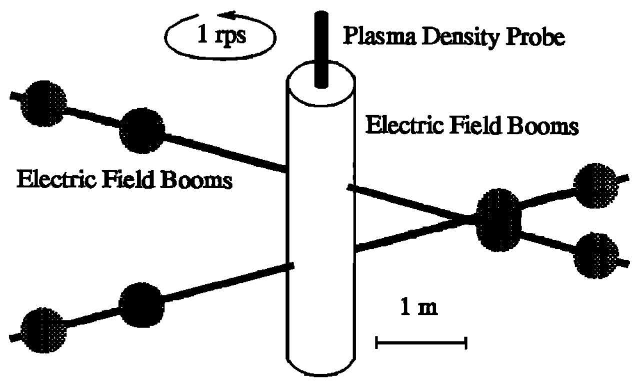

Figure 6. A schematic of a "generic modern" sounding rocket payload showing multiple booms with multiple plasma contacts and a plasma density probe (of which there may be several). There will generally be other instruments aboard as well: vector magnetic field, energetic partical detectors, VLF receivers, etc. Such payloads typically rotate about once per second; the axis may or may not be aligned with **B**.

3. Wave phase velocities: Although it is difficult, reasonable estimates of the phase velocity of electrostatic waves can be made by correlating multiple measurements of electric fields, especially with "interferometer" electric field booms. The measurements show a predominant meter scale wave travelling in the $\mathbf{E} \times \mathbf{B}$ direction at the $\mathbf{E} \times \mathbf{B}$ drift velocity.

4. Sinusoidal structures: Sounding rockets may observe a large scale ($\sim$ 500—4000 m) sinusoidal structure in the electrojet.

5. Differential structure: Sounding rockets observe distinctly different spectral signatures on the top and bottom limits of the instability region [*Pfaff*, 1986; *Pfaff et al.*, 1992].

6. Fine altitude structure: There is substantial structure on hundred-meter and kilometer scales within the irregularity region.

7. Strong field alignment: It is apparent that the wave parallel electric fields are much smaller than the perpendicular fields.

8. Energetic events: Auroral irregularities are frequently observed in or adjacent to regions of energetic particle precipitation. Note that precipitation can also be detected by satellites flying well above the E region.

Joint Rocket/Radar Experiments

There have been two recent experimental campaigns in which coherent and incoherent scatter radars observed the same volume of space in which sounding rockets were flown [*Pfaff et al.*, 1992; *Rose et al.*, 1992]. These experiments are difficult to coordinate and expensive to perform; it is remarkable that they have been performed at all.

1. Apparent similarity of radar and rocket data sources: Sounding rockets detect enough density perturbation to account for the scatter observed by small radars while the radars are operating. Furthermore, the phase speeds and directions are consistent between in situ and coherent radar data. Given the present state of theoretical understanding, this is not surprising. However, it is important to realize that this point has been established.

2. Strong spatial inhomogeneity: It is possible for the sounding rocket trajectory to pass through regions of little turbulence while radars observe strong scatter. In other words, the radar scattering volume is not very (statistically) stationary in space or time, at least with respect to the capabilities of modern instruments.

Experimental Challenges

In order to test and construct theories of auroral electrojet irregularities, we hope to have access to accurate, precise data. However, several fundamental barriers challenge experimentalists, and may especially confound theorists who depend upon the data. Two imperatives fall out immediately. Theorists should always consult the experimentalists about their interpretations of the data; Experimentalists should attempt to provide parameters which are of use to theorists.

Many experiments are "event driven" rather than statistically driven. Thus extreme events receive concentrated effort. It is possible that the community as a whole has a biased view of the "normal" radar aurora.

Radar Experimental Challenges

Traditional radar scatter measurements of the radar aurora suffer from three kinds of difficulties: signal processing problems associated with range, time, and Doppler shift (the delay coordinate); problems associated with transverse measurements (angle of arrival); and ground clutter and interference and signal strength (signal amplitude).

Range and power spectrum estimation issues. At high latitudes E region irregularities can be observed all the way to the horizon, a slant range of 1200 km, or about an 8-ms delay. The Doppler velocity is usually less than 1500 m/s; at 50 MHz this compels a pulse repetition period less than once per millisecond to avoid frequency aliasing. However, both conditions cannot be met, a fundamental contradiction which prevents measuring the true range and correct power spectrum without ambiguity, at least when using ordinary time series analysis.

This problem is addressed in different ways. Ultimately, something must be sacrificed, such as time or frequency resolution, or perhaps absolute certainty about the range or the power spectrum. The different approaches complicate detailed comparisons of the different radars' data difficult. A brief survey of the methods is shown in Table 2, as a warning to theorists.

As a particular example of a pitfall, Figure 3 shows double peaked spectra at many ranges, particularly near

Table 2. The Major Classes of Radar Operating Methods Used by Coherent Scatter Radars

Technique	Instruments	High-Resolution			Alias-Free?	
		Time	Velocity	Range	Velocity	Range
ACF	STARE*, SuperDARN†	no	no	no	yes	yes
CW	Canadian multistatic‡	yes	yes	no	yes	yes
Pulse mode	CUPRI§	yes	yes	yes	yes	no
Power map	HLMS¶	yes	n.a.	yes	n.a.	yes

Instrument	Full Name and Scattering Center
CUPRI (50 MHz)	Cornell University Portable Radar Interferometer; southern Canada; also Greenland, northern Scandinavia
STARE (140 MHz)	Scandinavian Twin Auroral Radar Experiment; northern Scandinavia
SAPPHIRE (50 MHz)	Saskatchewan Auroral Polarimetric Phased Array Ionospheric Radar Experiment; north-central Canada
HLMS (50 MHz)	High Latitude Monitoring Station; north central Alaska
SuperDARN (12 MHz)	Super Dual Auroral Radar Network; most of the northern polar cap and some of the southern

390 km. A careful study of the data shows that the higher velocity peak was range aliased to 690 km [*Sahr et al.*, 1991]. Thus one could be misled into developing a theory to predict double-peaked spectra when they do not, in fact, exist (in this data set). A more detailed discussion of radar operating modes, receiver topologies, and signal processing algorithms is beyond the scope of this article. Unfortunately there is no good single reference for coherent radar techniques for ionospheric applications, but the interested reader is directed to work by *Brekke* [1977], *Skolnik* [1990], *Farley* [1969], and *Hunsucker* [1991].

Transverse resolution. Additional information about the irregularities can be extracted from the structure of the scatter perpendicular to the radar beam. All theories predict a relatively narrow altitude range and magnetic aspect angle. Furthermore the horizontal structure near auroral arcs is quite important.

Because the VHF operating wavelength is large (several meters), it is very difficult (and expensive) to build a high gain antenna that can be steered to provide fine azimuth and elevation information. Thus angular resolution at VHF is always derived from multiple antenna methods. For azimuthal measurements two distinct methods are used: filled aperture "imaging" antenna systems (STARE, Sweden and Britain Radar Experiment (SABRE), Saskatchewan Auroral Polarimetric Phased Array Ionospheric Radar Experiment (SAPPHIRE), SuperDARN) using an evenly spaced array; and interferometric methods (Cornell University Portable Radar Interferometer (CUPRI)) using a sparse, irregular array of antennas. Elevation measurements are more difficult still, and only interferometric methods are used (CUPRI, STARE [*Ierkic et al.*, 1992]; see also work by *Unwin* [1967]).

Because of the strong field-aligned nature of the irregularities and the steep inclination of the terrestrial magnetic field at high latitudes, all echoes are necessarily observed within about 15° of the horizon. This means that the ground image is very important; primarily, it acts in such a way as to eliminate the effective gain on the horizon for both polarizations. Although the low gain on the horizon is awkward, there are two other problems which are more serious. First, refraction is maximized for such low elevation angles. Second, interferometric elevation angle estimates are a strong function of the moderate conductivity of the the ground, especially if the antennas are at different heights above ground.

Signal amplitude. There are several problems associated with the amplitude of the received signals. VHF radars cannot (yet) estimate the absolute scattering cross section with any reliability. The broad antenna pattern, unknown system constant, and ground image all contribute very large uncertainty to any estimates of the scattering cross section.

In addition, the amplitude information my also be degraded by unwanted signals arising from ground clutter and other interference. Ground clutter arises from any signal detected by the radar receivers which has scattered from an undesired target. For a variety of reasons, ground clutter is rarely a problem in auroral coherent scatter radar. On the other hand, interference can be quite troublesome. Interfering signals may be generated by the radar itself or by external sources. In the authors' experience interference almost always appears as a narrowband signal which is relatively simple to recognize and remove.

Comparison of Radar Capabilities

There really is no simple way to compare the capabilities of the several instruments, but we have sketched volumes of representative space, time, and velocity resolution and suggested the differing geographic coverage

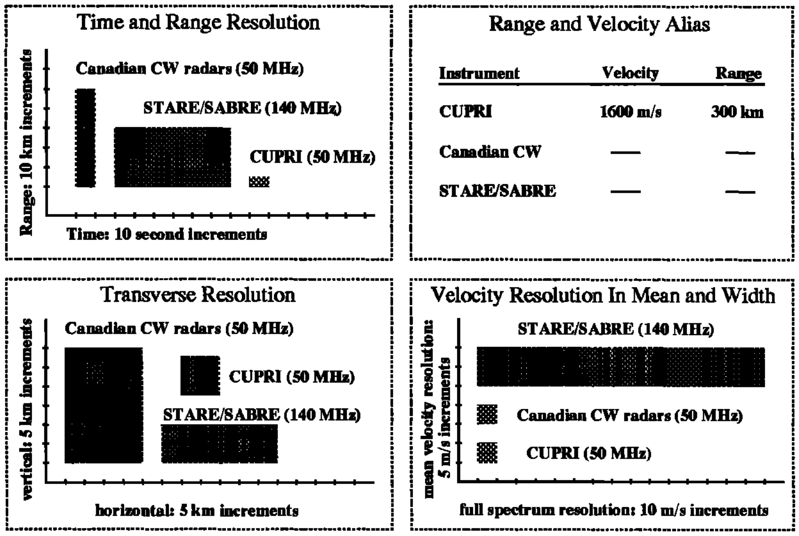

Figure 7. A rough comparison of the differing capabilities of the most important VHF radars used for high-latitude electrojet studies. In general, the smaller the rectangles, the better the resolution in space, time, and velocity. However, in achieving high resolution in all the parameters, CUPRI suffers potential ambiguities in range and velocity (upper right panel).

in Figure 7. The differing resolutions and coverage have no doubt been the source of rather different interpretations of the data. Large range resolution smooths fine detail; CUPRI's narrow beam width may provide a confusing "slit" through which east-west convection is viewed.

One of the most significant data interpretation difficulties arises from the substantially different range, time, and Doppler resolutions of the coherent scatter radars. In Figure 7 we've sketched the "typical" resolution volumes of several radars used to study auroral electrojet irregularities. This figure shows only "typical" performance, as each radar can vary its operating parameters rather widely. In particular, the Doppler velocity resolution of the STARE system is approximately 300 m/s, which is comparable to the ion acoustic speed. The mean of a STARE spectrum can be calculated reliably and precisely; however, in the absence of a theory of spectral shape the equivalent velocity resolution is only about one datum every 300 m/s. This coarse resolution is in contrast to the relatively fine velocity resolution of the CUPRI and Canadian systems, which are typically operated in a way that produces resolution of the order 10 m/s.

Although the CUPRI system provides the highest resolution by far, it would be incorrect to conclude that it is the "best" instrument. Its small resolution volume comes at the expense of range and frequency aliasing problems. The STARE resolution volume is large, but STARE provides excellent wide area coverage of irregularity distribution and electric field maps. The poor range resolution of the Canadian prairie CW systems is balanced by excellent resolution in spectrum and no frequency aliasing problems.

The different resolution volumes cause significant disagreements about irregularities. A good example has recently arisen with regard to type 4 echoes. The 50-MHz radars agree on the existence of such type 4 waves, and some workers have noticed that type 4 echoes tend to appear simultaneously with type 1 echoes in the Canadian radar data set. They have thus concluded that there is some sort of mechanism which favors such simultaneous appearance [*Haldoupis and Schlegel*, 1990; *Haldoupis et al.*, 1991; St.-Maurice et al., 1994]. On the other hand, CUPRI data does not show such type 1/type 4 coincidence. Since the CUPRI range resolution is much finer than the Canadian range resolution, one can surmise that the type 1 echoes and type 4 echoes may occur at the same time but at significantly different locations. This introduces a new problem, which is to find a mechanism which generates type 1 echoes in one region and type 4 echoes 10 or more kilometers distant.

Sounding Rocket Experimental Challenges

Sounding rockets provide vital in situ measurements of the DC and perturbation electric fields, magnetic fields, densities and density fluctuations, and perhaps other parameters such as composition, temperature, and energetic paraticle precipitation. Sounding rockets perform mostly spatial sampling over a short period of time, while radars perform time sampling averaged over a fixed volume of space. Like radars, sounding rockets present numerous experimental challenges.

1. Episodic nature: Sounding rockets are expensive and are launched infrequently. A single flight may dwell

in the E region for 2 min at most. The conscious choice to launch a sounding rocket into a specific event may bias understanding of the "normal" ionosphere.

2. Vechicle charging and wake effects: The moving payload body will acquire an electrostatic charge and leave a wake which may affect the performance of plasma-sensing instruments such as electric field probes and Langmuir probes.

3. Payload orientation: The payload attitude can usually be computed to accuracies of a few degrees; because electric fields parallel to $\mathbf{B}$ are small compared to the perpendicular fields, the important parallel fields have not been measured. Payloads with active attitude control periodically interfere with plasma instrumentation.

4. Spatial aliasing in electric field measurements: The electrostatic potential difference between two plasma contacts with known spatial separation provides electric field estimates. If two probes are separated by one wavelength, the potentials are identical and the simplistic measurement will be zero, which is incorrect. Probes cannot be placed too near the payload or spacecraft charge and wake will injure the measurements; typical probe separations are tens of centimeters to a few meters.

5. Frame of reference: Sounding rocket payloads in the E region typically travel at speeds somewhat greater than but comparable to ion-acoustic irregularity speeds. Thus the payload trajectory is only approximately space-like (passing rapidly through a "constant" medium). This complicates analysis, especially for payloads whose trajectory is parallel to the electron drift.

6. Interference: Sounding rockets compress many electronic payloads into a small volume with a common power source and data system; this introduces many opportunities for spurious signals in the data.

Many of the problems outlined above have been mediated by clever design and thoughtful analysis. In particular, "interferometric" electric field probes provide multiple independent electrostatic potential baselines to resolve ambiguities and vector directions [*Labelle and Kintner*, 1989; *Pfaff et al.*, 1992].] Technological improvements may enable the construction of very light weight payloads, permitting frequent use of inexpensive small sounding rocket motors and gun launches.

Theoretical Understanding

Considerable theoretical effort has been devoted to the study of these irregularities, with some success. The irregularities are well understood to be large amplitude ion-acoustic turbulence moving in approximately the electron drift frame. But the results are not nearly as satisfying as incoherent scatter theory, for which the magnitude and spectral form are extremely well understood. Numerical simulations are increasingly important and may very well provide the best complete theoretical understanding we can hope to attain.

Linear Theory

Fluid and kinetic linear theories produce nearly identical results for irregularity wavelengths greater than few tens of centimeters. Most of the linear theory has been based upon fluid theory, although the original development was kinetic [*Farley*, 1963] (see work by *Stubbe* [1989], *Pécseli et al.* [1989], *Gurevich et al.* [1995], and *Dimant and Sudan* [1995] for recent kinetic theory efforts). Most linear fluid theories are closed beyond the momentum equation using a perfect gas law for the electrons and ions; notable exceptions are those by *Robinson and Honary* [1993] and *Kissack et al.* [1995]. The fundamental model contains weakly collisional, magnetized electrons, collisional unmagnetized ions, ambient electric field, and an ambient density gradient. Electron-neutral and ion-neutral collisions dominate collisions among plasma species. The linear fluid theory is fairly simple and has the virtue of explaining many observed features; a physical rationale is presented here (with the benefit of hindsight!).

When the ionosphere is homogeneous, the only source of free energy is the ambient electric field. If we break the density into background and perturbation quantities $N = N_0 + n$, and the electron drift into an $\mathbf{E} \times \mathbf{B}$ drift and perturbation velocity $\mathbf{U}_e = \mathbf{V}_d + \mathbf{u}_e$, we can write the Fourier transformed electron continuity equation as

$$(\omega - \mathbf{k} \cdot \mathbf{V}_d)\, n = N_0 \mathbf{k} \cdot \mathbf{u}_e \tag{1}$$

In the limit of infinite electron magnetization, the right-hand side is zero, and we have the simple dispersion relation

$$\omega = \mathbf{k} \cdot \mathbf{V}_d \tag{2}$$

To the extent that the electron fluid is not completely magnetized (or the perturbation electric field not quite parallel to $\mathbf{k}$), the right-hand side will modify this dispersion relation. It is reasonable to suppose that the waves will grow if their phase speed exceeds the ion acoustic speed, and that otherwise the waves will decay. If we express the sensitivity to such Landau damping through a parameter $\beta > 0$, the dispersion relation could be modified simply as follows:

$$\omega - \mathbf{k} \cdot \mathbf{V}_d = i\beta \left(\omega^2 - k^2 C_s^2\right) \tag{3}$$

This dispersion relation is almost exactly right for waves propagating perpencidicular to the magnetic field.

A more complete expression is provided by *Fejer and Providakes* [1987] (see references within their section 2.1), whose notation we slightly modify. Restricting our attention to the lower E region (from which most echoes seem to arise), an appropriate solution to the dispersion relation for waves with wavelength greater than a few meters and less than a few hundred meters can be stated in the following way:

$$\omega_k = \frac{1}{1+\psi} \mathbf{k} \cdot \mathbf{V}_d \tag{4}$$

$$\gamma_k = \frac{1}{1+\psi}\left[\frac{\psi}{\nu_i}\left(\omega_k^2 - k^2 C_s^2\right) - k_z^2 D_{ez} + \frac{\omega_k \nu_i}{k L_N \Omega_i}\right] \quad (5)$$

Here ω_k is the radian frequency measured in the frame of the ions (which is almost the same as the neutral wind), and $\gamma > 0$ is the growth rate associated with the wave vector of interest, $\mathbf{k}$. The electron and ion collision frequencies (ν_e, ν_i) and gyrofrequencies (Ω_e, Ω_i) also appear together to form the anisotropy parameter $\psi = \nu_e \nu_i / \Omega_e \Omega_i$, which is much smaller than 1, and expresses the field-aligned nature of the irregularities. It is common to modify the anisotropy ψ to include the parallel component of $\mathbf{k}$ [*Fejer and Providakes*, 1987], so one will occasionally see more complicated definitions of ψ; thus it is important to refer to the dispersion relation from which the definition arose.

The collisions are dominated by electron-neutral and ion-neutral interactions; at these altitudes the neutral atmosphere is 4–6 orders of magnitude denser than the plasma. Electrons have very rapid diffusion along the magnetic field, expressed through $D_{ez} \approx T_e/m_e\nu_e$ [*Sahr*, 1990].

Large scale gradients in the density N_0 are expressed through the scale length L_N which is defined as follows:

$$L_N = \frac{N_0|\mathbf{k}\times\mathbf{B}|}{\mathbf{k}\cdot\nabla N \times \mathbf{B}} \quad (6)$$

The complexity of the definition reflects the fact that the density gradient may be stabilizing or destabilizing depending upon its direction with respect to $\mathbf{k}$ and the sign of ω_k. It is possible to manipulate this contribution of the density gradient into a somewhat simpler form; the gradient is destabilizing if

$$[\mathbf{E}\cdot\mathbf{k}\times\mathbf{B}]\,[\nabla N\cdot\mathbf{k}\times\mathbf{B}] > 0 \quad (7)$$

This inequality is sometimes written as $\mathbf{E}\cdot\nabla N > 0$, but this is incorrect (counter examples are easy to construct).

The fluid theory dispersion relation explains many features observed in radar and sounding rocket data.

1. Ion-acoustic waves: The characteristic wave phase velocities observed by radars are those of ion sound waves. Sounding rockets universally confirm the existence of meter scale density perturbations.

2. E region source: Magnetized electrons and unmagnetized ions exist only in the region below 150 km and above about 80 km. Collisional damping and low plasma densities preclude significant irregularities below 95 km, while increasing temperatures (higher ion acoustic speed) and ion magnetization shuts off the instability above about 125 km.

3. Threshold electric field: Echoes appear when the ambient electric field causes the $\mathbf{E}\times\mathbf{B}$ velocity to exceed the ion acoustic speed.

4. Unstable region: The strongest echoes are due to irregularities propagating nearly parallel to the $\mathbf{E}\times\mathbf{B}$ direction, and these "type 1" echoes fit linear theory well. Examining the dispersion relation (5) for $\gamma > 0$ reveals the unstable region of k space to be fan-shaped perpendicular to $\mathbf{B}$, with the center of the fan in the $\mathbf{E}\times\mathbf{B}$ direction.

5. Stable region: Outside the linearly unstable region the method of excitation is not understood in detail, but weaker "type 2" echoes whose Doppler velocities are less than the ion-acoustic speed also follow the dispersion relation.

6. Aspect sensitivity: Fluid and kinetic theories provide extremely strong damping of plasma perturbations with significant component parallel to the magnetic field. Thus the basis (if not the details) of the strong field alignment is completely understood.

F region irregularity Doppler shifts observed by HF radars satisfy a cosine law ($\omega = \mathbf{k}\cdot\mathbf{V}_d$) quite precisely. However the cosine law suggested by the E region dispersion relation is not a precise predictor of Doppler shifts (cf. *Robinson*, 1993). It is important to remember that the E region ions are strongly coupled to the neutral fluid, so that the drift velocity $\mathbf{V}_d$ depends not only upon the electric field but also upon the neutral wind. The "cosine law" may be precise but in a way that is unknowable from ground observations.

Although some linear theoretical development has been kinetic [*Farley*, 1963], most has been fluid [*Fejer and Kelley*, 1980, *Fejer et al.*, 1984]. With respect to incoherent scatter theory, the linear theory of electrojet irregularities has some deficits. Of particular note are the following.

1. Equation of state: The adiabaticity or isothermality (γ_e and γ_i) of the electron and ion gases is not understood in detail, and therefore the ion acoustic speed, a crucial parameter, is poorly defined [*Farley and Providakes*, 1989].

2. Ion acoustic speed: Because the auroral electrojet irregularities are formed in a plasma which is clearly not in thermodynamic equilibrium (unequal electron and ion temperatures, large amplitude irregularities), the thermodynamic equilibrium notion of an ion-acoustic speed is problematic.

3. Spectral form: The irregularity velocity spectrum is very well measured for 3 meter waves, but since it is not excited by thermal fluctuations it cannot (yet) be quantitatively interpreted in the sense of the incoherent scatter spectrum.

4. Scattering cross section: Since there is no amplitude closure through a fluctuation-dissipation theorem, the theoretical scattering cross section is unknown (see comments on nonlinear theories, below).

It is often suggested that linearly unstable irregularities have a phase velocity characteristic of the ion acoustic speed rather than the somewhat faster electron drift velocity, as predicted by linear (fluid) theory [*St.-Maurice et al.*, 1994], but there is no unambiguous evidence of this at high latitudes. For example, the electron and ion temperatures are rarely known when irregularities are present, and the functional dependence of the ion acoustic speed upon the electron and ion temperatures is also not clearly understood, so theories which depend upon this "saturation velocity" of the irregularities rest on shaky ground. There is a fairly simple radar experiment which provides evidence of a saturation velocity in the equatorial electrojet [*Farley and Providakes*, 1989; *Balsley and Farley*, 1971], but the geometry of the magnetic field prohibits an equivalent ground-based experiment at high latitudes.

Nonlinear Theory

The detection of irregularities by rather small radars is immediate evidence of the large amplitude, and thus turbulent, nature of the irregularities. Most of the nonlinear theory results from extension of the two-fluid linear theory to include the largest nonlinear term, which is proportional to $\mathbf{B}\cdot\nabla n\times\nabla\phi$, where $\mathbf{B}$ is magnetic field, ∇n is the gradient of the density perturbation, and $\nabla\phi$ is the electric field associated with the perturbation.

There are three major contemporary approaches in nonlinear theory: (1) global theories of turbulence in a homogeneous, anisotropic plasma [*Sudan*, 1983; *Hamza and St.-Maurice*, 1993ab]; (2) three wave interaction studies of restricted systems [*Albert and Sudan*, 1991; *Sahr*, 1990; *Sahr and Farley*, 1995]; and (3) numerical studies [*Janhunen*, 1992, *Schlegel and Thiemann*, 1994, *Oppenheim*, 1995, *Newman*, 1979]. The recent numerical studies are quite interesting and seem to represent Nature well. The numerics are very difficult because of the very large electron-ion mass ratio, the marginal applicability of fluid theory, and the minimum of two spatial dimensions necessary for appropriate representation. Janhunen uses a kinetic particle model for both electrons and ions; to permit longer time steps, the electrons are artificially massive. Oppenheim uses particle ions and fluid electrons, which permits the correct mass ratio. Thiemann and Schlegel investigated the $\mathbf{B}-\mathbf{V}_d$ plane instead of the plane perpendicular to $\mathbf{B}$. These kinetic and hybrid kinetic codes suffer the usual problem of having high statistical noise from finite numbers of particles.

In including the predominant nonlinear term and performing a spatial Fourier transform, we arrive at the following nonlinear partial differential equation [*Sahr and Farley*, 1995]:

$$L_k=\frac{\psi}{\nu_i}\left(k_\perp^2C_s^2+\frac{\partial^2}{\partial t^2}\right)+(1+\psi)\frac{\partial}{\partial t}+i\mathbf{k}\cdot\mathbf{V}_d+D_{ez}k_z^2 \quad (8)$$

$$L_kn_k=\frac{c}{B}\sum_{\mathbf{p}+\mathbf{q}=\mathbf{k}}\hat{z}\cdot(\mathbf{p}\times\mathbf{q})\;\phi_pn_q \quad (9)$$

Thus the amplitude of some Fourier mode n_k is coupled to the amplitude and electrostatic potential associated with all other modes n_p,ϕ_q. With further manipulation the electrostatic potential can be eliminated. A common approximation is derived from the continuity of current [*Sudan*, 1983, *Sahr*, 1990]:

$$\phi_k\approx-i\frac{m_i\nu_i}{k^2e}\mathbf{V}_d\cdot\mathbf{k}\;\frac{n_k}{N_0} \quad (10)$$

Using this approximation as well as the symmetry which must exist in the convolution sum, we have

$$L_kn_k=-\sum_{\mathbf{p}+\mathbf{q}=\mathbf{k}}M_{kpq}\,n_pn_q \quad (11)$$

$$M_{kpq}=i\frac{\nu_i}{2\Omega_i}\frac{\hat{z}\cdot\mathbf{p}\times\mathbf{q}}{1+\psi}\left(\frac{\mathbf{p}\cdot\mathbf{V}_d}{p^2}-\frac{\mathbf{q}\cdot\mathbf{V}_d}{q^2}\right) \quad (12)$$

The coefficient M_{kpq} represents the extent to which a particular wave k is affected by the amplitudes of two other waves p and q which "conserve momentum" in the sense that

$$\mathbf{k}=\mathbf{p}+\mathbf{q} \quad (13)$$

This property arises from a convolution of the nonlinear term during the Fourier transform. Examination of this term shows that although the waves have three-dimensional (possible) extent, the nonlinearity is primarily a purely perpendicular phenomenon. The strong damping for finite k_z has thus led most numerical modellers to investigate the purely perpendicular, two-dimensional problem. Alternatively, restricted systems have been investigated in which "three wave resonance" concepts are invoked. The basic argument here is that not only must the momentum $\hbar\mathbf{k}$ be conserved, but the energy $\hbar\omega$ as well, namely

$$\omega_k=\omega_p+\omega_q \quad (14)$$

This approach has been used for both the equatorial [*Albert and Sudan*, 1991] and the auroral electrojets [*Sahr and Farley*, 1995]. Some useful results have appeared from nonlinear theories:

1. Two-step process: The periodic appearance and disappearance of meter-scale scatter is readily explained by a modulation of the plasma parameters due to the passage of a kilometer-scale wave, which is itself probably excited by the large-scale gradient [*Sudan et al.*, 1973, *Riggin*, 1987, *Fejer and Providakes*, 1987].

2. Spectral widths: Although the agreement is far from precise, there is a general understanding of the spectral widths observed by VHF radars [*St.-Maurice and Schlegel*, 1982; *Sahr*, 1990; *St.-Maurice et al.*, 1994]. *Hamza and St-Maurice* [1993a, b] offered a particularly simple expression relating the Doppler velocity and width, namely,

$$\omega_k^2+\Delta\omega_k^2=k^2C_s^2$$

This expression is particularly valuable because it can be experimentally tested.

Beyond this, nonlinear theory has not yielded much information that can actually be used to understand radar data. Although the nonlinear theories are fairly consistent with data, they are not very predictive, nor are they readily disprovable by experiments. *Sudan*

[1983] developed a very influential reasoning; he postulated that the effective electron collision frequency ν_e becomes substantially larger in the presence of turbulence. This modifies the anisotropy parameter ψ^* whose new (larger) value is injected into the theory as a turbulently modified parameter. A further development of this idea was presented by *Robinson and Honary* [1990]. While one can manipulate the value of ψ to better conform to some observed features, the theoretical link explaining how and why to do this is weak, and there are consistency problems. If one increases ψ to a value large enough to explain the detection of echoes at an aspect angle of 4°, very large electron drift velocities are required, and many more perpendicular modes become linearly unstable.

Outstanding Problems in Electrojet Irregularity Studies

Two major classes of problems impede the understanding of electrojet irregularities: problems created by humans and problems supplied by Nature. Nature challenges us to carefully run and interpret experiments; as humans, we hope to progress in an orderly and understandable way.

The "type" nomenclature is widely used but poorly defined. It addresses a need to describe the phenomenon empirically and if pursued further, can be used to "classify" spectra in ways that are phenomenologically useful. The "type 1" label has been attached to strong, narrow spectra with mean velocity near the ion acoustic speed. Broad Doppler spectra with Doppler velocities below the ion acoustic speed are called "type 2." Many have reported an apparent surplus of narrow Doppler spectra with mean velocities near $C_s/2$, and these spectra have come to be known as "type 3." Occasionally, very high velocity spectra (usually narrow) are observed, and these are denoted "type 4." It is worth noting that some investigators do not require types 1, 3, or 4 to be narrow. There is occasional reference to "type 2" as being synonymous with "gradient drift" and "type 1" as meaning "two stream," but the vector electric field and density gradients are rarely known in the scattering volume. Additional types in radar data have been suggested by some experimenters; without denying their existence, we leave them for now [*Haldoupis and Nielsen*, 1989b; *Tanaka et al.*, 1990; *Kunitake et al.*, 1993].

The "Watermann plot" is by far the most reasonable basis for classification of radar power spectra (see Figure 3 of *Watermann et al.* [1989]). It is simply a scatter plot of the second versus first moments of a Doppler power spectrum; an example of a Watermann plot is shown in Figure 8. The axes may be calibrated in either velocity or frequency; since it now appears that there are no gyrophenomena in auroral electrojet irregularities, a velocity calibration will simplify interinstrument comparisons. One practical problem is the lack of useful algorithmic definition of "spectral width." Fourier domain methods must carefully subtract the noise power, which will bias conventional centered second moment estimates; there is an additional bias associated with the cyclic nature of the discrete Fourier transform [*Sahr*, 1990]. Correlation domain methods may be more robust, but one will get different answers if fitting the

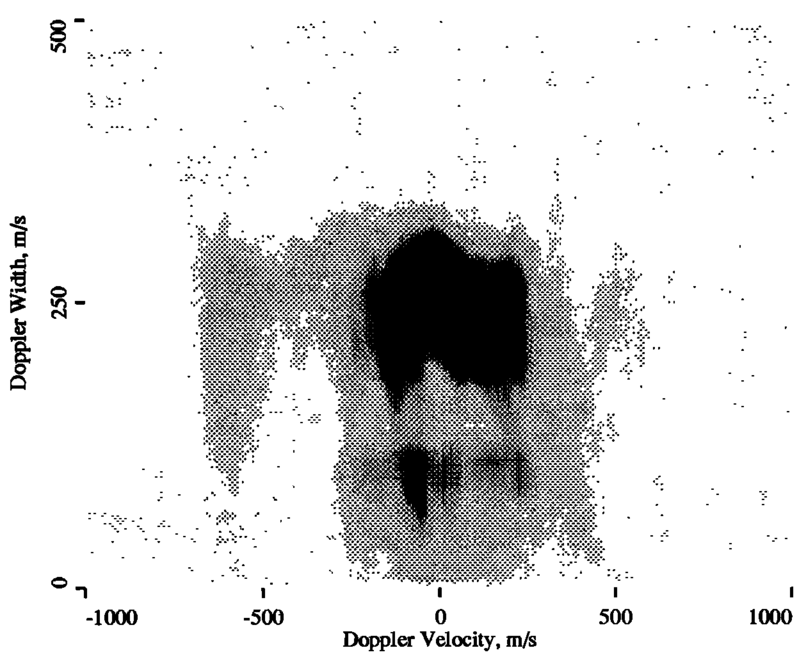

Figure 8. An example of a "Watermann Plot" of 60,000 second vs. first moments taken from one hour of CUPRI data during the 1989 ERRRIS campaign. The darker the shade, the more echoes present with the given first and second moments.

correlation function to gaussian or exponential forms, or computing the mean autocorrelation time. There is some evidence that the spectra are actually characterized by different spectral forms anyway [*Hanuise et al.*, 1993]. However, it is clear that the several radars should agree as well as provide a parameter of use to theorists.

All these radars observe the same phenomenon, but it is difficult to make detailed comparisons of their data. Several reports compare mean Doppler shifts [*Haldoupis and Nielsen*, 1989a; *Watermann et al.*, 1989], and important information about type 3 waves has been revealed this way. Nevertheless, other comparisons are problematic.

Type 3 waves have enjoyed an especially colorful career [*Fejer and Providakes*, 1987; *Providakes and Seyler*, 1990; *Prikryl et al.*, 1987; *Watermann et al.*, 1989; *Farley et al.*, 1991; *Haldoupis et al.*, 1992]. While it appears that radars observe a noticable abundance of echo power with Doppler velocity $C_s/2$, it is not at all clear that a "type 3" echo indicates a physically distinct type of wave. The most recent work reflects the understanding that VHF observations of type 3 echoes cannot be attributed to electrostatic ion cyclotron waves. Among other evidence, it appears that the type 3 echo is better characterized by a characteristic Doppler velocity rather than a characteristic Doppler frequency shift. Recently, *Sahr and Farley* [1995] have offered a three-wave resonance theory which suggests that type 3 waves are the linearly stable waves which are "most likely" to be excited by linearly unstable waves of comparable wavelength.

While not well understood or characterized (chiefly through their relative rarity), type 4 waves are distinguished by phase velocities well in excess of ordinary ion acoustic speeds (about 450 m/s) [*Haldoupis et al.*, 1991]. Three principle theoretical viewpoints exist. *Providakes et al.* [1988] argue that type 4 waves are essentially identical to type 1 waves in an E region subject to high temperatures (large C_s) and large electric fields. *Haldoupis et al.* [1995] suggest that extremely steep electron density gradients in the vicinity of auroral arcs can provide substantial free energy in addition to the ambient electric field. *Haldoupis et al.* [1993] also suggest that a three-wave resonance mechanism preferentially generates waves whose phase velocity is twice the ion acoustic speed. The first two theories seem to be compatible, while the third theory contradicts the fairly explicit nonlinear theory of *Sahr and Farley* [1995] regarding type 3 echoes, in which they argue that the three-wave resonance interaction excites waves without substantial modification of the normal linear phase velocity and certainly not exceeding the ion acoustic speed.

Promising Avenues for Future Study

Referring to the previous section on outstanding issues, we offer some avenues for exploration.

Experimental Studies

Radar Experiments. There are several important radar experiments that should be performed. Many of the experiments may seem natural for sounding rockets but with radar one has the possibility of long-term studies, which are impossible with any current in situ technology.

1. Spatial spectra: A few multi-frequency radar experiments have been performed [cf. *Eglitis et al.* [1995]], but the database is quite sparse and essentially uncalibrated. Such experiments are difficult, given the wide bandwidth radio gear required. On the other hand, multistatic geometries do yield a range of k vectors for a given frequency and may at least provide a local slope to the k spectrum.

2. Spatial scale: Recent radar observations of equatorial electrojet irregularities reveal 100-m structure of 3-m irregularities (this is the resolution limit of the instrument). Given the more energetic high-latitude habitat, there is every reason to expect such anhomogeneity in the auroral electrojet.

3. Transverse spatial scale: The fine scale referred to above is parallel to the radar k vector; the three-dimensional structure is important. If we define 100-m as a desirable resolution, it is obvious that VHF antennas with sufficiently narrow beams are impractical. Thus interferometric experiments with antenna baselines of several kilometers are needed.

4. Scattering studies: On the other hand, the very large amplitude of the irregularities suggests that multiple scattering may play a role in radar returns. Is fine spatial and temporal structure an artifact of multiple scatter? There is a need to develop radar experiments which can deduce the presence of multiple scatter.

Sounding rocket experiments. Sounding rockets provide access to all spatial scales from tens of kilometers to tens of millimeters, and in contrast to radars these measurements are made in physical space rather than in (spatial) Fourier space. It is probably a funding impossibility, but the fundamental requirement for advance with in situ experiments is, quite simply, lots of flights. The manner in which "lots of flights" can be accomplished may encourage novel technological approaches, which may in turn attract new funding.

1. Auroral arc structure: The high-latitude problem is obfuscated by density and temperature features associated with auroral arcs. Some authors propose that large phase velocity irregularities may be excited directly, even at meter scales, by very steep density gradients. Thomson scatter radars are almost certainly incapable of measuring the hundred meter scale sizes proposed, leaving in situ measurements as the only available tool.

2. Time variability: The more energetic the auroral phenomena, the shorter lived they are. It is unreasonable to expect a suitable statistical ensemble of type 3 and type 4 in situ data without expecting that many

Table 3. World Wide Web Addresses for Some E Region Irregularity Research Using Radars

Web Address	Name
http://hyperion.haystack.edu/homepage.html	Millstone Hill
http://seldon.eiscat.no/homepage.html	EISCAT
http://www.naic.edu	Arecibo
ftp://ee.cornell.edu/pub/jro/jro.html	Jicamarca
http://grant.jhuapl.edu/RADAR/SD_homepage.html	SuperDARN
http://dac3.gi.alaska.edu/PFRR94-0/WWW/DATA/VHF.HTM	HLMS
http://isdl.ee.washington.edu/SPP/Projects/CUPRI	CUPRI
http://www.mpae.gwdg.de/mpae_projects/STARE.html	STARE
http://ion.ac.le.uk/sabre/sabre.html	SABRE

flights will completely miss regions in which such echoes are occurring. It takes approximately 2 min for a sounding rocket to reach the E region; a "type 3 event" may last 20 s (although there are also long-lived examples).

3. Instrument enhancement: Although great advances have been made in electric field "interferometric" measurements, sounding rocket payloads are always compromises in instrument capability, in terms of numbers of and complexity of booms, data rates, and electromagnetic compatibility (interference). Measurements can be improved, very likely through new techniques.

4. Parallel electric fields: Any reasonable theoretical inquiry into these irregularities leads to questions about the tiny component of the wave and DC electric fields parallel to the magnetic field. This is a very difficult measurement to make; it should be made.

5. Novel approaches: There are some nontraditional methods of placing many payloads in the E region with considerably less expense than conventional "heavy" sounding rockets. Some enhanced meteorological engines should be able to loft 5-kg payloads to 110 km or more; special howitzers can also achieve E region altitudes. It is becoming possible to construct tethers longer than 100 km which might descend from satellites in relatively stable orbits into the E region. A rotating, tethered payload could have fairly low velocity (and low aerodynamic drag) in the E Region.

Multi instrument campaigns. Some multi-instrument campaigns have occurred which combine remote sensing and in situ experiments. Obviously a great deal can be learned from such campaigns [*Providakes et al.*, 1988; *Pfaff et al.*, 1992; *Rose et al.*, 1992]. However there is enough apparent disagreement in radar observations, and a relative paucity of in situ observation that simpler, single instrument investigations remain useful. The striking onset of the World Wide Web (WWW) will permit the post facto synthesis of multi instrument campaigns. A partial list of WWW links appears in Table 3.

Theoretical Studies

Theoretical studies are at a bit of an impasse. There seems to be no need to develop linear theories further, and formal turbulent theoretical developments have problems with prediction and verification. Numerical studies show a great deal of promise, but are clearly running into the usual compuational resource problems that "big" simulations face.

Linear Theory. The field has enjoyed a fairly complete linear theory for thirty years, with useful embellishments appearing through the 1980s. Two areas could use a bit of work. First, the short wavelength boundary of fluid theory applicability should be investigated. Second, thermal transport (the energy equation) should be further tested.

More generally, we should study the reasonableness of assuming thermodynamic equilibrium in what is apparently a non equilibrium plasma. To what extent can one even define the ratio of specific heats γ needed to compute an ion acoustic speed?

Nonlinear theory. Much of the nonlinear theory is dissapointing in that it does not make clear predictions about what we have observed or what we can observe. The most useful aspect of nonlinear theory has been the identification of the strongest nonlinear term. This provides a means to excite linearly stable waves.

There are exceptions; the relatively simple "two-step process" [*Kudeki et al.*, 1982] provides a very neat explanation for periodic excitation of meter-scale waves by the passage of kilometer-scale waves which modulate the back ground density gradient.

One also hopes that nonlinear theory can provide a simple statement about the spectral form. In particular, there is evidence for both gaussian and lorentzian spectral shapes in HF and VHF data; why should one or the other or both appear?

Numerical simulations. Recent numerical simulations of the E region are quite satisfying, but suffer from short runs and limited grids; they are still two-dimensional. The primary limitation seems to be one of supercomputer resource and capability, although one can also hope for revolutionary simulation techniques which require much less speed and memory to achieve contemporary results (in a convincing manner).

Cross Disciplinary Studies

The radar aurora is a fascinating phenomenon which we may study purely for its role in the larger tapestry of Nature. We may also stand back to see how this bit of fabric fits into larger garments.

1. Global modelling inputs: Successful modelling of the large-scale behavior of the ionosphere and magnetosphere is hindered by the enormous range of important spatial scales. The auroral E region is a singularly important electrical load to larger-scale sources in the magnetosphere and magneto tail. While it is probably impractical to include the centimeter-scale limit of electrojet irregularities, it probably is possible to produce theory or simulation-based effective conductivities and other transport coefficients that are modifed by the presence of turbulence.

2. Radio propagation and space weather: Despite its low contribution to the total electron content of the ionosphere, the E region contains large density irregularities which scatter and scintillate radio waves well into the microwave region. Furthermore, the electrojet occasionally carries sufficient current to strain power delivery systems at high latitudes. Prediction and real-time detection of radio scintillation and large electrojet currents would be a great service to many users beyond the space science community.

3. Formal instrument modelling: Despite the marvelous experimental results produced by small coherent scatter radars, some of the analysis methods should be improved. For example, the interferometric methods employed so far are quite primitive compared to what is actually possible with existing data sets. Even power spectra calculations are on very thin ice; averaging, filtering, and smoothing parameters are often chosen in completely ad hoc ways (this criticism certainly includes the authors!). Given the last decade's success in applying "inverse problem theory" to incoherent scatter, there is an imperative to apply such robust (and satisfying) methods to coherent radars.

Conclusion

The sound wave turbulence generated near the northern lights and at the magnetic equator is one of the most tantalizing phenomena of Nature, at once easy to detect and difficult to quantify. It provides challenging problems in the study of Nature, while interfering with modern radio communications and precision tools for time, frequency, and location. Meter-scale ionospheric irregularities will continue to provoke new developments in our understanding of Nature and motivate engineering advances as we build new instruments to study them.

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J. D. Sahr, Department of Electrical Engineering, University of Washington box 352500, Seattle WA 98195-2500. (e-mail: jdsahr@ee.washington.edu)

B. G. Fejer, Center for Atmospheric and Space Physics, Utah State University, Logan UT 84322-4405

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