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Volumetric imaging of the auroral ionosphere: Initial results from PFISR ☆

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ABSTRACT

The Poker Flat Incoherent Scatter Radar (PFISR) is the first dedicated ISR built with an electronically steerable array. This paper demonstrates the capabilities of PFISR for producing three-dimensional volumetric images of *E*-region ionization patterns produced by the aurora. The phase table was configured to cycle through 121 beam positions arranged in an 11×11 grid. A 13-baud Barker coded pulse was used, which provided ~1.5-km range resolution out to a maximum range of 250 km. Backscattered power was converted to electron density by correcting for path loss and applying the Buneman approximation assuming equal electron and ion temperatures. The results were then interpolated onto a three-dimensional cartesian grid. Volumetric images are presented at 5-min, 1-min, and 14.6-s integration times (corresponding to 960, 192, and 48 pulses-per-position, respectively) to illustrate the tradeoff between spatio-temporal resolution and data quality. At 14.6 s cadence, variability in plasma density within the volume appears to be fully resolved in space and time, a result that is supported by both observational evidence and theoretical predictions of ionospheric response times. Some potential applications of this mode for studying magnetosphere–ionosphere interactions in the auroral zone are discussed.

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1. Introduction

The high-latitude ionosphere is subject to magnetospheric forcing through a variety of mechanisms (Thayer and Semeter, 2004). These sources impart a high degree of variability on the density, composition, temperature, and flows of the ionized and neutral gases. Resolving this variability in space and time is desirable for a variety of reasons. For instance, variability in the ionospheric conductance affects the rate at which Earthward poynting flux is dissipated in the neutral gas (Codrescu et al., 1995), and serves to structure electromagnetic coupling between the magnetosphere and ionosphere (Heelis and Vickrey, 1991; St. Maurice et al., 1996) possibly influencing, via feedback, the mechanism of auroral arc formation (Atkinson, 1970; Sato, 1978; Lysak, 1991). Shears in ionospheric flows mark sites of field aligned currents (Weber et al., 1991), the concomitant heating drives an outward ion flow to the magnetosphere (Tsunoda et al., 1989). Outward ion flows are also produced by soft, non-ionizing, particle fluxes (Zettergren et al., 2007), which may occur in narrow channels in the poleward regions of the auroral oval (Semeter et al., 2005).

The most comprehensive ionospheric remote sensing diagnostic is incoherent scatter radar (ISR). In the ISR technique, measurements of the backscattered power spectrum about the carrier frequency are analyzed to estimate the ion temperature (T_i), electron temperature (T_e), plasma density (N_e), and line-of-site bulk velocity (V_i) as a function of range. Information about the spatial and temporal variability in the medium is acquired by scanning the antenna. In principle, such an approach could be used to construct three-dimensional images of these parameters at some cadence. For dish antennas, such direct imaging modes have been limited to two-dimensions (e.g., range versus elevation, or range versus azimuth), owing to mechanical limitations (see Semeter et al., 2005 for an example of high-resolution two-dimensional imaging of the auroral ionization patterns using the Sondrestrom radar).

The Poker Flat ISR (PFISR) represents a new radar modality for investigating how the ionosphere responds to the rapidly varying sources of energy flux in the aurora. PFISR employs an electronically steerable array that may be re-pointed on a pulse-by-pulse basis. Direct imaging of an ionospheric volume can be achieved by acquiring range-resolved measurements over a two-dimensional array of beam positions (Nicolls and Heinselman, 2007a, b). Tradeoffs between resolution and data fidelity are controlled by

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choosing pulse pattern, number and distribution of beam positions, and integration time. Because PFISR has the ability to store returns from each pulse, integration times do not have to be chosen a priori and, indeed, do not even have to be uniform over the sampled volume.

This article presents initial results from an experiment designed to image the spatiotemporal variability in the *E*-region electron density caused by auroral precipitation. To facilitate rapid formation of volumetric images, the imaged quantity is electron density estimated from range-corrected backscattered power, rather than full fitting of the computed autocorrelation function. With the current PFISR configuration, volumetric images with $\sim$14% uncertainty may be obtained at 14.6 s cadence, which is comparable to time scales associated with *E*-region ionization. The volumetric results are compared, quantitatively, with auroral brightness measured by a collocated all-sky camera using a simple continuity calculation. The all-sky camera provides an independent measure of the ionizing source and constitutes a 'ground truth' for the ISR analysis. Limitations, tradeoffs, and future improvements are discussed.

2. Experimental description and data processing

PFISR is located at the Poker Flat Research range (65.13N, 147.47W) near Fairbanks, AK. The antenna is tilted towards the geomagnetic North so that its boresight direction corresponds to elevation 74° and azimuth 15°. The beam formed by PFISR has angular dimensions of $\sim 1^\circ \times 1.5^\circ$, with the larger dimension in north–south plane. Geomagnetically, PFISR is located near the center of the statistical auroral oval at a magnetic L-shell of $\sim$5. Auroras at this location are typically associated with geomagnetic storms and substorms and, hence, highly dynamic. The expected scales of spatial and temporal variability in the auroral ionization patterns must be carefully considered in designing a volumetric imaging strategy and interpreting the results. These issues are discussed quantitatively in Section 4.

For this experiment, 121 beam positions were used, arranged in an 11×11 grid. Fig. 1(a) shows the full set of beam positions in a horizon-based coordinate system. The beam separation was 3-degree separation in each orthogonal direction, 4.24° along the diagonal. At 100 km altitude (the nominal altitude of the ionization peak for energetic aurora) the sampled angular region subtends an approximately rectangular region with dimensions 65 km × 60 km; the horizontal spacing between the beam centers at this altitude varies from 5.2 to 6.2 km, and the beamwidth varies from $\sim 1.7 \times 2.6$ to $\sim 2.1 \times 3.1$ km.

Fig. 1(b) shows the beam positions superimposed on an image recorded with the collocated all-sky camera. The aurora near the horizon are artificially saturated to emphasize detail within the PFISR volume. Note that in an image of the sky from the ground, east and west directions are flipped compared with map coordinates since the ground-based perspective is a mirror of the map perspective. Both the radar and all-sky image in Fig. 1 are depicted in the native coordinate system of an all-sky image—i.e., west is clockwise from north.

PFISR has the ability to transmit and receive on multiple frequency channels near 450 MHz, allowing for multiple pulse patterns to be transmitted within the duty cycle. For this experiment, three channels were used. On one channel an uncoded 480 μs pulse was used. These returns allow for estimation of the plasma autocorrelation function (derived from lag products), from which plasma parameters may be estimated via model fitting. However, because of the long pulse length (72 km), these measurements are of limited use for studying the narrow layers associated with auroral ionization.

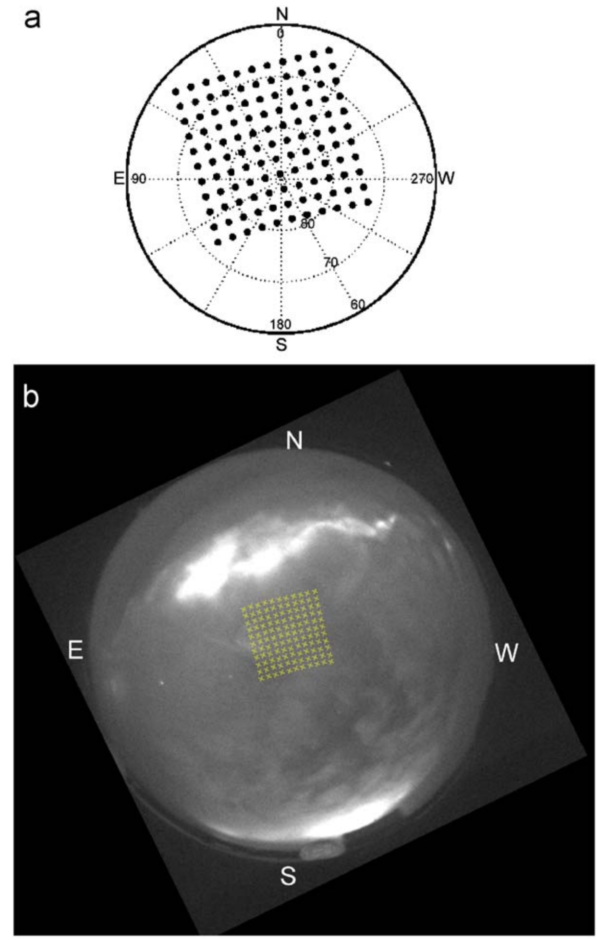

Fig. 1. (a) PFISR beam positions used in this experiment, depicted in a horizon-based polar coordinate system. (b) Beam positions superimposed on an image recorded with the collocated all-sky camera.

On the other two channels, a 13-baud Barker coded pulse was transmitted (Gray and Farley, 1973). The pattern was constructed using 10 μs bauds. After demodulation, these measurements provided estimates of backscattered power at $\sim$1.5 km range resolution. Power was then converted to N_e using the Buneman approximation (Evans, 1969) under the assumption that the electrons and ions are thermalized ($T_e = T_i$), which results in the expression

$$N_e(z) = \frac{2C_s r^2 P_r(z)}{P_t \tau}, \tag{1}$$

where r, range to target volume determined by time delay; P_t, transmitted power; P_r, backscattered power; τ, pulse length; C_s, constant term, embodying physical and radar system constants.

The $T_e = T_i$ assumption is generally valid in the collision-dominated *E*-region (see, e.g., Semeter and Kamalabadi, 2005) but may be violated within the auroral electrojet (near 110 km) as a consequence of anomalous heating associated with the Farley–Buneman (F–B) instability (Schlegel and St. Maurice, 1981). The instability would cause a reduction in backscattered power and an underestimation of N_e from Eq. (1). However, the F–B instability requires electric fields exceeding $\sim$50 mV/m. Such fields are not generally found within regions of auroral ionization (de la Beaujardiere et al., 1977; Marklund, 1984) owing to the high electrical conductivity within the arc regions. Although the lack of knowledge of plasma temperatures is a clear limitation of this mode, it is likely that Eq. (1) is valid within the auroral structures we are observing.

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