Advanced Modular Incoherent Scatter Radar

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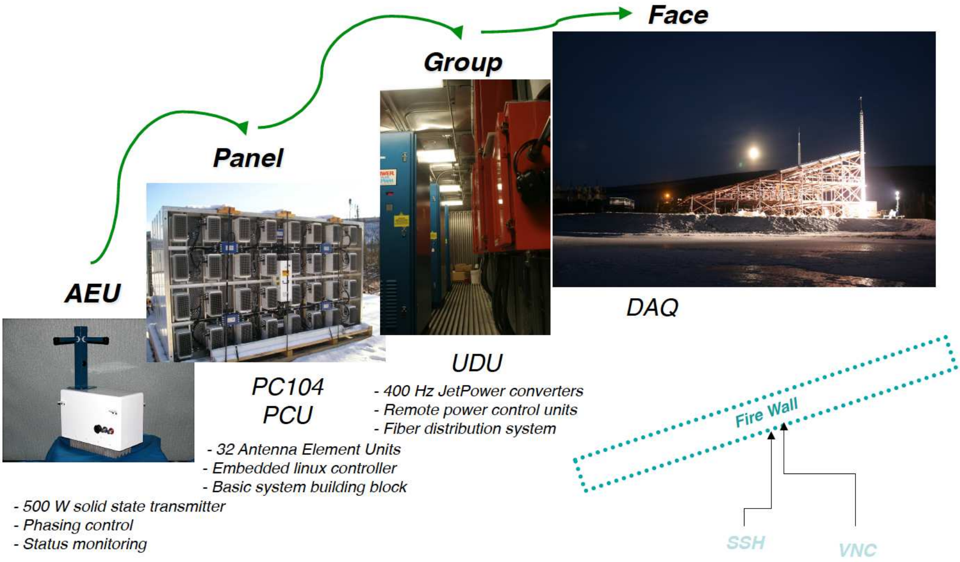
With thanks to Ashton Reimer, Mike Greffen, Leslie Lamarche, Pablo Reyes, Rob Gillies, Mike Nicolls, and Craig Heinselman.

1. AMISR Technology
   - Modular Design
   - Electronic Beam Steering Capabilities
   - Fields of View

2. AMISR Analysis Products
   - Scalar Imaging
   - Velocity Estimation

3. AMISR Science Highlights
   - PFISR Hightlights
   - RISR Hightlights

AMISR Modular Design



Antenna Element Unit (AEU) Specifications

- Distributed Solid State Power Amplifiers (SSPAs)
- 430-450 MHz instantaneous bandwidth
- 10% Maximum duty cycle
- Minimum PRF interval 500 usec
- Maximum pulsewidth 2 msec
- Passive cooling (no moving parts
- 400 Hz prime power

- Crossed dipoles, circular polarization on axis
- Balun built into the antenna support shaft
- Constant impendence over bandwidth and scan angle
- Spacing is hexagonal for efficiency
- Tx/Rx polarizations are opposite and fixed (not measureable)

The AMISR UHF System

Antenna Element Unit (AEU)

Face

AMISR AEU = Tx/Rx Unit
- *500 W solid state transmitter*
- *Phasing control*
- *Status monitoring*
- *4096 AEUs/AMISR radar face*

32/panel

AMISR Panel
- *32 Antenna Element Units arranged in hexagonal pattern*
- *3.5 x 2 meters; 19.8 dBi / panel*
- *16 kW peak power per panel*
- *Basic system building block for AMISR*
- *Embedded linux controller*

Panel (with PCU)

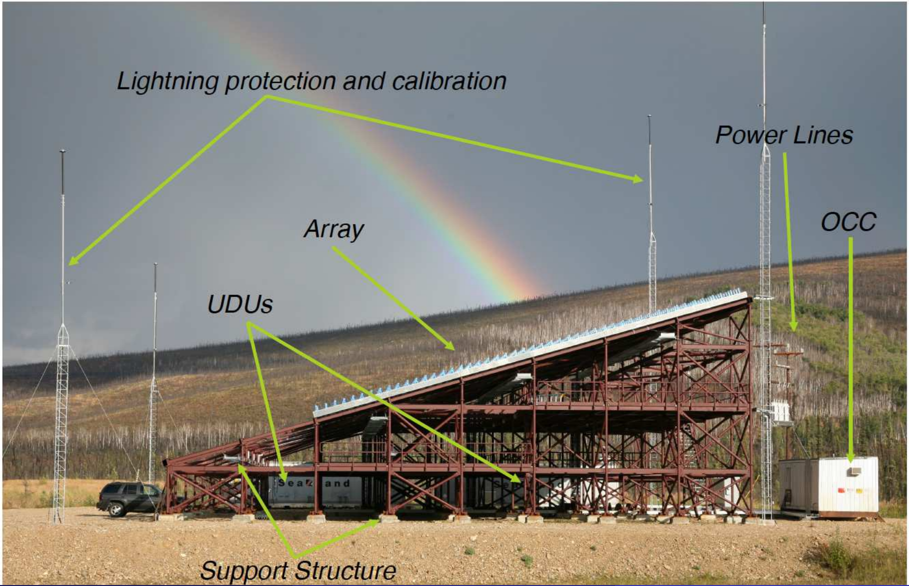
Utility Distribution Unit (UDU)

AMISR Control System (ACS)

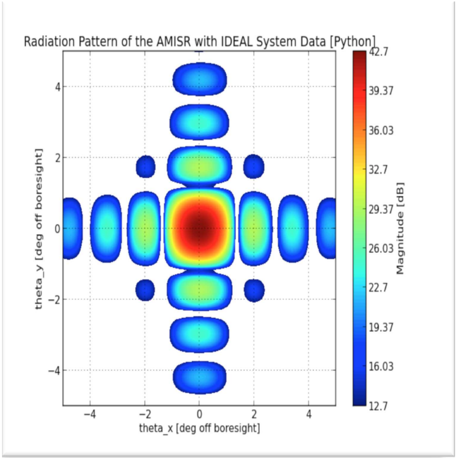
AMISR UDU
- *400 Hz JetPower converters*
- *Remote power control units*
- *Fiber distribution system*

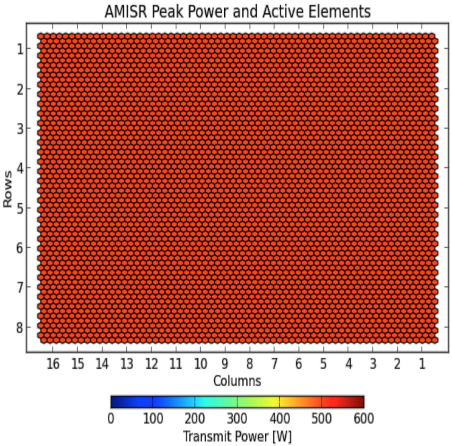
AMISR ACS
- *Flexible transmit and receive system*
- *Completely remotely controlled*
- *Experiments run off a scheduler*

Poker Flat Incoherent Scatter Radar (PFISR)

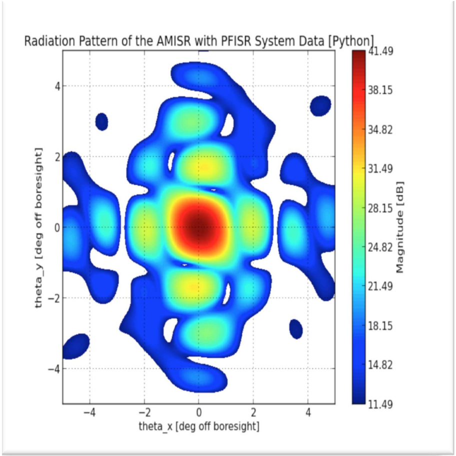


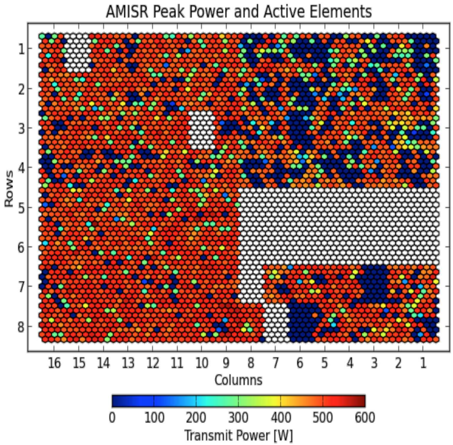
Ideal AMISR Radiation Pattern



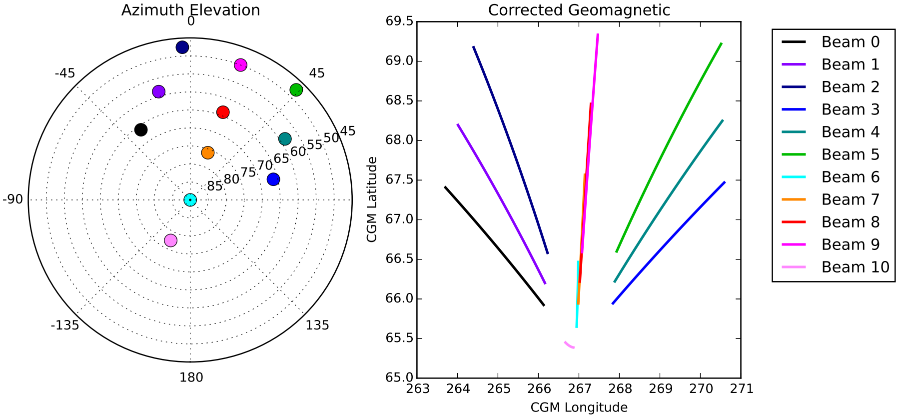


AMISR Graceful Degradation





Electronic Beam Steering



- Time to steer beam is ∼400 μs. Less than typical IPP (1-10 ms).
- Beam steering happens pulse-to-pulse.

Mechanical Steering vs Electronic Steering

Mechanical Steering Experiment

- Steer to position 1
- Send many pulses for 1 min
- Steer to position 2
- Send many pulses for 1 min
- Steer to position 3
- Send many pulses for 1 min
- Steer to back to position 1

Electronic Steering Experiment

- Pulse in beam 1
- Pulse in beam 2
- Pulse in beam 3

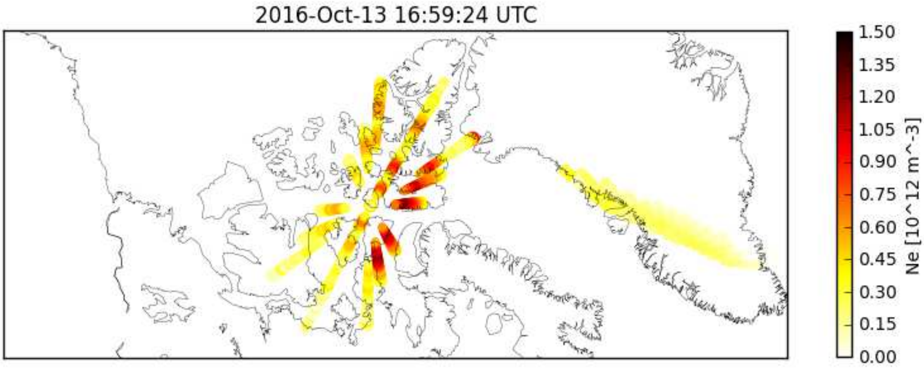
⋮

- Pulse in beam N
- Pulse in beam 1 again

Advantages of Electronic Steering:

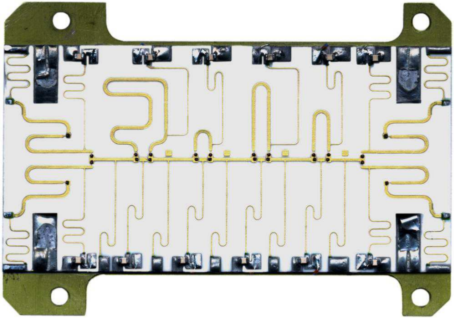
- Each beam is revisited once every $N\tau_{IPP}$.
- Can average data at any multiple of $N\tau_{IPP}$. Incoherent integration time is adjustable after the fact.
- Data being combined is nearly simultaneous.
- No time lost steering between pulses.

Combined RISR and Sondrestrom View of Patches



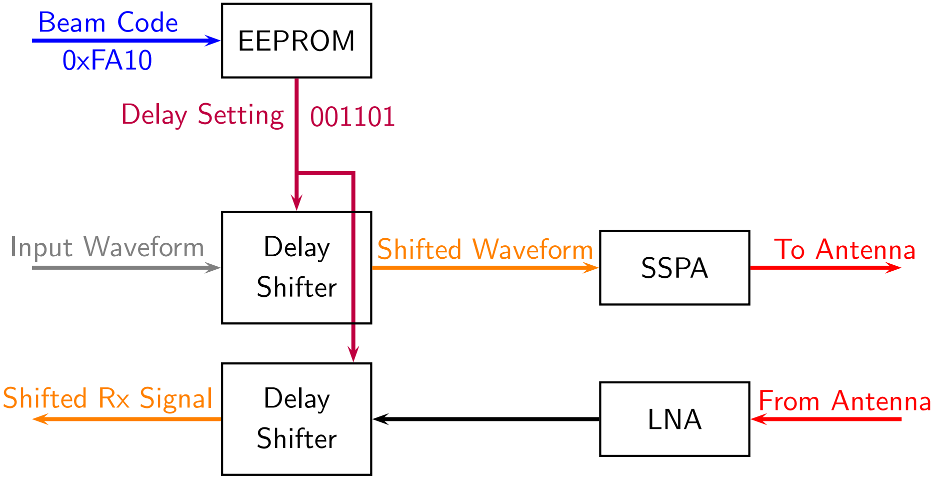
Electronic Steering with Delay Shifters

Example 4-bit delay shifter:



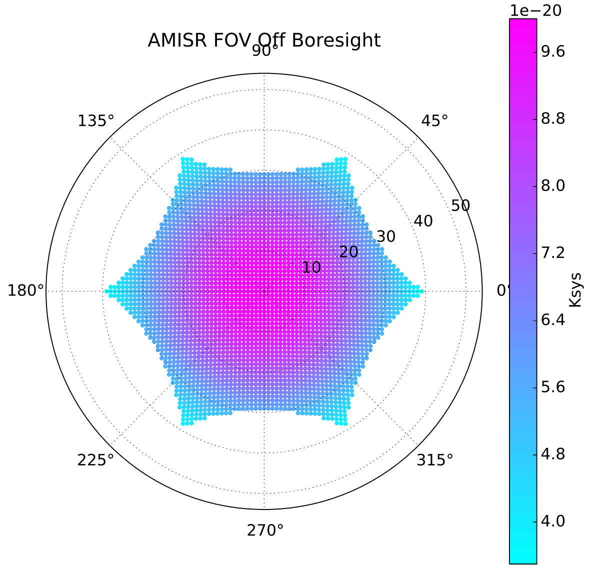
- AMISR uses 6-bit delay shifters
- $2^6 = 64$ steps spaced by $\pi/32 = 5.625°$

Conceptual Diagram of Steering with AMISR



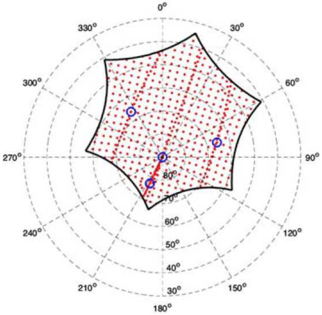
Limitations of Phased Array Beam Steering

- FOV limited by grating lobe limit $\sim 30^\circ - 40^\circ$
- Antenna gain decreases with steering angle off of boresight
- Antenna works best within $\sim 25^\circ$ off of boresight



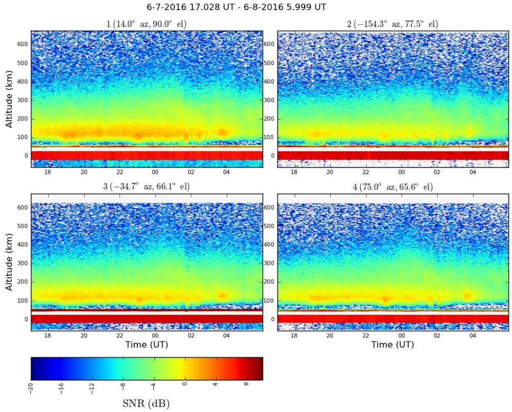
The PFISR Up-B Compromise

IPY Beam Pattern



The Up-B beam is close to the grating lobe limit, and therefore has reduced sensitivity.

Reduced SNR in Up-B (Beam 2)



Statistical Considerations with Pulse Steering

$$\frac{\delta \hat{S}}{S} = \frac{1}{\sqrt{K}} \left(1 + \frac{1}{S/N} \right)$$

- Larger number of beams $\Rightarrow$ fewer pulses per beam
- If I can confortably integrate for 1 min using 7 beam positions $\Rightarrow$ I would need to integrate 6 min to get the same data quality using 42 beams.

Multiple frequency channels can help statistics. Example: RISR-N "ImagingLP" mode for imaging F-region polar cap patches.

- 51 beam positions
- Long pulses on 3-frequency channels
- In each IPP 2 frequencies Tx, 3rd collects noise/cal samples
- Same statistics as a single frequency experiment on 17 beams

Sizing an AMISR for ISR

Statistical Accuracy of ISR Measurements:

$$\frac{\delta \hat{S}}{S} = \frac{1}{\sqrt{K}}\left(1 + \frac{1}{S/N}\right) \approx \frac{1}{\sqrt{K}}\frac{1}{S/N}$$

Soft Target Radar Equation:

$$\frac{S}{N} \propto P_{\mathrm{Tx}} \frac{G}{4\pi R^2} \eta V_s \frac{A_{\mathrm{eff}}}{4\pi R^2}$$

$$G \sim \frac{4\pi}{\Omega} \qquad V_s \sim R^2 \Omega$$

$$\frac{S}{N} \propto P_{\mathrm{Tx}} \frac{1}{\cancel{4\pi R^2}} \frac{\cancel{4\pi}}{\cancel{\Omega}} \eta \cancel{R^2} \cancel{\Omega} \frac{A_{\mathrm{eff}}}{4\pi R^2}$$

$$\frac{S}{N} \propto \frac{1}{4\pi R^2} P_{\mathrm{Tx}} A_{\mathrm{eff}} \eta$$

For an active phased array

$$P_{\mathrm{Tx}} \propto \text{Panels}$$

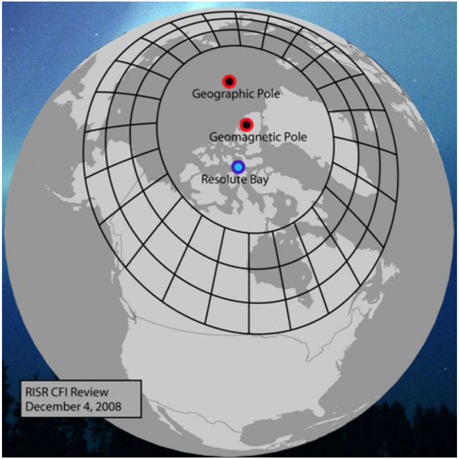
$$A_{\mathrm{eff}} \propto \text{Panels}$$

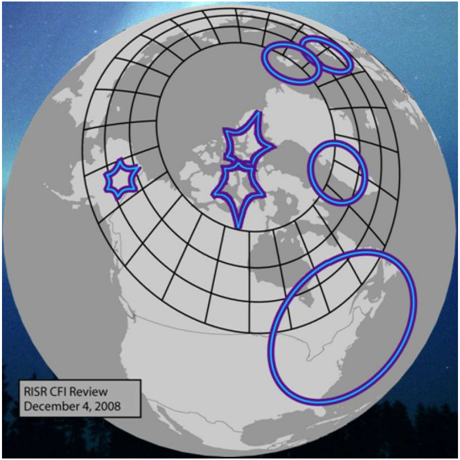
$$\frac{S}{N} \propto (\text{Panels})^2$$

$$K \propto (\text{Panels})^4$$

1 min integration with 128 panels ⇒ 16 min integration with 64 panels

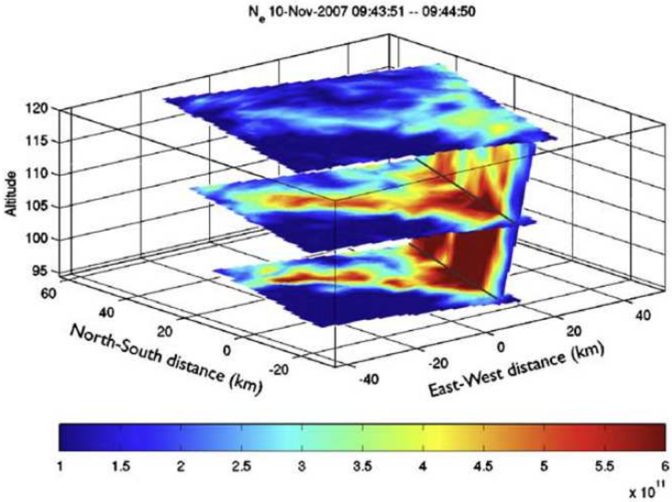
Unique Location of Resolute Bay





Figures courtesy Eric Donovan

Imaging Auroral Structure [Semeter et al. (2009)]

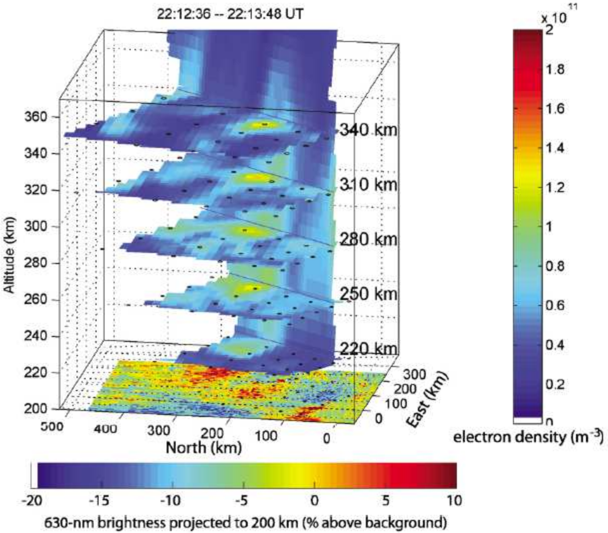


Imaging PMSE

Movie

Nicolls et al. (2007) *GRL*

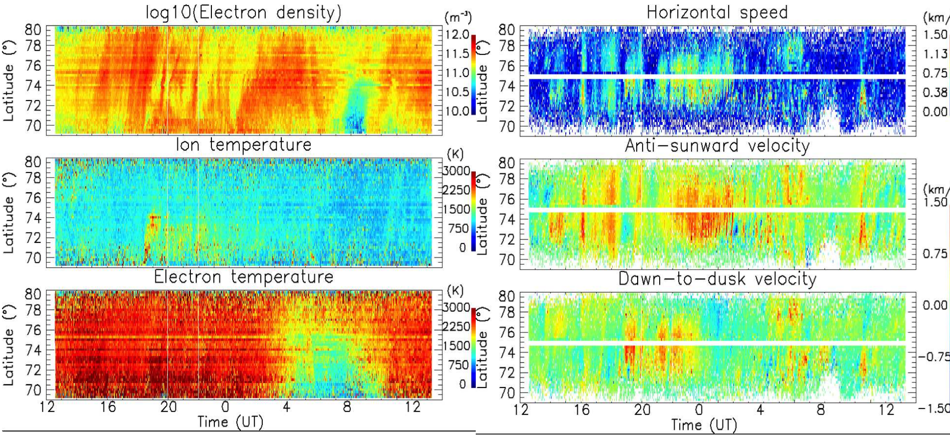
Polar Cap Patch Imaging



RISR-N Volumetric Images of Polar Cap Patches

Dahlgren et al., 2012, GRL.

RISR "Keograms" (from Rob Gillies)



Interpretation of Ion Velocities

Ion Momentum Equation:

$$0 = e\left(\mathbf{E} + \mathbf{u}_i \times \mathbf{B}\right) - m_i \nu_{in} \left(\mathbf{u}_i - \mathbf{u}_n\right)$$

Collisional Limit (D-region): $\mathbf{u}_i = \mathbf{u}_n$

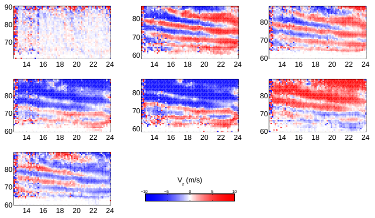
Collisionless Limit (F-region): $\mathbf{u}_i = \dfrac{\mathbf{E} \times \mathbf{B}}{B^2}$

E-region: $\mathbf{u}_i = \begin{pmatrix} \frac{1}{1+\kappa_i^2} & \frac{-\kappa_i}{1+\kappa_i^2} & 0 \\ \frac{\kappa_i}{1+\kappa_i^2} & \frac{1}{1+\kappa_i^2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \left[\mathbf{u}_n + \dfrac{e}{m_i \nu_{in}} \mathbf{E}\right]$

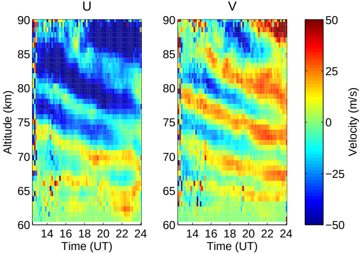
$$\kappa_i \equiv \frac{eB}{m_i \nu_{in}}$$

Mesospheric Vector Neutrals Winds

Line of Sight Velocities



Fitted Horizontal Velocities



$$\begin{pmatrix} V_{r,1} \\ \vdots \\ V_{r,7} \end{pmatrix} = \begin{pmatrix} \cos(\theta_1)\sin(\phi_1) & \cos(\theta_1)\sin(\phi_1) & \sin(\theta_1) \\ \vdots & \vdots & \vdots \\ \cos(\theta_7)\sin(\phi_7) & \cos(\theta_7)\sin(\phi_7) & \sin(\theta_7) \end{pmatrix} \begin{pmatrix} u \\ v \\ w \end{pmatrix}$$

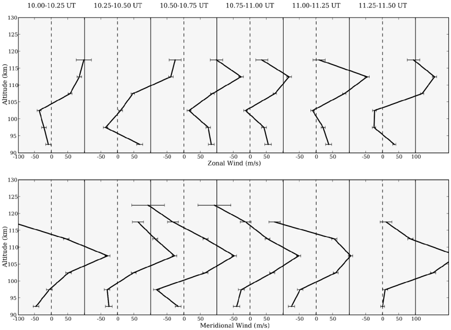
$$\mathbf{V}_r = \mathbf{DU}$$

$$\mathbf{U} = (\mathbf{D}^{\mathrm{T}} C_{V_r}^{-1} \mathbf{D})^{-1} \mathbf{D}^{\mathrm{T}} C_{V_r}^{-1} \mathbf{V_r}$$

E-region Neutral Wind Estimation

- Estimate vector E-region ion velocities from E-region LOS velocity
- Estimate vector F-region electric fields from F-region LOS velocity
- Map electric fields from F-region to E-region along equipotential field lines
- Solve for $\mathbf{u}_n$

$$\mathbf{u}_n = \mathbf{u}_i - \frac{e}{m_i \nu_{in}} \left(\mathbf{E} + \mathbf{u}_i \times \mathbf{B} \right)$$

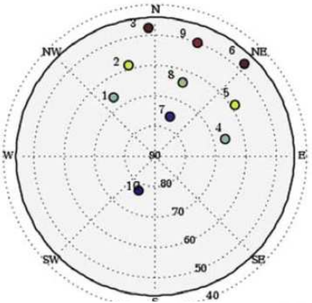


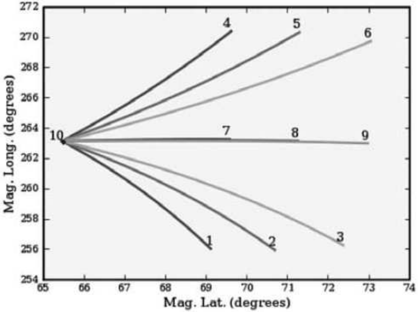
Heinselman and Nicolls (2008) Radio Sci.

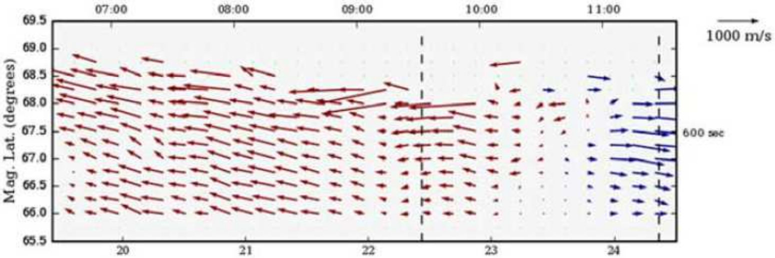
F-region 1-D Vector Electric Fields

- In F-region assume $\mathbf{v}_i = \frac{\mathbf{E}\times\mathbf{B}}{B^2}$
- Assume $\mathbf{E} \cdot \mathbf{B} = 0$ (no parallel fields)
- LOS velocity is related to **E** perpendicular to LOS and **B**
- Assume **E** is uniform in magnetic longitude, but varies with magnetic latitude
- Assume **E** fields map along equipotential field lines
- Different range gates correspond to different magnetic latitudes
- Fit for 2-components of **E** as a function of magnetic latitude

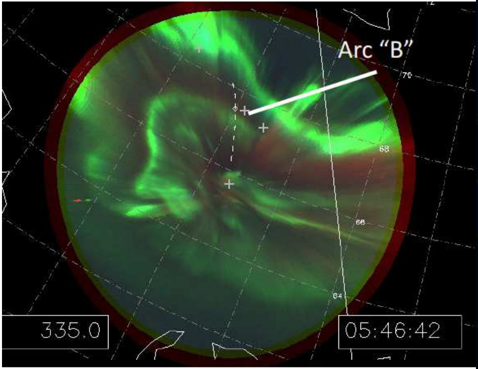
Vector Electric Fields [Heinselman and Nicolls (2008)]

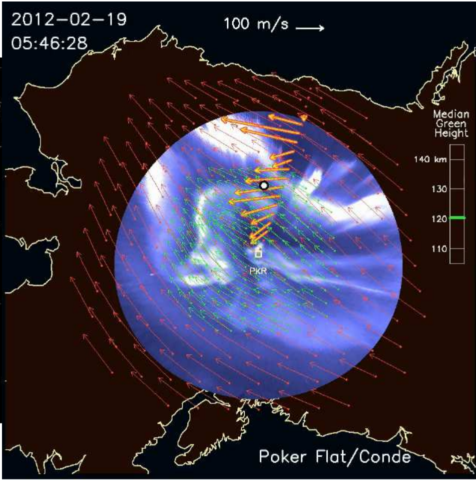






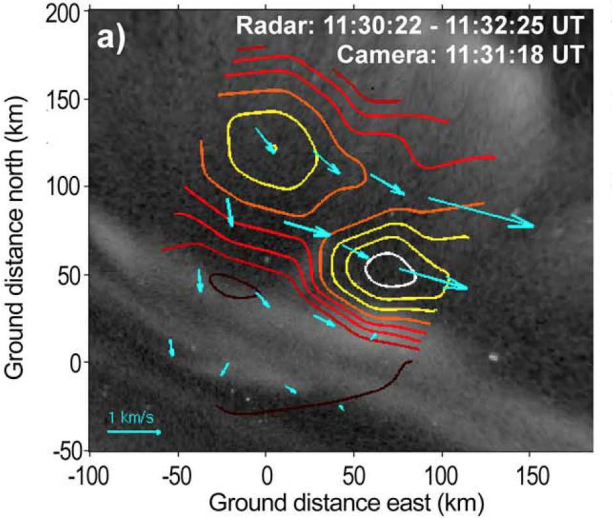
MICA Sounding Rocket Support



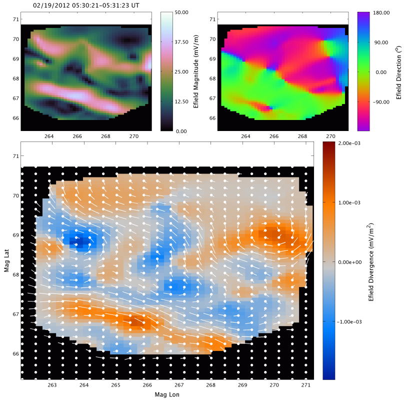


Lynch et al. (2015) *JGR*

Arc-Scale Joule Heating (Semeter et al. 2010)



Regularized Curl-Free 2-D **E**-Estimation



Assumptions:

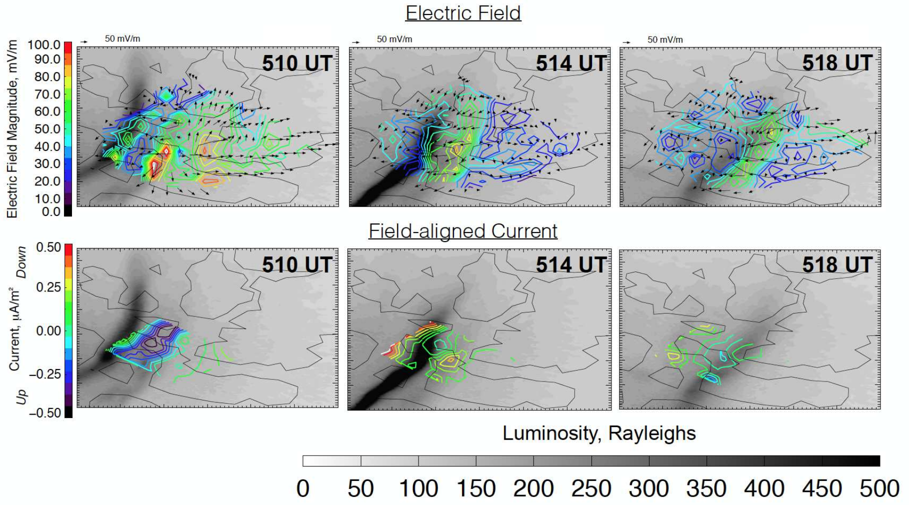
- **E** maps along equipotential field lines
- $\nabla \times \mathbf{E} = 0 \Rightarrow \mathbf{E} = -\nabla\Phi$
- **E** is "smooth" in that it minimizes a curvature measure G

Constrained optimization problem using Lagrange multipliers:

$$\mathcal{L} = ||\Phi||_G^2 + \lambda^\dagger \left(\tilde{\mathbf{v}}'_{los} - \mathbf{e} - M\Phi\right) + \Omega\left(||\mathbf{e}||_{C^{-1}}^2 - N + 1\right)$$

Nicolls et al. (2014) *Radio Sci.*

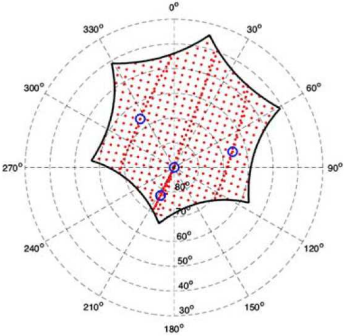
Electrodynamics of Polar Cap Arcs

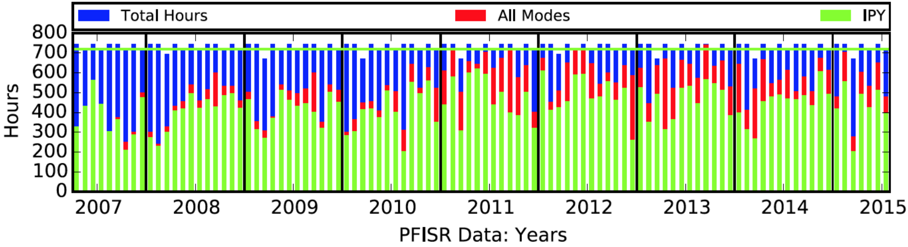


Perry et al. (2015) *JGR*

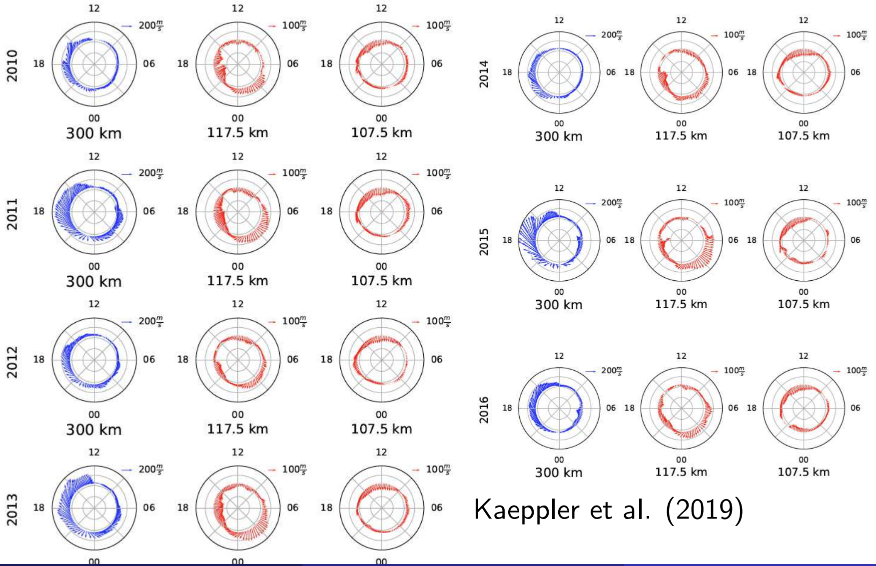
PFISR IPY Mode (Continuous Operations)

- 1% duty cycle
- 4 beams, including up-B
- Alternating code (E-region), Long Pulse (F-region)
- 5 min integration and fitting:
  - $N_e, T_e, T_i, V_{\mathrm{LOS}}$
  - Vector electric field
  - E-region neutral wind



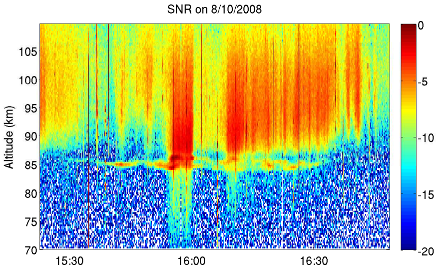


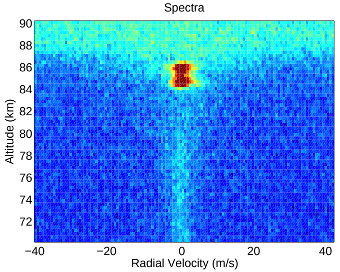
Long Term Study of E-region Neutral Winds

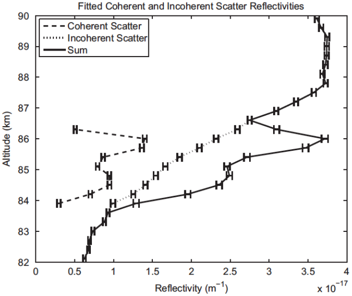


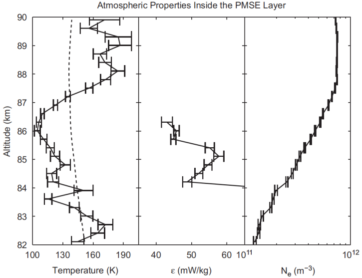
Kaeppler et al. (2019)

Precipitation and PMSE



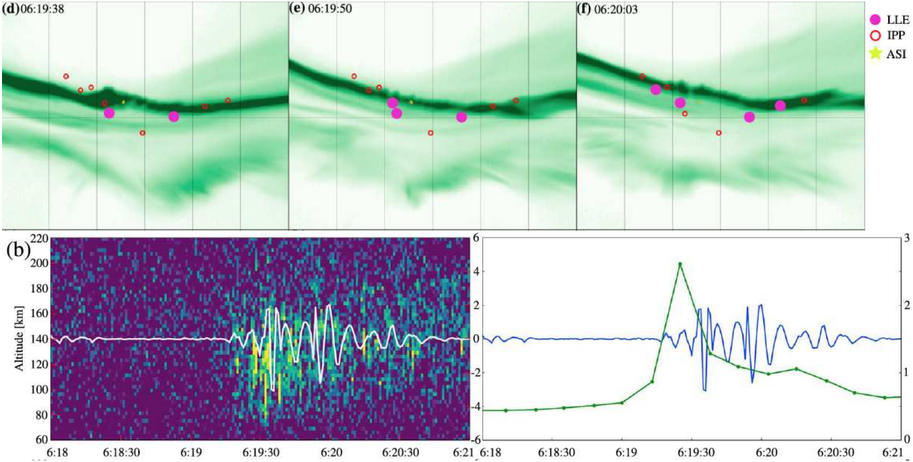






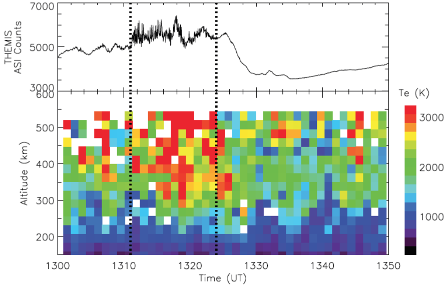
Varney et al. (2011) *JASTP*

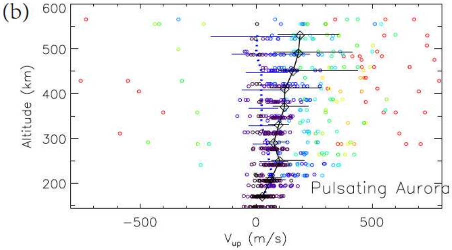
Aurora and GPS Scintillation



Mrak et al. (2018), JGR

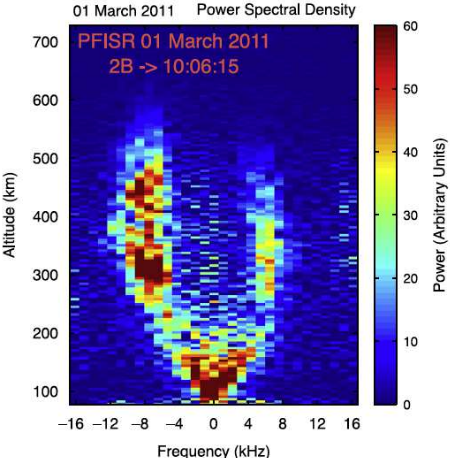
Electron Heat Flux Above PsA (Liang et al. 2018)





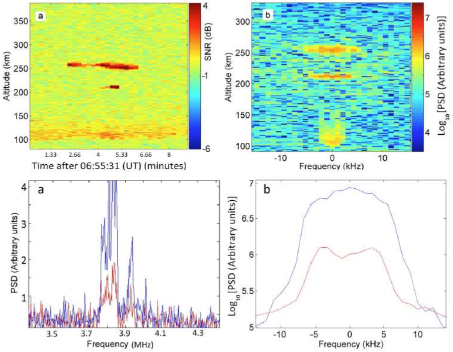
Natural Plasma Instabilities

Naturally enhanced ion acoustic lines



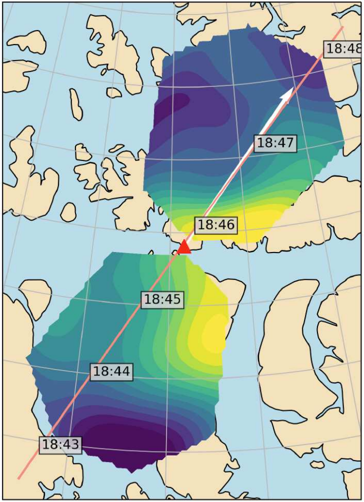
Michell and Samara (2013)

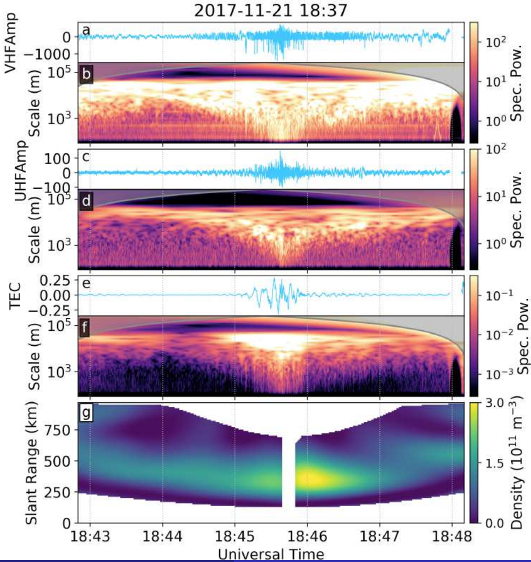
Strong Langmuir Turbulence



Akbari et al. (2013)

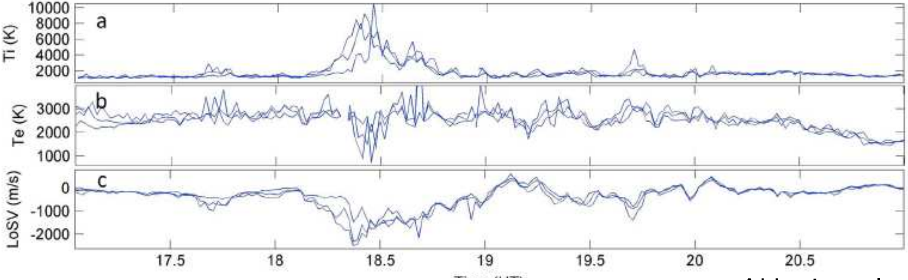
Polar Cap Scintillation

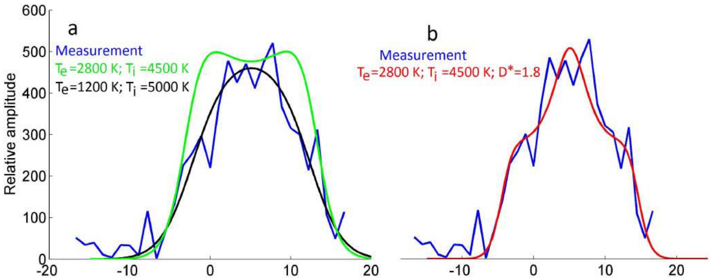




Lamarche et al. (2019)

Extreme Frictional Heating and Torodial Distributions

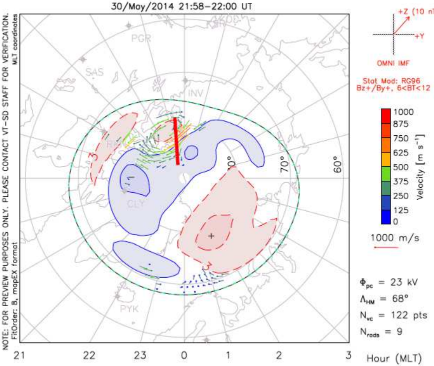




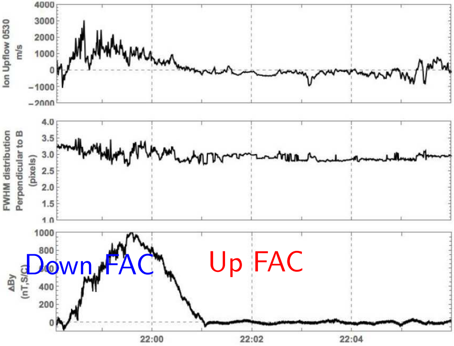
Akbari et al. (2017)

e-POP Observations on May 30, 2014

SuperDARN Context



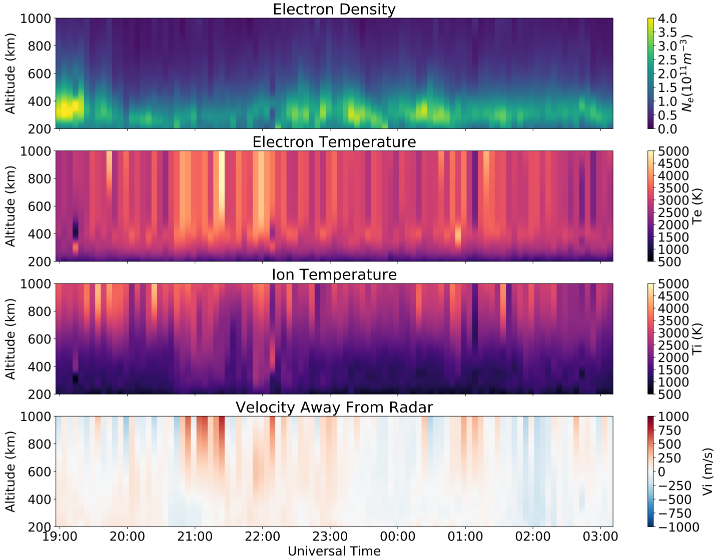
e-POP SEI and MGF



e-POP descends from 1150 to 1050 km altitude over this pass.

Shen et al. (2016), JGR.

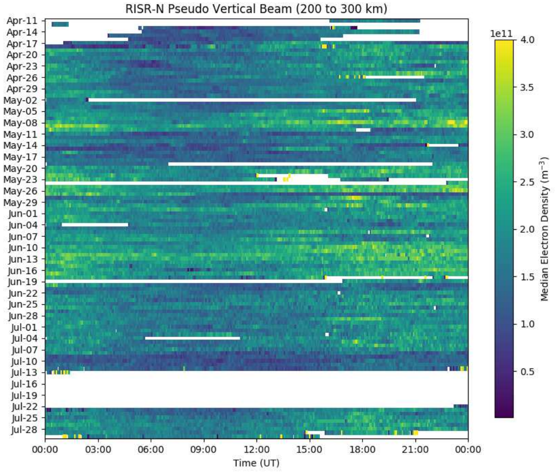
RISR-N Observations on May 30, 2014



New Low Duty Cycle Capability at RISR-N

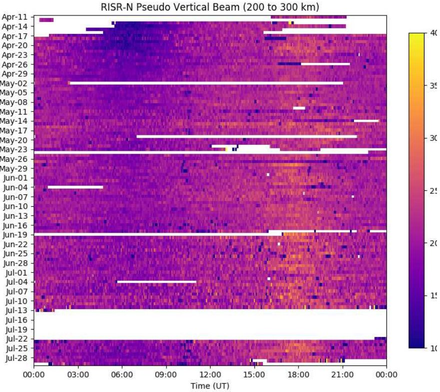
New small generator

Summary of N_e April 11 - July 30

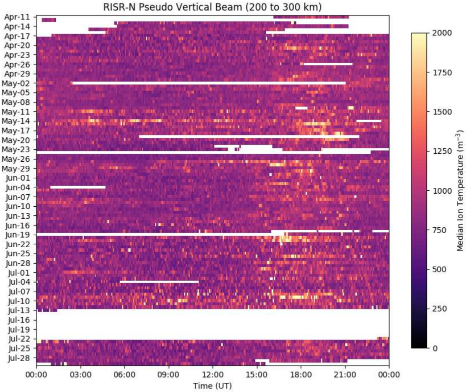


New Low Duty Cycle Capability at RISR-N

T_e

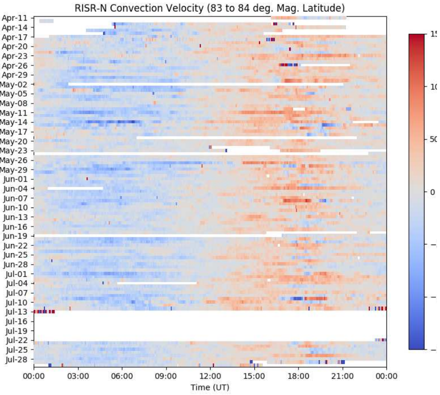


T_i

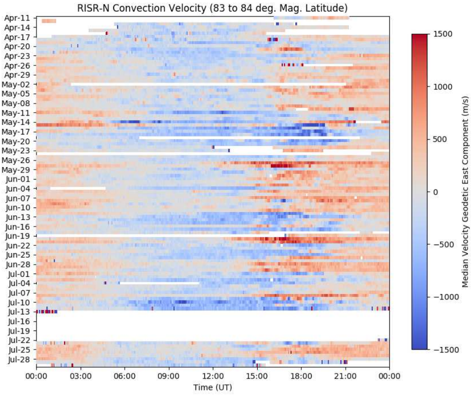


New Low Duty Cycle Capability at RISR-N

North Velocity



East Velocity



Requesting AMISR Experiments

- All science operations funded by NSF. Users do not need to pay for time.
- International collaboration is encouraged by NSF. International researchers are welcome to request experiments.
- All data is distributed publicly as soon as feasible, regardless of who requested the experiment.
- Send requests to the PI with detailed descriptions of the science motivation and requirements.
- Ideally requests should be received 2-4 weeks in advance to help us resolve conflicts between users.
- We can react very rapidly if geospace conditions warrant it (e.g. CMEs and SSWs).