Advanced Modular Incoherent Scatter Radar

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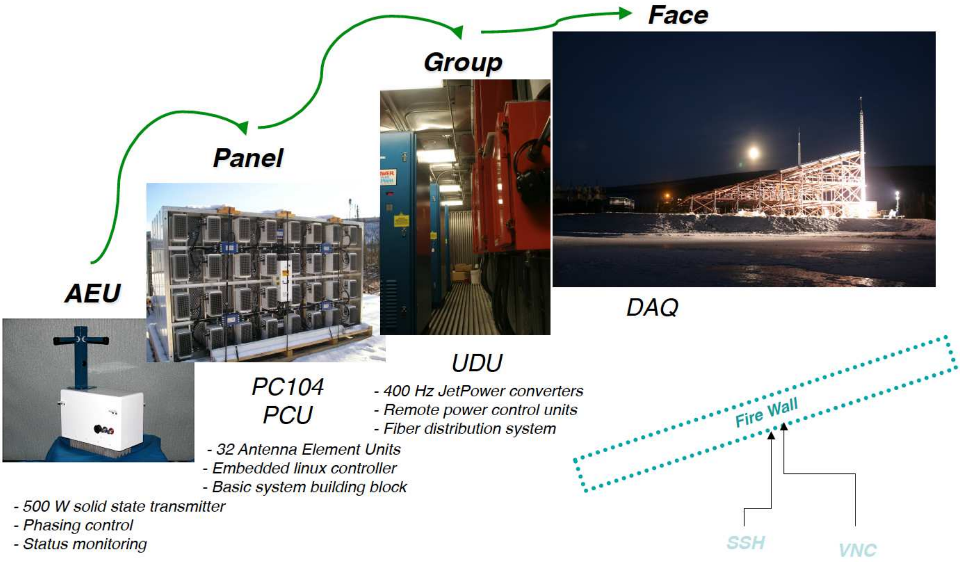
1. AMISR Technology
    - Hardware
    - Electronic Beam Steering Capabilities
    - Design Considerations for ISR Science
2. AMISR Science
    - PFISR Science
    - RISR-N Science
    - RISR-C First Results
    - UMET-14 Science

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)

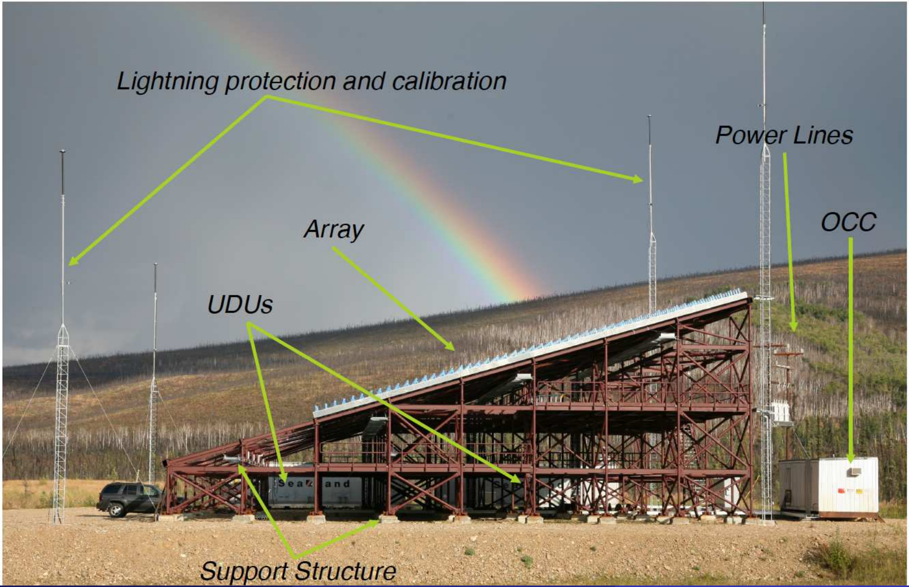
Utility Distribution Unit (UDU)

AMISR Control System (ACS)

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

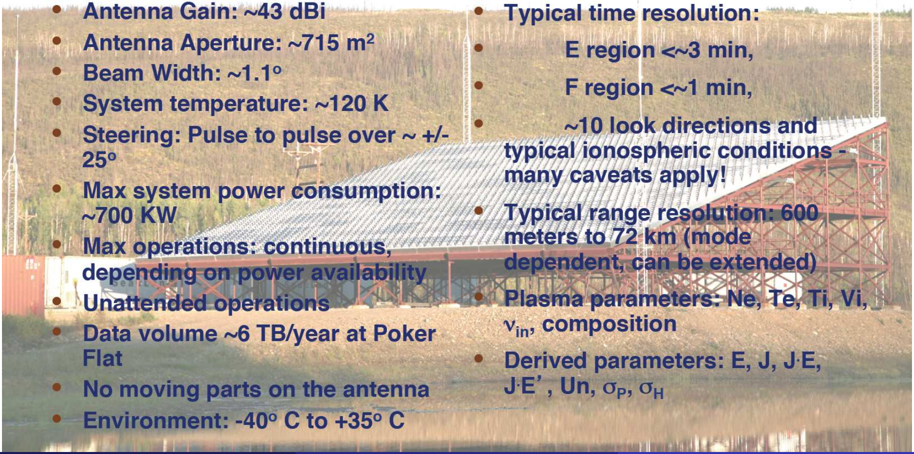
AMISR ACS
- *Flexible transmit and receive system*
- *Completely remotely controlled*
- *Experiments run off a scheduler*

Poker Flat Incoherent Scatter Radar (PFISR)

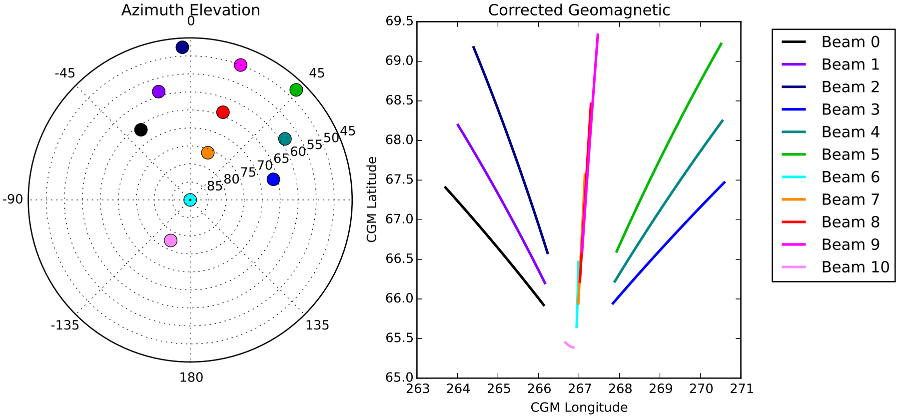


AMISR Technical Specifications

- Peak Power: 2 MW
- Max RF Duty: 10%
- Pulse Length: 1 μsec - 2 msec
- TX Frequency: 430-450 MHz
- Antenna Gain: ~43 dBi
- Antenna Aperture: ~715 m^2
- Beam Width: ~1.1°
- System temperature: ~120 K
- Steering: Pulse to pulse over ~ +/- 25°
- Max system power consumption: ~700 KW
- Max operations: continuous, depending on power availability
- Unattended operations
- Data volume ~6 TB/year at Poker Flat
- No moving parts on the antenna
- Environment: -40° C to +35° C
- Altitude coverage: ~60 km to ?? km (depending on Ne)
- Minimum measurable electron densities: ~1e9 m^{-3}
- Typical time resolution:
- E region <~3 min,
- F region <~1 min,
- ~10 look directions and typical ionospheric conditions - many caveats apply!
- Typical range resolution: 600 meters to 72 km (mode dependent, can be extended)
- Plasma parameters: Ne, Te, Ti, Vi, ν_{in}, composition
- Derived parameters: E, J, J·E, J·E', Un, σ_P, σ_H



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.

Statistical Considerations with Pulse Steering

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

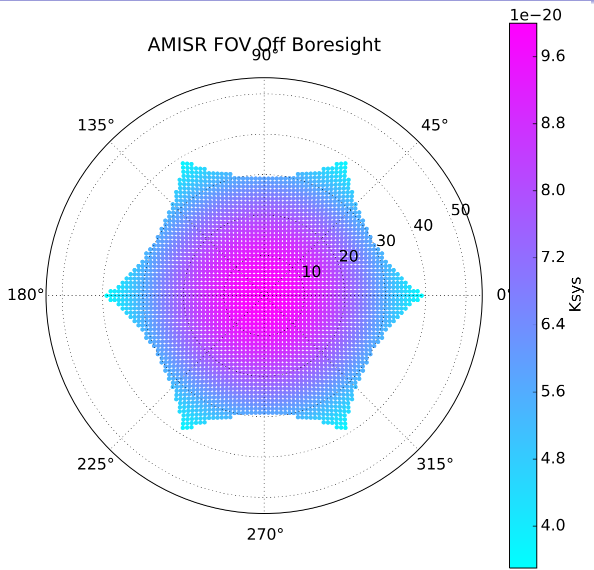
- Larger number of beams $\Rightarrow$ fewer pulses per beam
- If I can confortably integrate for 1 min using 7 beam positions $\Rightarrow$ I would need to integrate 6 min to get the same data quality using 42 beams.

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

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



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:

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

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

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

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

For an active phased array

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

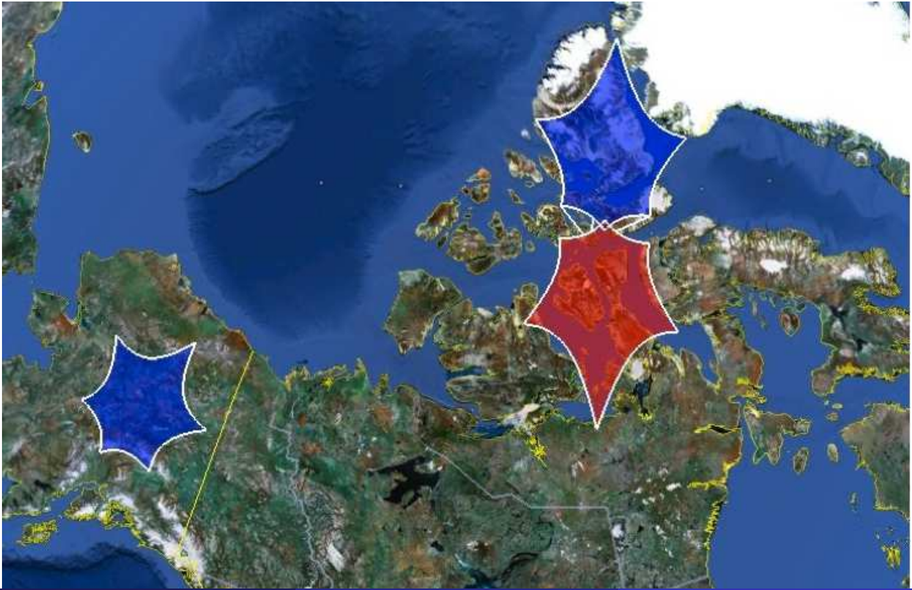
$$A_{\mathrm{eff}} \propto \text{Panels}$$

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

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

1 min integration with 128 panels $\Rightarrow$
16 min integration with 64 panels

Existing AMSIR Fields of View

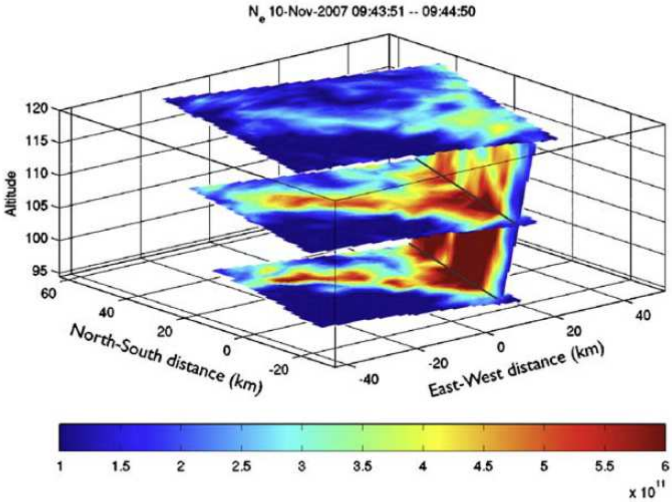


PFISR Field of View at Multiple Altitudes

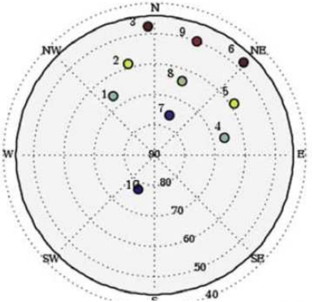
PFISR Overview

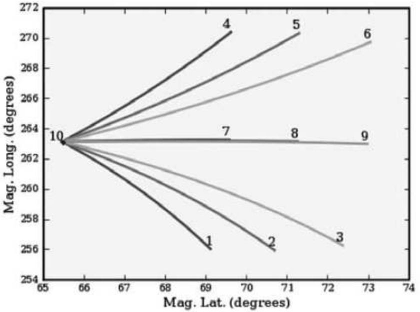
- 128 Panels
- Science operations began in 2007
- 65.13° geographic latitude (a few degrees south of Tromsø)
- 65.39° geomagnetic latitude (Auroral Region)
- Common Tx Frequencies 449.3, 449.6, 449.8 MHz
- Powered by grid
- Funded by the US National Science Foundation (NSF)
- Operated by SRI International

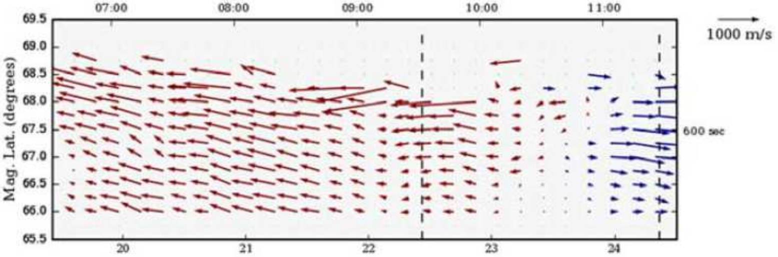
Imaging Auroral Structure [Semeter et al. (2009)]



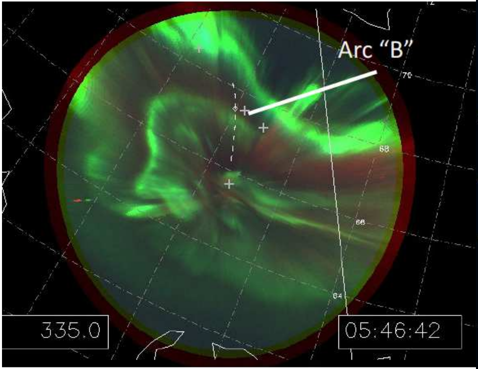
Vector Electric Fields [Heinselman and Nicolls (2008)]

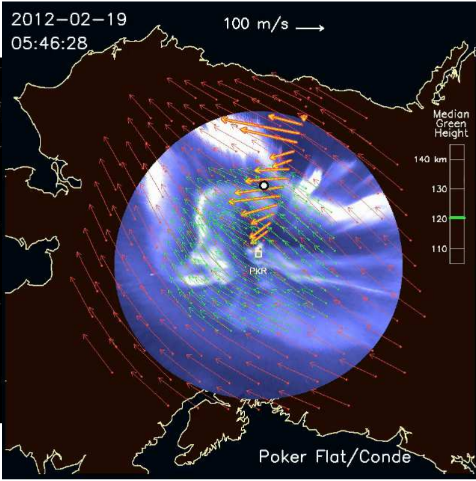






MICA Sounding Rocket Support



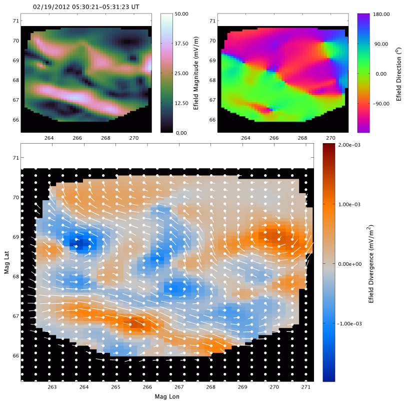


Lynch et al. (2015) *JGR*

Imaging Electrodynamics: 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

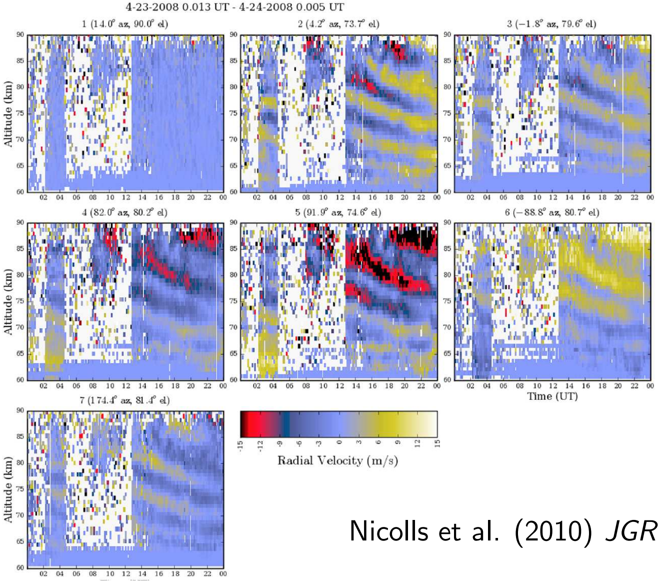


Constrained optimization problem using Lagrange multipliers:

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

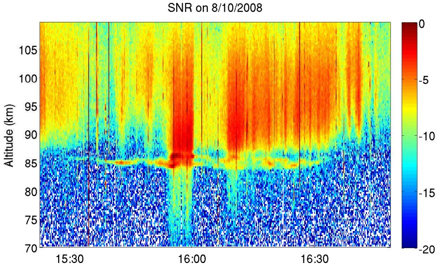
Nicolls et al. (2014) *Radio Sci.*

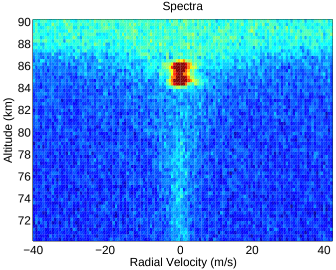
Mesospheric Winds and Gravity Waves

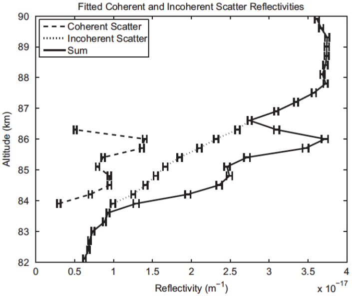


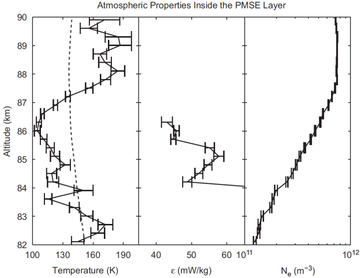
Nicolls et al. (2010) *JGR*

Polar Mesospheric Summer Echoes









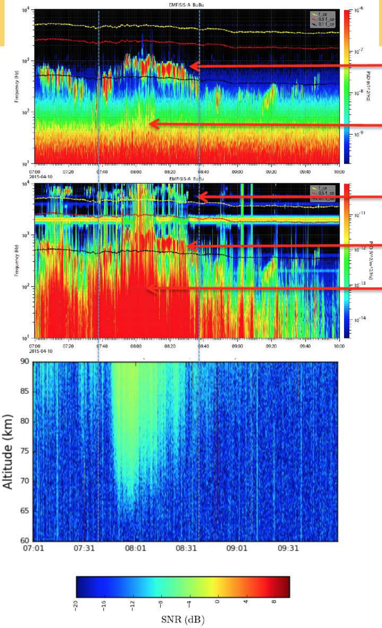
Varney et al. (2011) *JASTP*

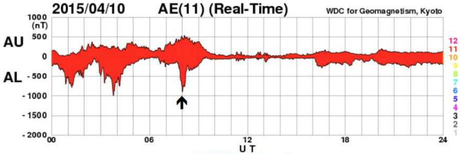
Imaging PMSE

Movie

Nicolls et al. (2007) *GRL*

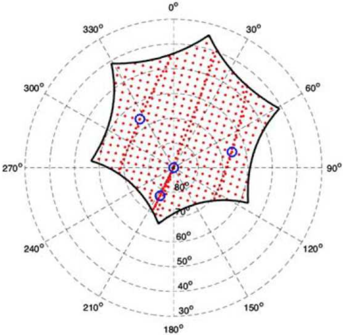
RBSP event #1 – 10 April 2015

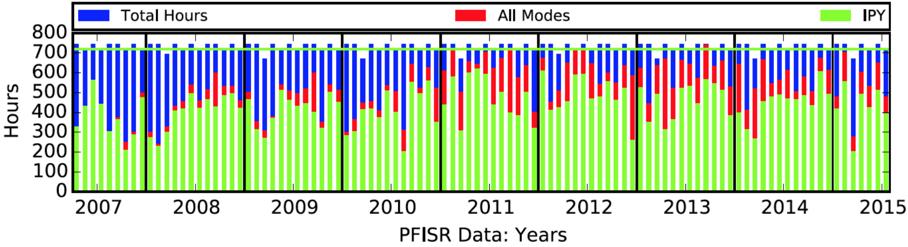




PFISR IPY Mode (Continuous Operations)

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

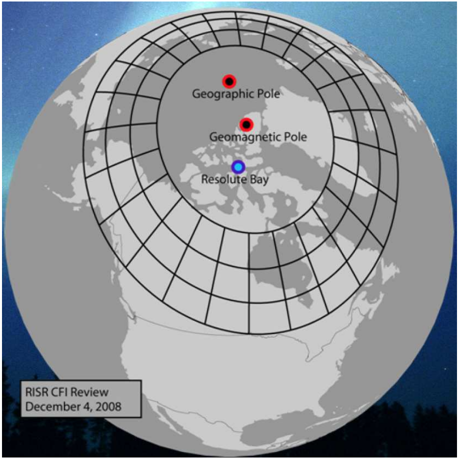


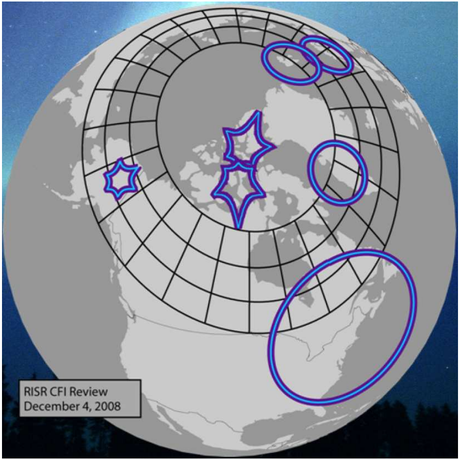


RISR-N Overview

- 121 Panels
- Science operations began in 2009
- 74.73° geographic latitude (not as high as Svalbard)
- 82.77° geomagnetic latitude (deep in the polar cap; highest of any ISR)
- Most common Tx Frequency 442.9 MHz
- Frequency flexibility, 4 MHz frequency allocation
- Powered by diesel generator
- Funded by the US National Science Foundation (NSF)
- Operated by SRI International

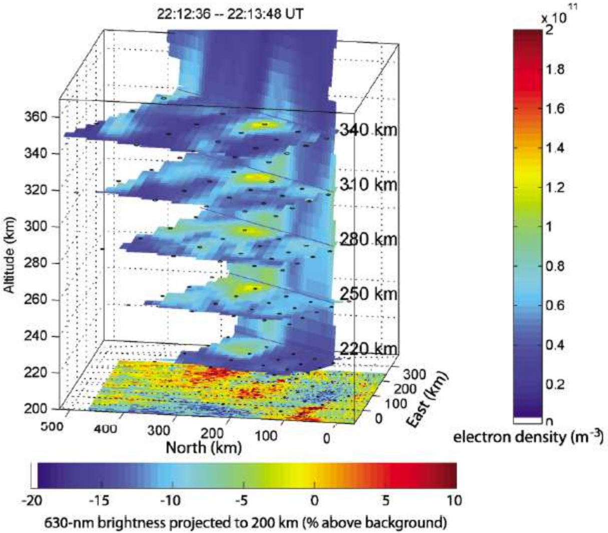
Unique Location of Resolute Bay





Figures courtesy Eric Donovan

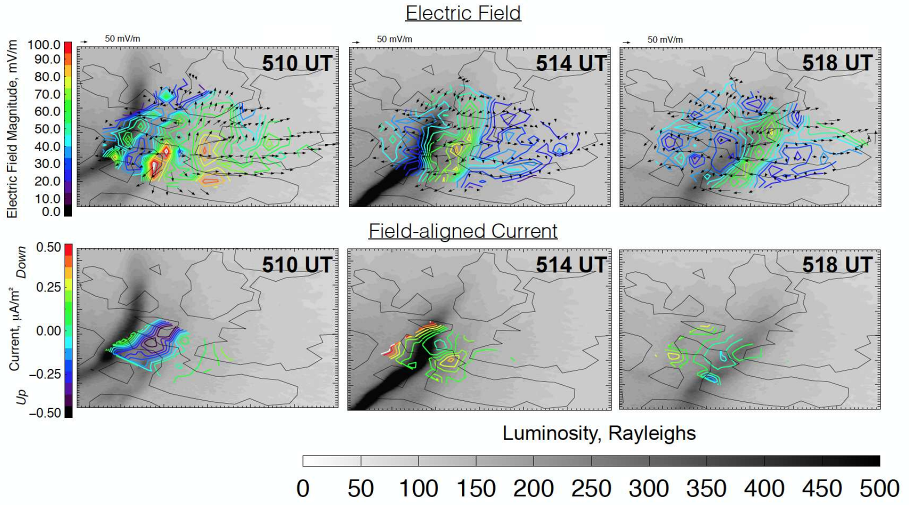
Polar Cap Patch Imaging



RISR-N Volumetric Images of Polar Cap Patches

Dahlgren et al., 2012, GRL.

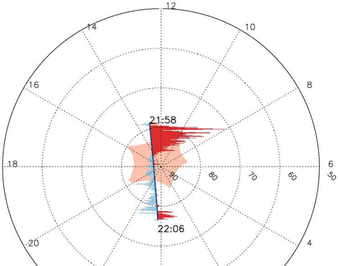
Electrodynamics of Polar Cap Arcs



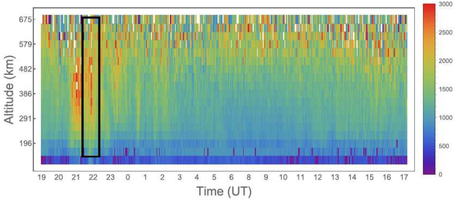
Perry et al. (2015) *JGR*

e-POP, SuperDARN, and RISR-N Observations

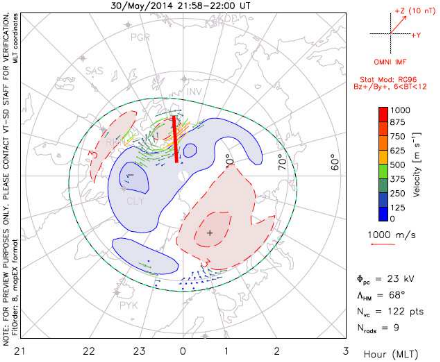
e-POP Upflow



RISR-N Ion Heating



SuperDARN Convection



Shen et al. (2016) *JGR*

Intense Frictional Heating and Ion Anisotropy

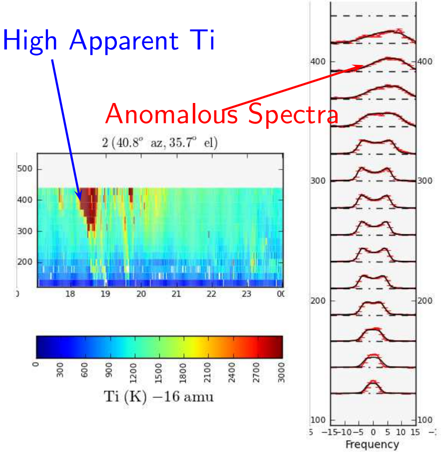
SWARM Ion Distributions

RISR-N Low-elevation Measurements

Horizontal

Vertical

Archer et al. (2015)

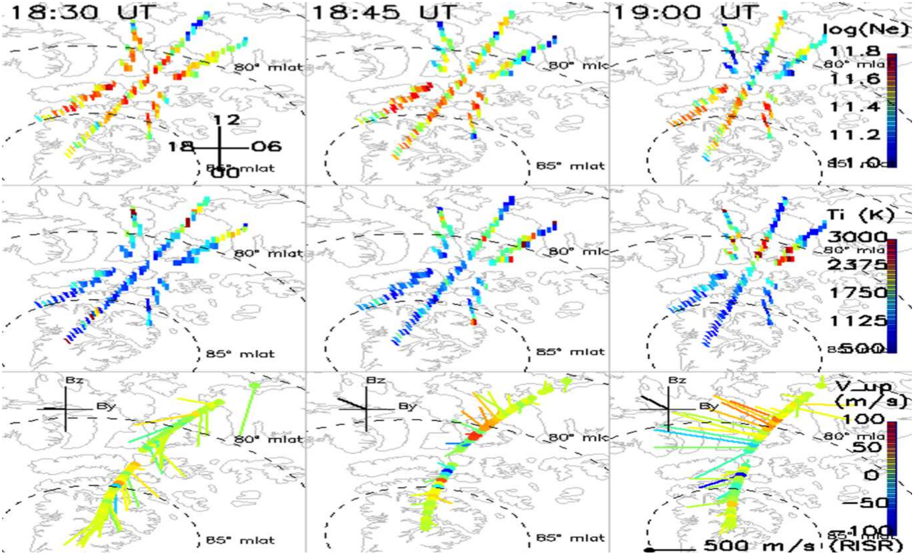


F-region anisotropy is common during intense frictional heating!

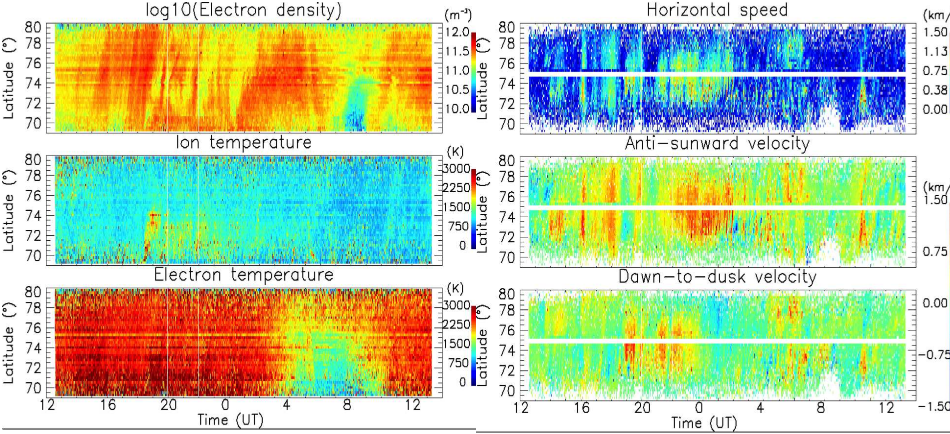
RISR-C Overview

- 121 panels (identical to RISR-N)
- Science operations began in 2016
- Pulses Synchronized to RISR-N. Both radars can operate simultaneously without interference
- Funded by the Canadian Foundation for Innovation (CFI)
- Operated by the University of Calgary

RISR-C and RISR-N Coordinated Observations

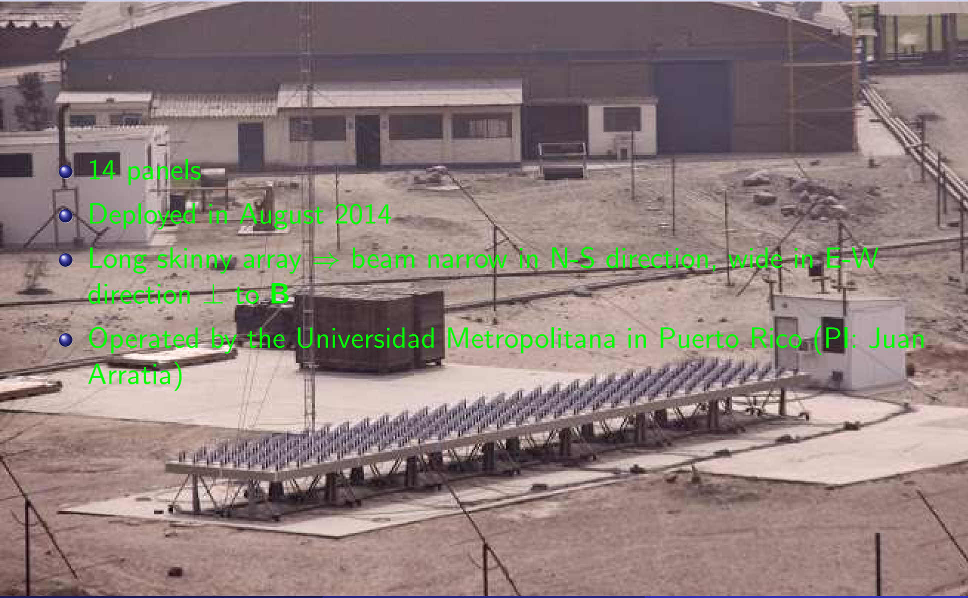


RISR "Keograms" (from Rob Gillies)

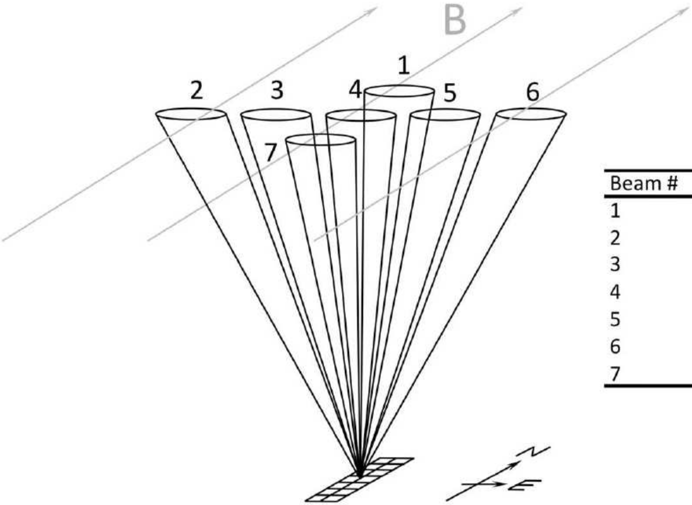


UMET-14 Overview

- 14 panels
- Deployed in August 2014
- Long skinny array $\Rightarrow$ beam narrow in N-S direction, wide in E-W direction $\perp$ to $\mathbf{B}$
- Operated by the Universidad Metropolitana in Puerto Rico (PI: Juan Arratia)

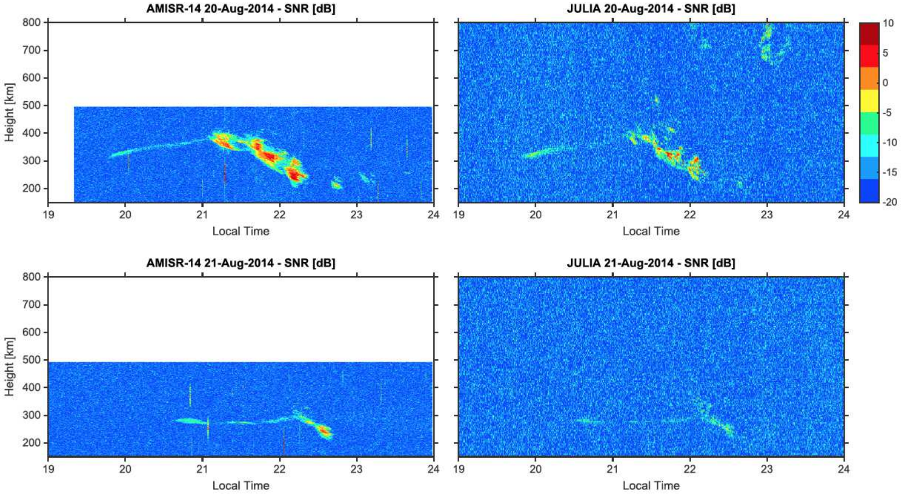


Beam Steering in Plane ⊥ to B



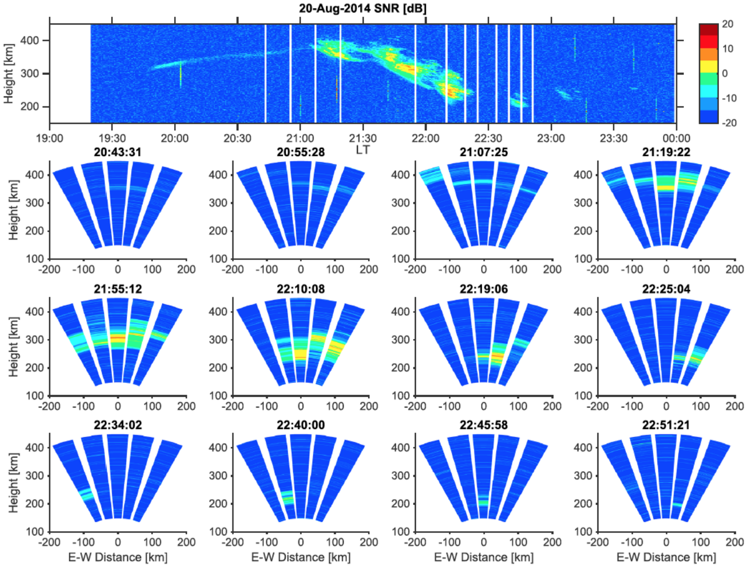
Beam #	Az	Elev
1	0°	85.2°
2	-90°	69.2°
3	-90°	80.4°
4	0°	90.0°
5	90°	80.4°
6	90°	69.2°
7	180°	85.2°

Spread-F Scatter at 33 cm vs 3 m Scales

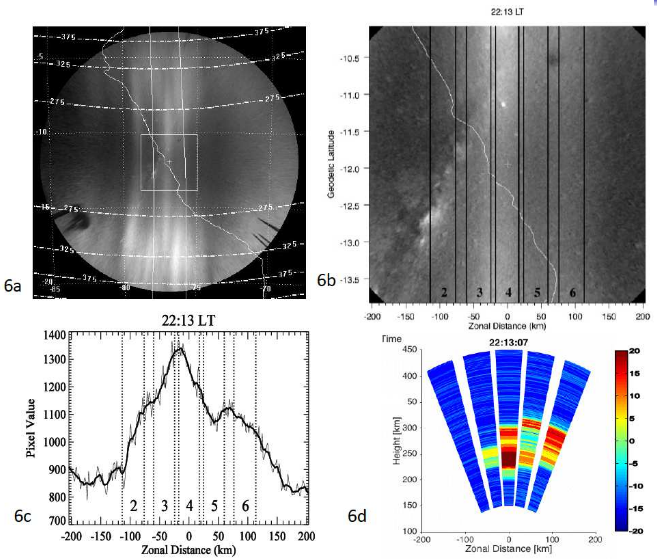


Rodrigues et al. (2015) *GRL*

Resolving Space-Time Ambiguity in Spread-F



Location of Scatter within Airglow Depletions



Hickey et al. (2015) *JGR*

Future of AMISR Science?

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