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Multi-scale structuring of the polar ionosphere by magnetosphere-ionosphere interactions

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14. ABSTRACT
This research used collaborative observations by UHF incoherent scatter radar (ISR), the HF SuperDARN radar network, and wide-angle optical imagers, supported by first-principles numerical modeling, to clarify the driving mechanisms and physical consequences of these interactions. Critical new observational evidence has been provided by the electronically steerable Resolute Bay Incoherent Scatter Radar (RISR, 74.7N, 94.8W), which has introduced a radically new sensing capability to polar ionospheric science. The results of this research include both technical contributions related to the application of phased array ISR in the polar cap, and scientific contributions arising from the application of these techniques. The major published results may be summarized as follows: 1) Numerical simulation of densities, temperatures, and cross-field plasma flows within density cavities along auroral boundaries has revealed extreme plasma parameters creating sites of instabilities and turbulence
[Zettergren et al., 2015]. 2) These extreme frictional heating events lead to anomalous spectral characteristics in Incoherent Scatter Radar (ISR) measurements [Akbari et al., 2017]. We have developed a Zakharov simulation framework that enables extraction of useful plasma information from such distorted spectra [Akbari et al., 2016]. 3) Application of tomographic analysis to fine-scale auroral forms appearing at the boundaries of these turbulent flow channels enabled us to quantify the width, temporal scales, and particle energies using model based inversion techniques. [Hirsch et al., 2017]. 4) The work on this project was synergistic with AF-sponsored efforts to develop a space-based sensor network comprised of cubesats for analyzing small-scale field-aligned current systems in the aurora [Parham et al., 2019a]. This project partially supported a feasibility study carried out in collaboration with Planet Labs using their 278-element cubesat constellation [Parham et al., 2019b]. The initial publication formed the basis of the Ph.D. project of Dr. Jonathan (Brent) Parham (now at Lincoln Laboratory).

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Multi-scale structuring of the polar ionosphere by magnetosphere-ionosphere interactions

FINAL REPORT

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1 Executive Summary

Ionospheric variability is a critical consideration for communication systems, GNSS, and space asset management. At high magnetic latitudes, the convergent magnetic field acts as a lens, focusing electromagnetic power originating from solar wind-magnetosphere interactions into a limited latitudinal range. The geometry and ensuing complex coupling processes result in extreme multi-scale time-dependent variations in the structure and composition of the ionized gases in Earth's outer atmosphere. Understanding the mechanisms and technological consequences of these interactions benefits from distributed heterogeneous time-dependent measurements of the ionosphere-thermosphere-magnetosphere system, and their application as constraints on predictive space weather models.

This research used collaborative observations by UHF incoherent scatter radar (ISR), the HF SuperDARN radar network, and wide-angle optical imagers, supported by first-principles numerical modeling, to clarify the driving mechanisms and physical consequences of these interactions. Critical new observational evidence has been provided by the electronically steerable Resolute Bay Incoherent Scatter Radar (RISR, 74.7°N, 94.8°W), which has introduced a radically new sensing capability to polar ionospheric science. The results of this research include both technical contributions related to the application of phased array ISR in the polar cap, and scientific contributions arising from the application of these techniques. The major published results may be summarized as follows:

1) Numerical simulation of densities, temperatures, and cross-field plasma flows within density cavities along auroral boundaries has revealed extreme plasma parameters creating sites of instabilities and turbulence [*Zettergren et al.,* 2015].

2) These extreme frictional heating events lead to anomalous spectral characteristics in Incoherent Scatter Radar (ISR) measurements [*Akbari et al.*, 2017]. We have developed a Zakharov simulation framework that enables extraction of useful plasma information from such distorted spectra [*Akbari et al.,* 2016]

3) Application of tomographic analysis to fine-scale auroral forms appearing at the boundaries of these turbulent flow channels enabled us to quantify the width, temporal scales, and particle energies using model based inversion techniques. [*Hirsch et al.,* 2017].

4) The work on this project was synergistic with AF-sponsored efforts to develop a space-based sensor network comprised of cubesats for analyzing small-scale field-aligned current systems in the aurora [*Parham et al.*, 2019]. This project partially supported a feasibility study carried out in collaboration with Planet Labs using their 278-element cubesat constellation [*Parham et al.*, 2017]. The initial publication formed the basis of the Ph.D. project of Dr. Jonathan (Brent) Parham (now at Lincoln Laboratory).

The software toolset developed under this grant enables routine analysis of common volume measurements of the ionosphere-thermosphere-magnetosphere system in response to changing solar wind conditions. This toolset is currently being extended to include data from the SuperDARN HF radar network, GPS scintillation sensors in the polar cap, and Fabry-Perot Interferometer (FPI) measurements of the neutral wind field. The high-level data products produced through this data fusion approach can be directly applied as constraints for regional and global models of the geospace system, improving space weather predictive capabilities.

2 Guiding Objectives of this Research

This research project was guided by two key questions:

1. **How is F-region plasma structure modified during polar cap transit?**
The relative contributions of transport, precipitation, recombination, field-aligned currents, and thermal diffusion in controlling plasma structures in the polar cap remains poorly understood. A major impediment has been the lack of diagnostic measurements able to provide the requisite three-dimensional view of the evolving ionospheric state. The electronically steerable Advanced Modular ISR (AMISR) sensors fill this need by allowing acquisition of information in multiple directions simultaneously. Using common volume observations by RISR, PolarDARN, and an all-sky spectral imaging system, we have carried out the first quantitative and experimentally verified calculation of three-dimensional plasma continuity at the geomagnetic pole [*Dahlgren et al.*, 2012a; *Perry et al.*, 2015; *Semeter et al.*, 2014].

2. **How do magnetospheric drivers alter ionospheric composition, and what are the global implications?**
The topside polar ionosphere serves as a significant reservoir of magnetospheric ions. During disturbed conditions, precipitation, frictional heating, and field aligned currents act to modify F-region ion composition, converting the ionosphere from predominantly atomic (O^+) to predominantly molecular (NO^+). But no systematic methodology has yet been developed to quantify this effect through ground-based measurements. Progress on this question has come in the form of clarifying the location and rate of energy deposition in the F-region and topside ionosphere [*Akbari et al.*, 2015; *Akbari and Semeter*, 2014], and developing a mathematical framework through which produce sufficient observational constraints to access composition information reliably [*Semeter and Zettergren*, 2014; *Swoboda et al.*, 2015]

3 Project publications

Six peer-reviewed papers were supported by this project and acknowledge AFOSR support under this grant, as listed below. These papers were also presented at international conferences (AGU, CEDAR, GEM, URSI) during the course of this project. In the remainder of this report we provide a synoptic overview of the major findings reported in this body of work.

1) Zettergren, M. D., J. L. Semeter, and H. Dahlgren, Dynamics of density cavities generated by frictional heating: Formation, distortion, and instability, *Geophys. Res. Lett., , 42,* 10, doi:10.1002/2015GL066806, 2015.

2) Akbari, H., P. Guio, M. A. Hirsch, and J. L. Semeter (2016), Zakharov simulations of beam-induced turbulence in the auroral ionosphere, *J. Geophys. Res. Space Physics, 121,* 4811–4825, doi:10.1002/2016JA022605

3) Hirsch, M., J. Semeter, M. Zettergren, H. Dahlgren, C. Goenka, and H. Akbari, Reconstruction of Fine-Scale Auroral Dynamics, *IEEE Transactions on Geoscience and Remote Sensing, vol. 54,* no. 5, pp. 2780-2791, doi: 10.1109/TGRS.2015.2505686, 2016.

4) Swoboda, J., J. Semeter, M. Zettergren, and P. J. Erickson, Observability of Ionospheric Space-Time Structure with ISR: A Simulation Study, *Radio Sci., 52,* 215-234, doi:10.1002/2016RS006182, 2017.

5) Akbari, H., Goodwin, L. V., Swoboda, J., St.-Maurice, J.-P., and Semeter, J. L. (2017), Extreme plasma convection and frictional heating of the ionosphere: ISR observations, J. Geophys. Res. Space Physics, 122, 7581– 7598, doi:10.1002/2017JA023916.

6) Parham, J., Semeter, J., and B. Walsh, Networked Small Satellite Magnetometers for Auroral Plasma Science, *J. of Small Satellites 8,* No. 1, pp. 801?814, 2019.

7) Parham, J. B., Beukelaers, V., Leung, L., Mason, J., Walsh, B., and Semeter, J. (2019). Leveraging commercial cubesat constellations for auroral science: A case study. Journal of Geophysical Research: Space Physics, 124, 3487-3500. https://doi.org/10.1029/2018JA025966

4 Research Accomplishments

This section highlights published results from the project. The results are organized into three categories: (i) results derived from radar-optical sensor Fusion, (ii) optimal experiment design approaches developed in support of these investigations, and (iii) F-region turbulence as a "hidden" term in ionospheric energy balance. In each category, a synoptic overview of the results are presented. For further details, see the full journal articles.

4.1 ISR-SuperDARN-Optical sensor fusion

Using the RISR facility, *Dahlgren et al.* [2012a] published the first direct three-dimensional time-dependent measurements of a transiting polar plasma patch. Figure 1 shows an example composite image. The plasma density slices at 340 km, 250 km and the vertical slice are produced by extracting cuts of the trilinear interpolation of RISR multi-beam measurements. The positions of the radar beams are marked on each horizontal slice as black circles (this method of RISR visualization has been previously discussed by [*Dahlgren et al.*, 2012b]). The structure has a peak electron density of $1.5 \times 10^1 1\text{m}^{-3}$, close to 250 km in altitude. The contemporary 630.0 nm allsky camera image is magnetically mapped to 200 km altitude for display purposes (the actual emission is closer to 250km). The emission ratio brightness of signal over average background is given by the horizontal color bar at the bottom of the figure. The optical enhancements correspond to the location of the plasma structures seen in the radar data. The coherent scatter from the SuperDARN radar is then plotted at 300 km altitude. The strongest echo (up to 30 dB, color bar to the left in the figure) comes from the region to the north-east of the vertical slice, partially overlapping the RISR-N plasma structure.

Perry et al. [2015] extended this experimental approach to investigate relationship between optical forms and derived electrodynamic parameters, in an effort to capture a full electrodynamic view of magnetosphere-ionosphere interactions during the formation of a plasma patch near the poleward auroral boundary. Figure 2 shows an example result from this work. Estimates of $|E_\perp|$ with vectors indicating the direction of the field, and $J_{||}$ are plotted along with 630-nm allsky camera data. The altitude of the contours for plasma density (Ne), ion temperature (Ti), Pedersen conductance

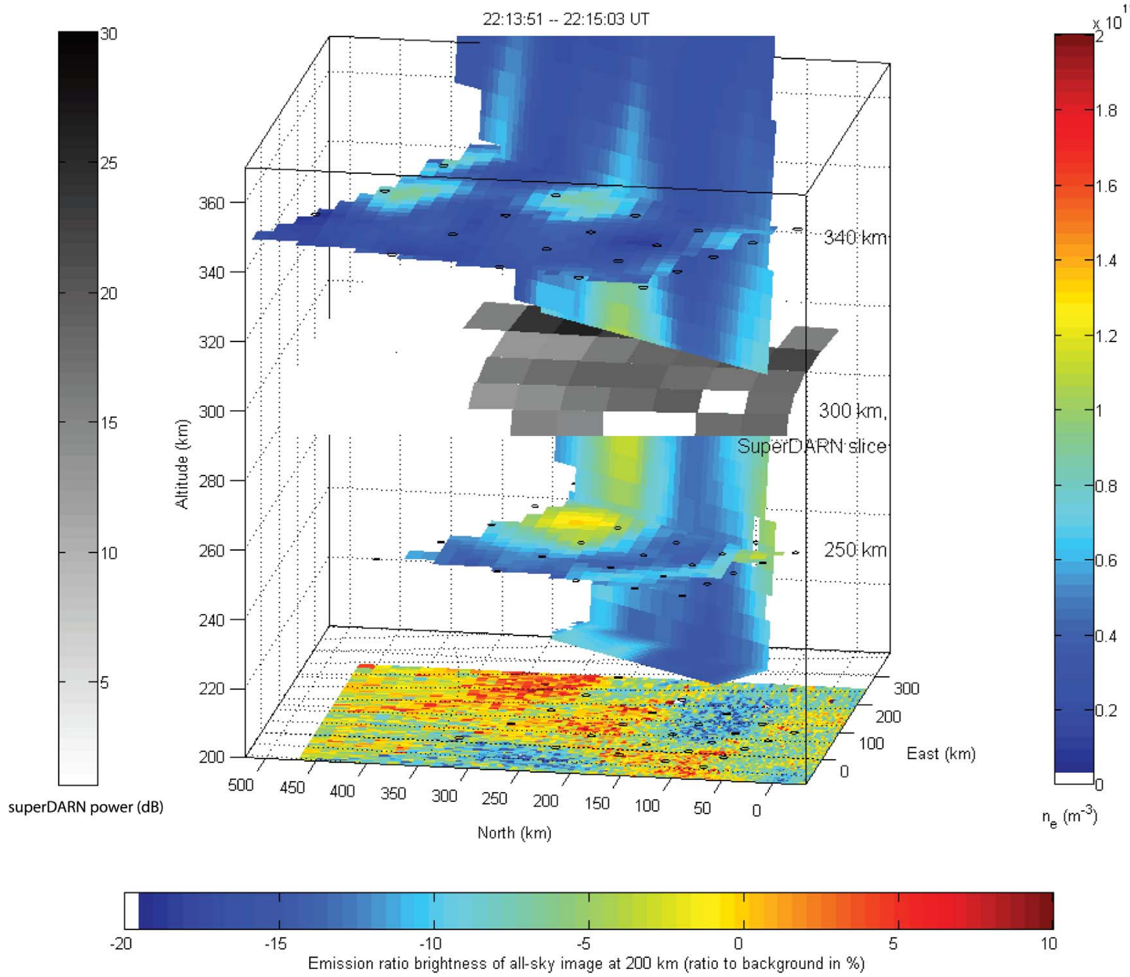

Figure 1: Three-dimensional view of an F region plasma density structure. The slices at 350 km and 250 km as well as the vertical slice show the electron density as derived from RISR-N data. The location of the radar beams are marked as black circles on the horizontal slices. At 300 km altitude, the Super- DARN echo is shown. The simultaneous 630.0 nm allsky image is projected to 200 km altitude, for which the emission brightness over the background level is indicated with the color bar below the combined plot. Optical signatures are seen in the location of plasma density enhancements, whereas the coherent echo from SuperDARN is strongest to the side of the plasma structure. [From *Dahlgren et al.*, 2012a]

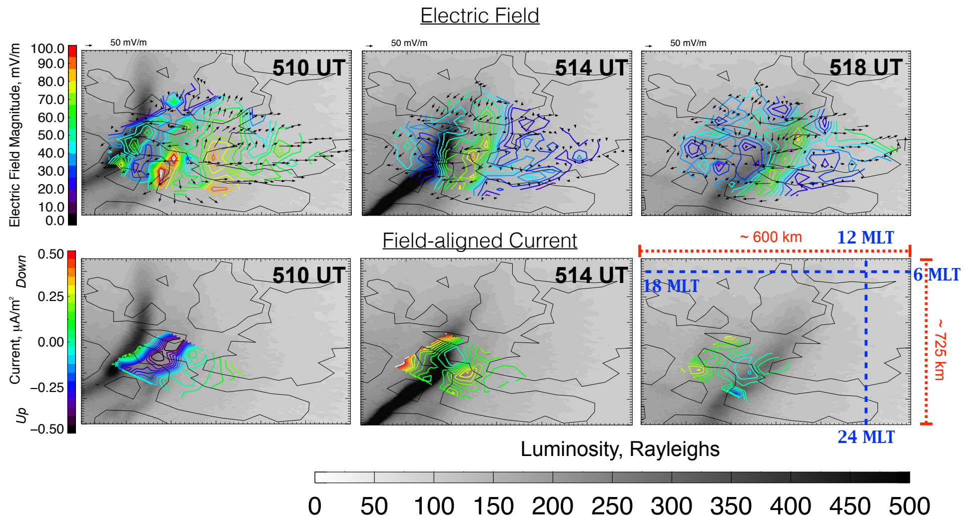

Figure 2: Combined plots of 630-nm allsky camera data (grayscale) and RISR contours for $|E_\perp|$ with corresponding vectors (top row), and $J_{||}$ (bottom row). Dimensions of the field-of-view and MLT meridians are indicated in red and blue, respectively. [From *Perry et al.*, 2015]

($\sum_P$), and $J_{||}$ are centered at 325 km. The $\sum_P$ estimates are a product of integrating the Pedersen conductivities between 200 and 500 km altitude along the magnetic field. The $|E_\perp|$ contours are constructed from data integrated over several hundred kilometres in altitude and mapped to 300 km altitude. The allsky data is mapped to 250 km altitude, the usual practice for 630.0 nm emissions.

Structuring in $|E_\perp|$ due to both arcs is significant and easily identifiable in this figure. Between 05:10 and 05:18 UT, meridionally extended $|E_\perp|$ structures moved towards dawn, coincident with the two optical arcs discussed earlier. At 05:10 UT, three structures with low —E— were in the FOV. Two of the structures, both with $|E_\perp|$ of $\sim$25 mV/m, were collocated with two optical arcs shown in grayscale. The low $|E_\perp|$ structures are indicative of the upward $J_{||}$ region of an arc; a region of electron precipitation in which plasma production is enhanced, increasing the ionospheric conductivities. With enhanced conductivities $|E_\perp|$ decreases to uphold current closure. The upward $J_{||}$ associated with the low $|E_\perp|$ structure of the brightest of the arcs is estimated to be approximately 0.5 μA/m^2, and maintains its intensity during the transit of the arc through the RISR FOV.

Semeter et al. [2014] used similar RISR experimental modes to focus on the interaction of plasma density patches and auroral processes. Figure 3 shows three frames of this time-dependent dynamic. The color contours are a vertical meridional representation of plasma density. The auroral images are displayed as flat perpendicular gray scale images. The red dashed line indicates the projection of the density cut into the allsky frame. These results suggested a time- steepening of F-region density gradients within a downward field-aligned current channel. The evacuating region was sandwiched in between a nascent sun-aligned arc and a plasma patch, indicating a mechanism of structuring via plasma removal. The challenge in quantifying this result lies in dealing with sampling issues associated with the limited number of radar beams and limited integration period used to construct the density images. Future work that fuses these measurements with 3-D physics-based modeling will contribute to clarifying this result.

The sensor fusion approach exemplified in these results represents a path forward for extracting optimal constraints on polar ionospheric dynamics. Such fused data products can be repackaged in a variety of formats, which can then provide valuable quantitative constraints for first-principles physical modeling efforts. As part of this effort, a mathematical framework and flexible software package have been developed in beta form, with the goal of providing such a tool to the modeling community. Activity on this effort is discussed in the following section.

4.2 Optimal experiment design for electronically steerable ISR

The aforementioned experimental results applied standard interpolation and mapping strategies, without the use of any physical knowledge of how the parameters should be connected or what spatiotemporal variations are allowed under known physics. An inverse-theoretic framework for incorporating physics knowledge into the analysis was developed by [*Semeter and Zettergren*, 2014] under this project. A schematic overview of the approach is shown in Figure 4. The basic approach is to develop parallel forward models between the magnetospheric drivers and the ionospheric response (both optical and ISR) which is subsequently inverted using Bayesian techniques. The Bayesian approach allows for incorporating uncertainties in model assumptions and tracking how they impact the results.

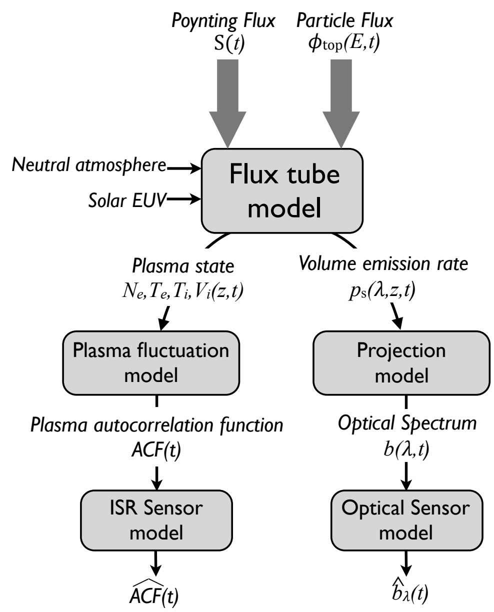

Figure 4: Schematic representation of the forward problem treated by [*Semeter and Zettergren*, 2014]. A flux of incident electrons ϕ_{top} impinges the atmosphere, which heats, ionizes, and excites the neutral gases. These rates are collectively represented by $p(x, y)$. A physical flux-tube model maps these inputs to changes in the ionosopheric state and optical emission rates. State parameters (left side) are sensed as changes in the plasma autocorrelation function measured by ISR, optical emissions (right side) are sensed as brightness variations in a camera system. This data flow describes a forward model, which may be reversed to reconstruct the magnetospheric drivers, in this case ϕ_{top}). [From *Semeter and Zettergren*, 2014]

A second track to improving sensor resolution was pursued by *Swoboda et al.* [2015], who exploited the unique multi-beam capability of RISR to deal with motion of the ionospheric target during the data acquisition period. Their approach developed the concept of a three-dimensional ISR ambiguity function. The essential idea is captured by considering a fixed ionospheric pattern moving through a field that is being sampled by a regular grid of radar beams. ISR backscatter is a stochastic process, and so time-integration is required to estimate the plasma parameters. If a plasma parcel moves into an adjacent beam during this integration period, then we have a classic deblurring problem (Figure 5), where echoes from multiple beams could be combined to improve fidelity.

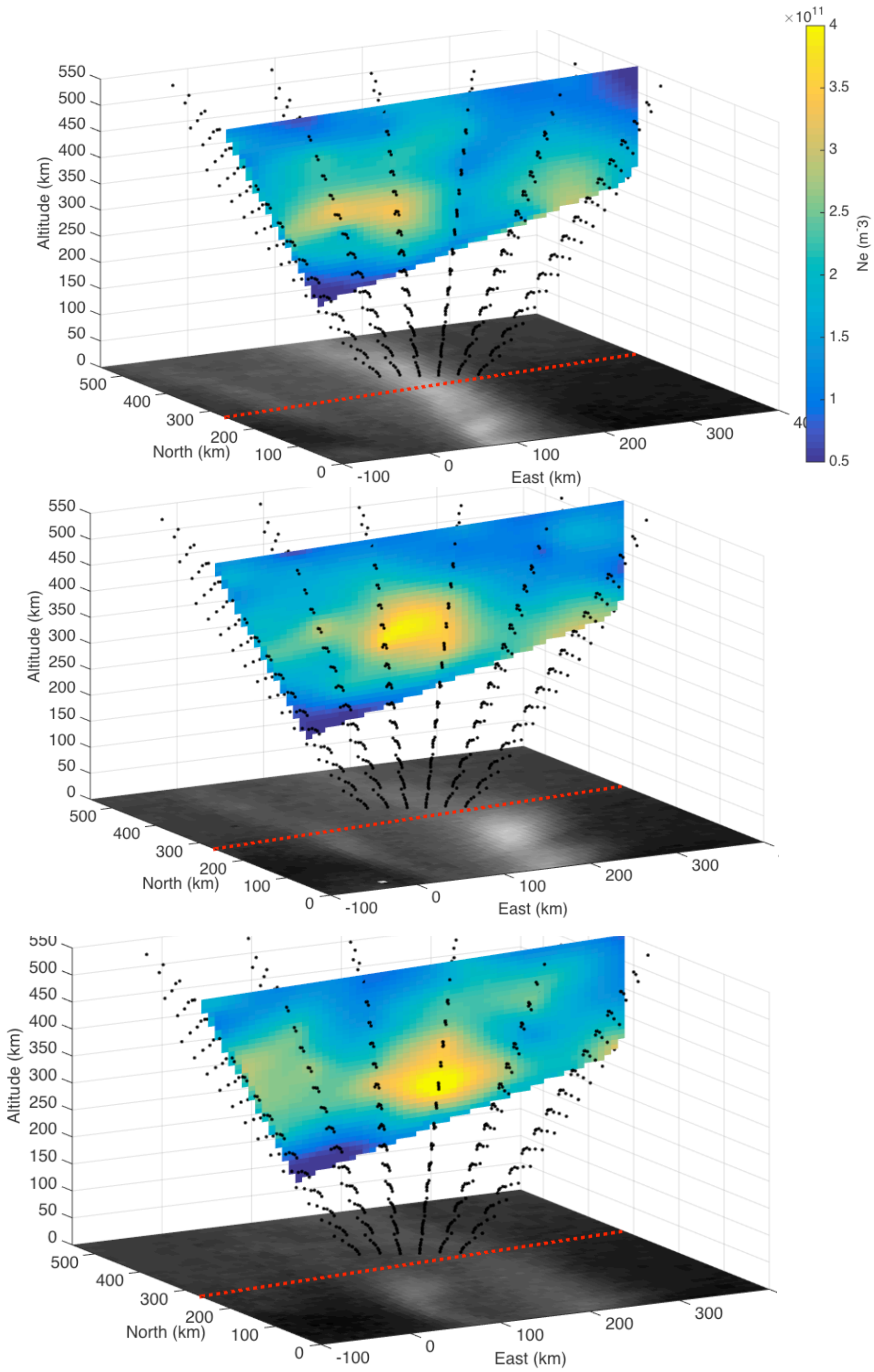

Figure 3: Snapshots of vertical meridional cuts through a plasma density structure in the polar cap (color contours) as rendered from RISR samples (black dots). These are overlain on on horizontal maps of 630-nm brightness (gray scale) observed by the collocated allsky camera. The red dashed line indicates the projection of the density cut into the camera frame. The figure illustrates an evolving plasma patch sandwiched between two polar cap arcs. [From *Semeter et al.*, 2014]

4.3 Langmuir turbulence: A hidden energy transfer mechanism

In addition to macro-scale (fluid) instabilities, such as gradient-drift and shear-driven, particle fluxes and field-aligned currents also produce micro-scale (kinetic) instabilities—e.g., unstable Langmuir waves which couple to other modes. These effects are manifested in ISR observations as enhanced non-thermal backscatter, sometimes known as "Naturally Enhanced Ion-Acoustic Lines" or NEIALs. [*Akbari et al.*, 2015] used PFISR to establish the geospatial context of these scattering events, suggesting an intriguing correlation with ground-based observation of "MF bursts". [*Akbari and Semeter*, 2014] used the unique electronic steering capabilities of PFISR to observed the dependence of NEIALs on magnetic aspect angle.

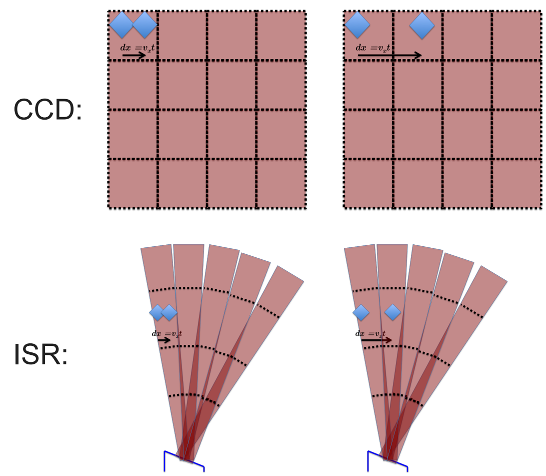

Figure 5: Illustration of digital blurring for a CCD focal plane (top) and for a set of ISR beams (right). Electronically steerable ISR is able to integrate in an effectively simultaneous manner in multiple beams, thus enabling integration across multiple beams as the plasma target moves. This framework has a strong analogy to deblurring in optical imagery. [From *Swoboda et al.*, 2015]

These results suggested that Langmuir turbulence may represent a "hidden" mode of energy transfer in the high-latitude F-region, which has direct effect on the structuring and composition objectives of this research. Exploration along these lines has lead to experimental modes able to isolate with unprecedented resolution the relationship between these instabilities to the bulk properties of the ionosphere. Figure 6 exemplifies this result. Enhanced UHF backscatter at 100-150 km is caused by the usual auroral energy deposition mechanism, namely, impact ionization of the neutral gases. But the enhanced echoes at 200-300 km are related to Langmuir turbulence produced by collisionless energy deposition in the low-energy regime of the impinging electron spectrum. The process is expected to occur broadly throughout the disturbed high-latitude geospace system. The significance of this latter energy deposition process to the structure and composition of the ionosphere is not known.

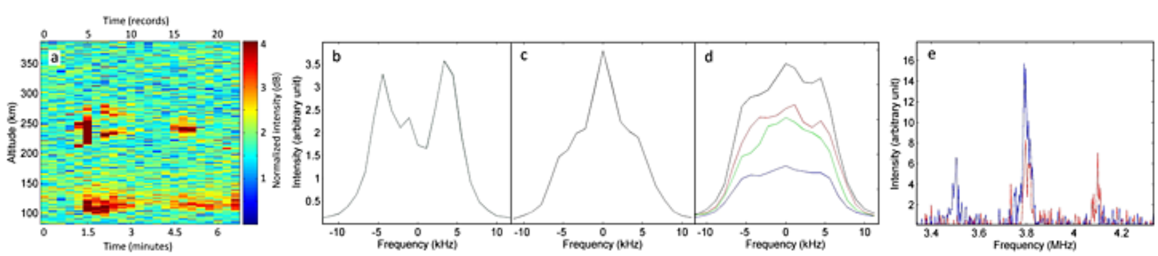

Figure 6: (a) Ion line range-time-intensity (RTI) plot derived from a separate 1 baud length pulse that accompanied AC. The time axis is shown in minutes as well as in 16 s intervals (records). Coherent echoes are originating from thin layers close to the F-region peak (∼250 km). (b–d) Examples of ion line spectra measured from the turbulence layers. Each spectrum corresponds to different times. (e) Up- (blue) and down-shifted (red) plasma line spectra produced by long-pulse measurements for record 16 in panel a. The spectra are averaged over a 70 km range gate centered at 290 km. [From *Akbari et al.*, 2015]

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