Midlatitude Ionospheric Physics

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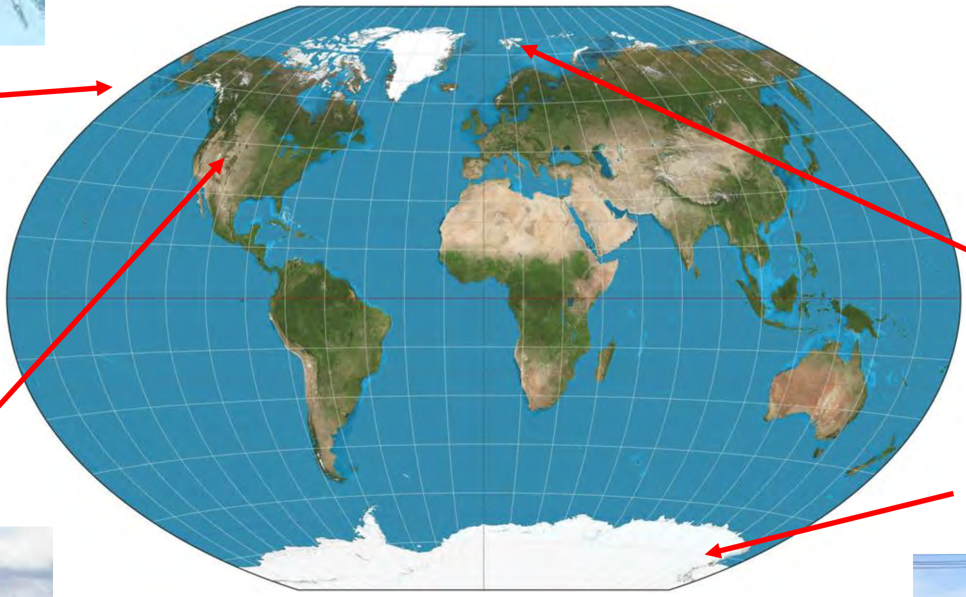
Nathaniel’s travels as a Virginia Tech grad student

Adak (Alaska)



Svalbard (Norway)

Independence Pass

McMurdo (Antarctica)

Blacksburg

First HamSCI-flavored publication

AGU PUBLICATIONS

Space Weather

FEATURE ARTICLE

10.1002/2014SW001132

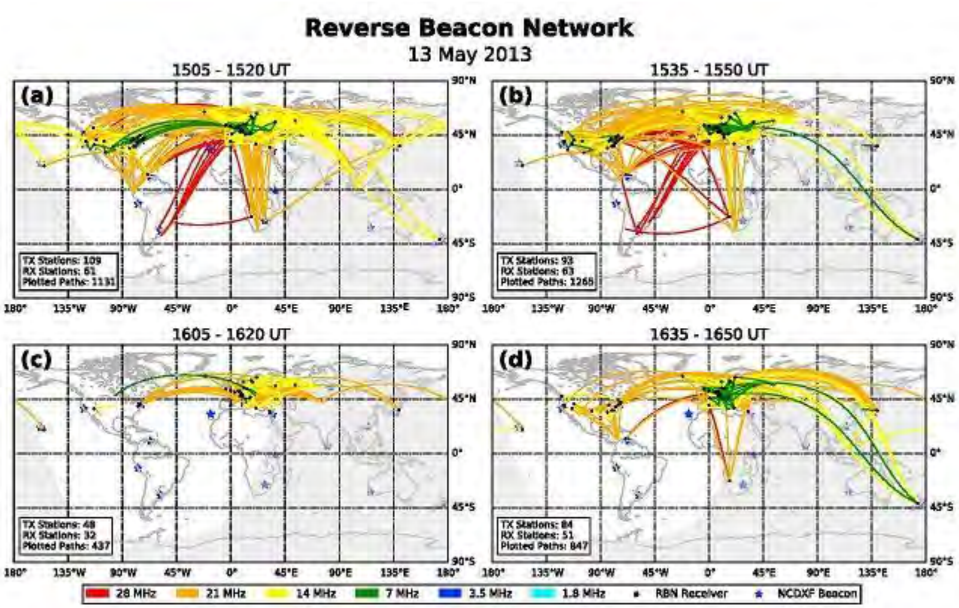
Ionospheric Sounding Using Real-Time Amateur Radio Reporting Networks

N. A. Frissell, E. S. Miller, S. R. Kaeppler, F. Ceglia, D. Pascoe, N. Sinanis, P. Smith, R. Williams, and A. Shovkoplyas

Supporting Information:
- Readme
- Data Set S1

Citation:
Frissell, N. A., E. S. Miller, S. R. Kaeppler, F. Ceglia, D. Pascoe, N. Sinanis, P. Smith, R. Williams, and A. Shovkoplyas (2014), Iono-

Abstract Amateur radio reporting networks, such as the Reverse Beacon Network (RBN), PSKReporter, and the Weak Signal Propagation Network, are powerful tools for remote sensing the ionosphere. These voluntarily constructed and operated networks provide real-time and archival data that could be used for



The impact of a solar flare on radio wave propagation in the ionosphere is demonstrated with the Reverse Beacon Network (RBN)

Midlatitude Ionospheric Physics

Outline:

Part I Properties of Earth’s atmosphere and ionosphere

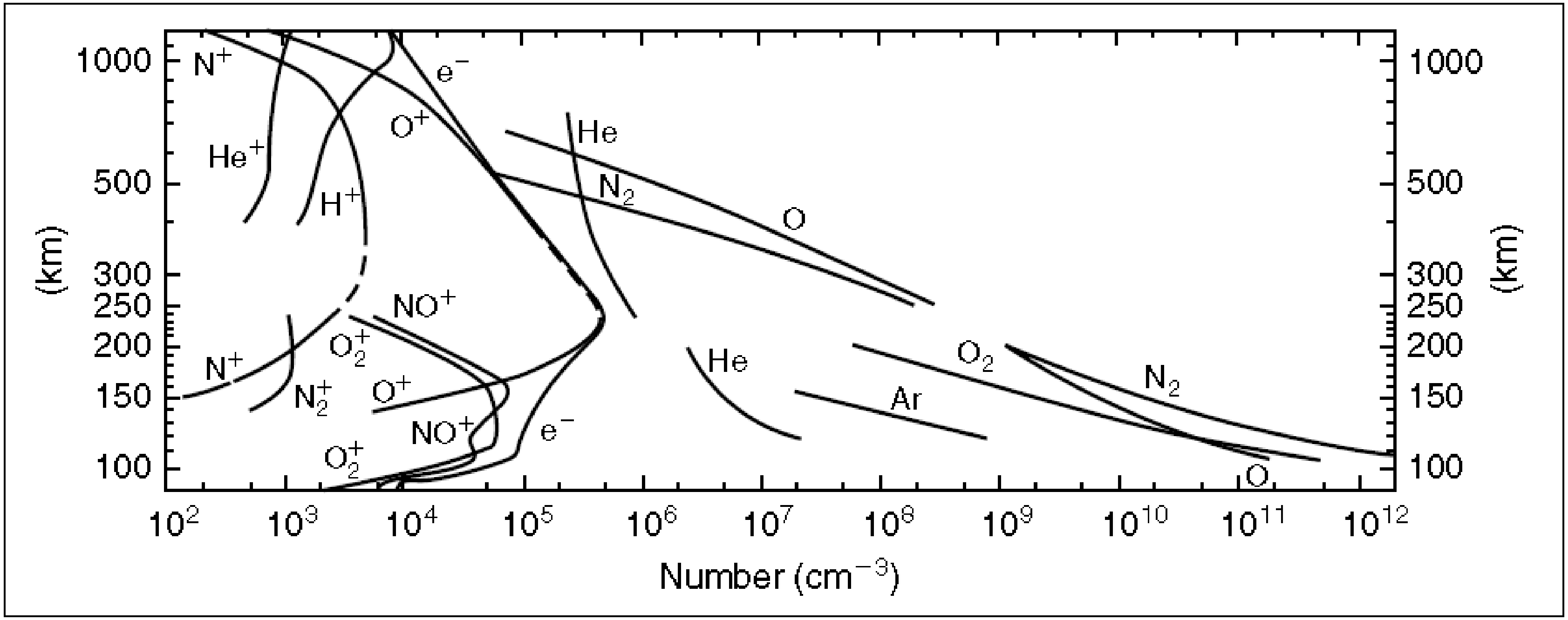
Part II Regions of the ionosphere

Part III Observations in the midlatitude ionosphere

Part IV Open research questions

Earth has an atmosphere!

Atmospheric composition



- The atmosphere consists mostly of nitrogen and oxygen
- Densities decrease exponentially with altitude
- The breathable atmosphere (< 20,000 feet) is very thin compared to the dimensions of Earth (it is truly an ‘envelope’)

Properties of Earth's atmosphere

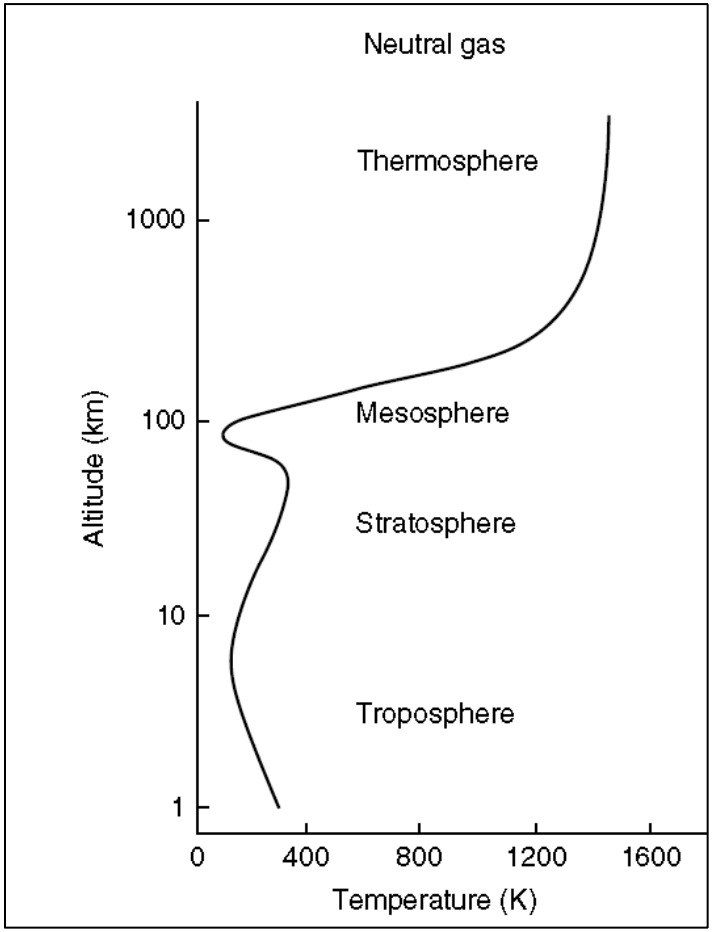
- Surprising fact:

If the entire atmosphere were compressed to sea level density it would be only 8.5 km thick!

Photo from the ISS of the top of the atmosphere

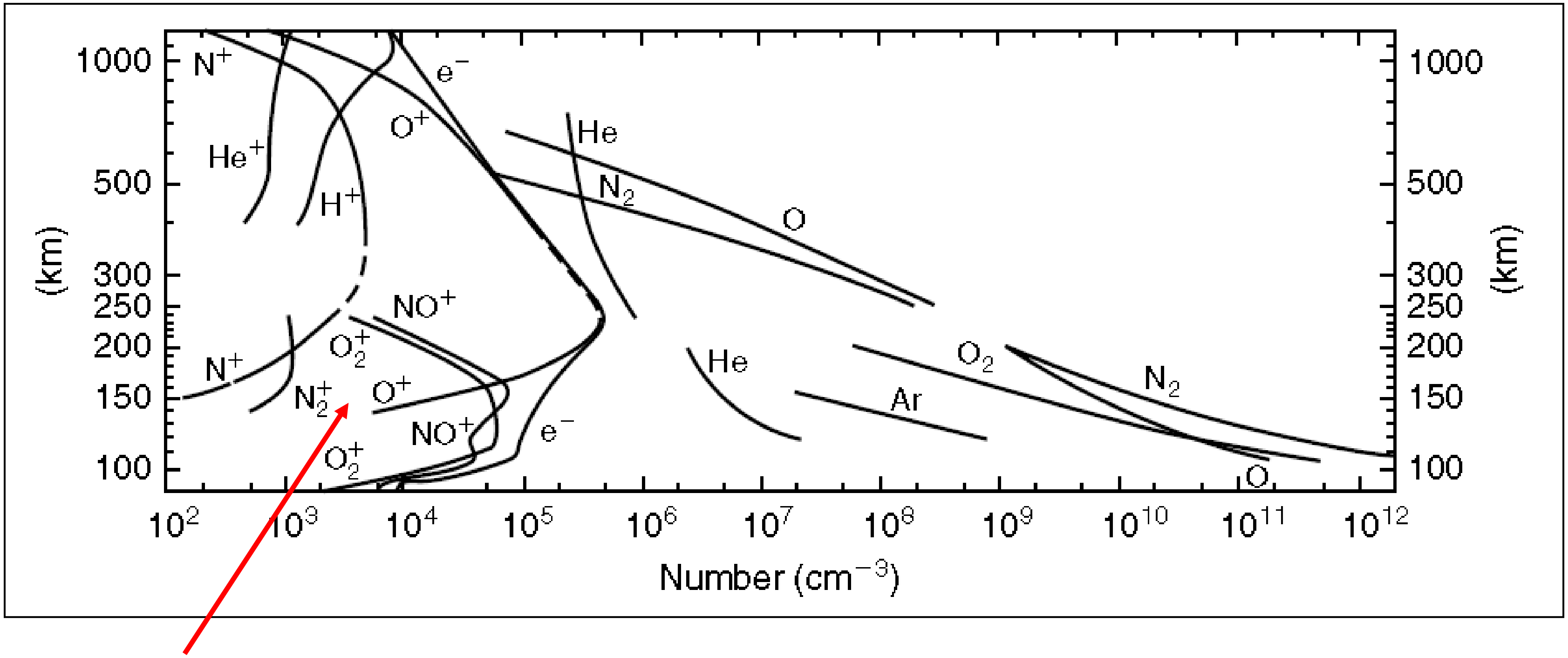
Properties of Earth's atmosphere

- Earth's atmosphere can be organized into layers on the basis of the variation of temperature with height
- The temperature increase in the stratosphere is due to absorption of UV rays by ozone
- In the lower atmosphere the *lapse rate* averages 3.6º F per thousand feet of increase in altitude



Kelley [2009]

Atmospheric composition – what else is going on?



- There are also populations of ions and electrons and these carry electric charge
- The charged particle densities are much lower than the neutral particle densities
- Nonetheless, they are sufficient to give the atmosphere electrical properties

Properties of Earth's ionosphere

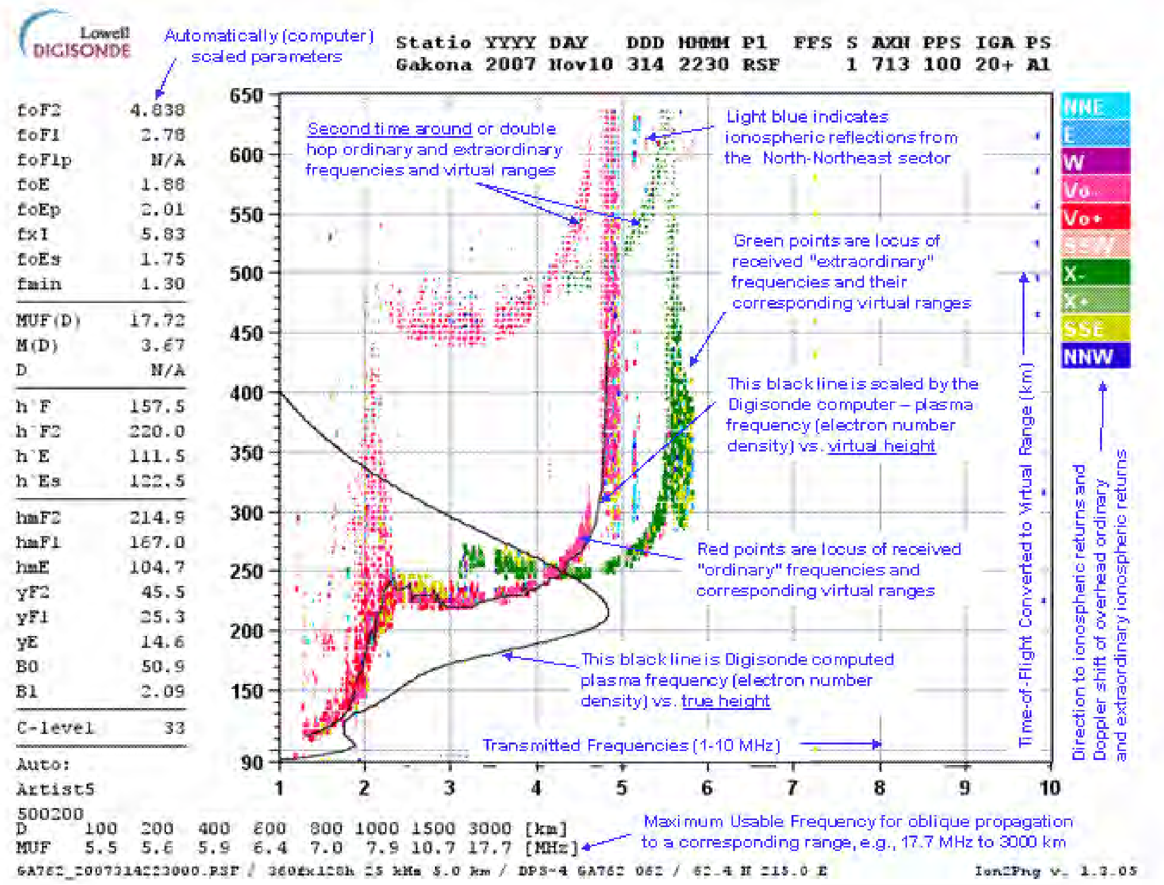
- The *ionosphere* is the layer of Earth's atmosphere that contains a relatively high concentration of ions and free electrons
- The dominant source of charged particles is photoionization
- The ionosphere is capable of reflecting radio waves

Pictured: Airglow from the vicinity of the lower ionosphere that results from the recovery of ionized and excited particles. (Photo taken from the ISS)

‘Sounding’ the ionosphere with radio waves

- Reflections are received from the ionosphere for vertical incidence at HF frequencies
- Analysis of variations with frequency reveals properties of the ionosphere

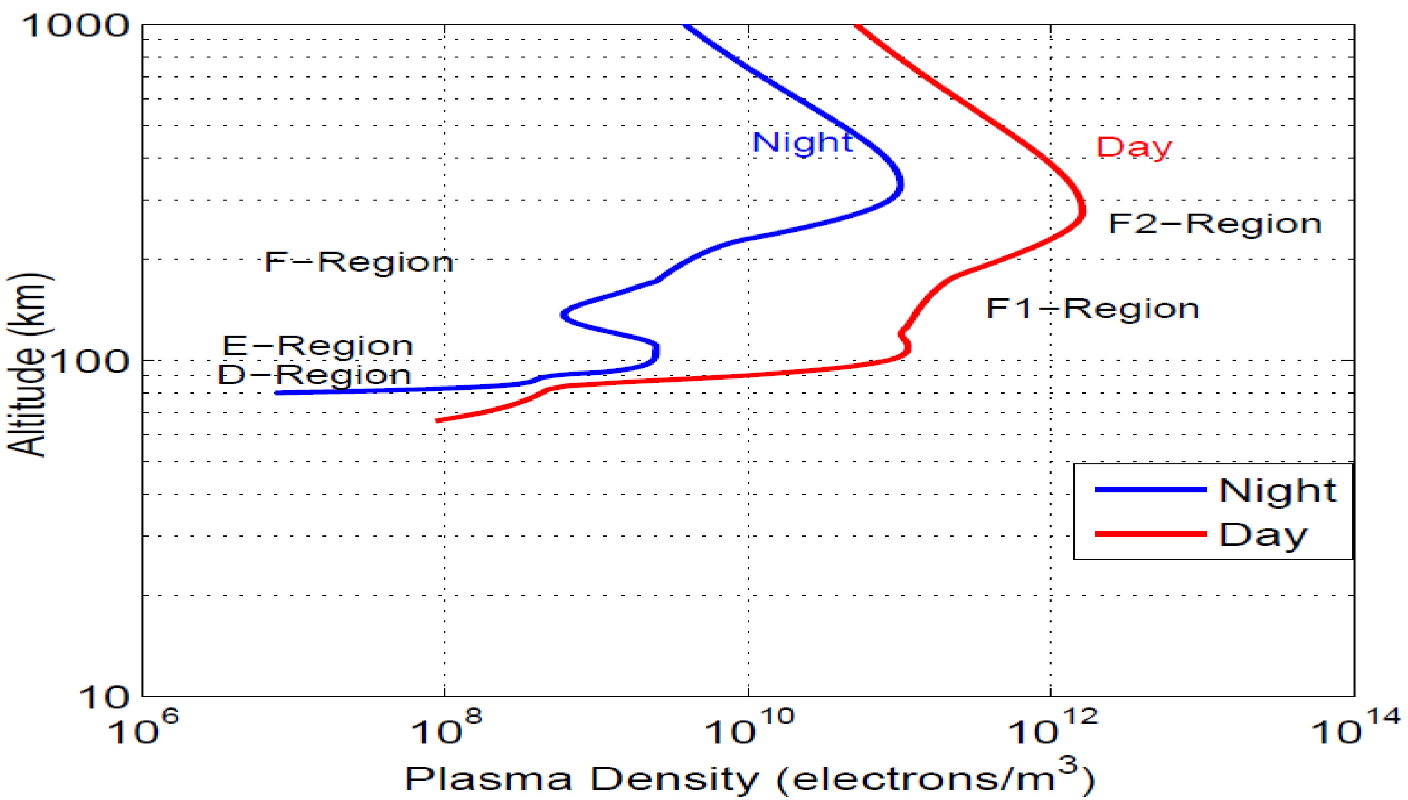
Figure: Ionogram from the HAARP digisonde located in Alaska. The virtual height of reflection is plotted as a function of swept frequency. The inferred plasma density profile is plotted as a black trace. Diagnostic notes are shown in blue.



Properties of Earth's ionosphere

The ionosphere is generally divided into three regions based on altitude and the physics that controls the motion of charged particles:

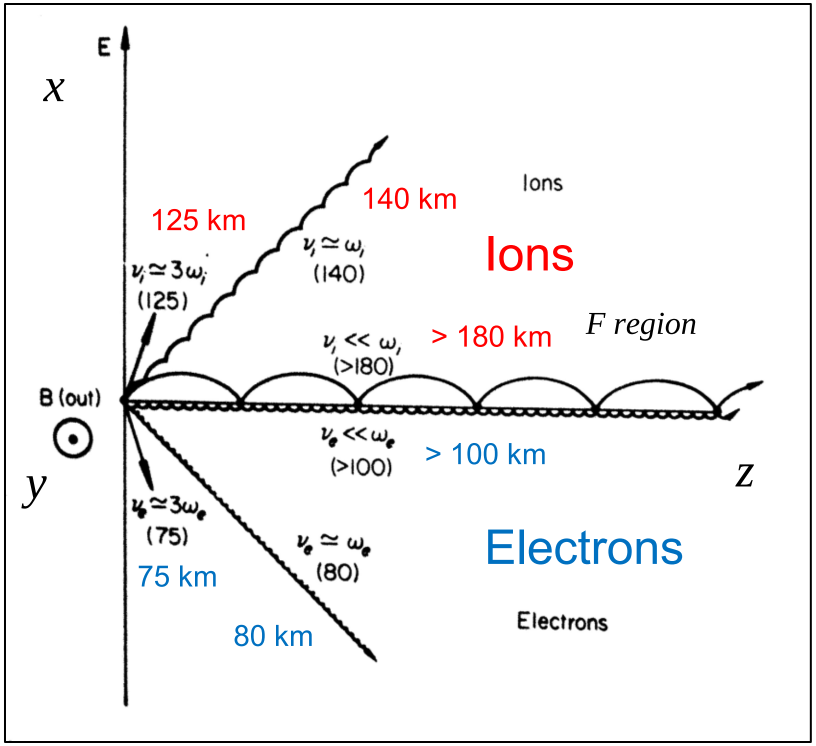
- F region (150 - 1000 km): both i^+ and e^- controlled by **B** (geomagnetic field)
- E region (90 - 130 km): i^+ controlled by collisions with neutrals, e^- by **B**
- D region (50 - 90 km): both i^+ and e^- controlled by collisions with neutrals



Motion of Charged Particles in the Ionosphere

- The charged particles 'feel' the presence of any electric field (**E**) and the geomagnetic field (**B**) – the neutral particles do not
- At lower altitudes the motions of charged particles are limited by frequent collisions with neutral particles
- When ions and electrons move with different velocities, electric current results (peaks in the E region)

Figure: Schematic showing particle motions for various ratios of collision frequency, ν, and gyrofrequency, ω (related to **B**) given the presence of an electric field, **E**. The collision ratios and hence motions vary with altitude (shown in brackets in km)



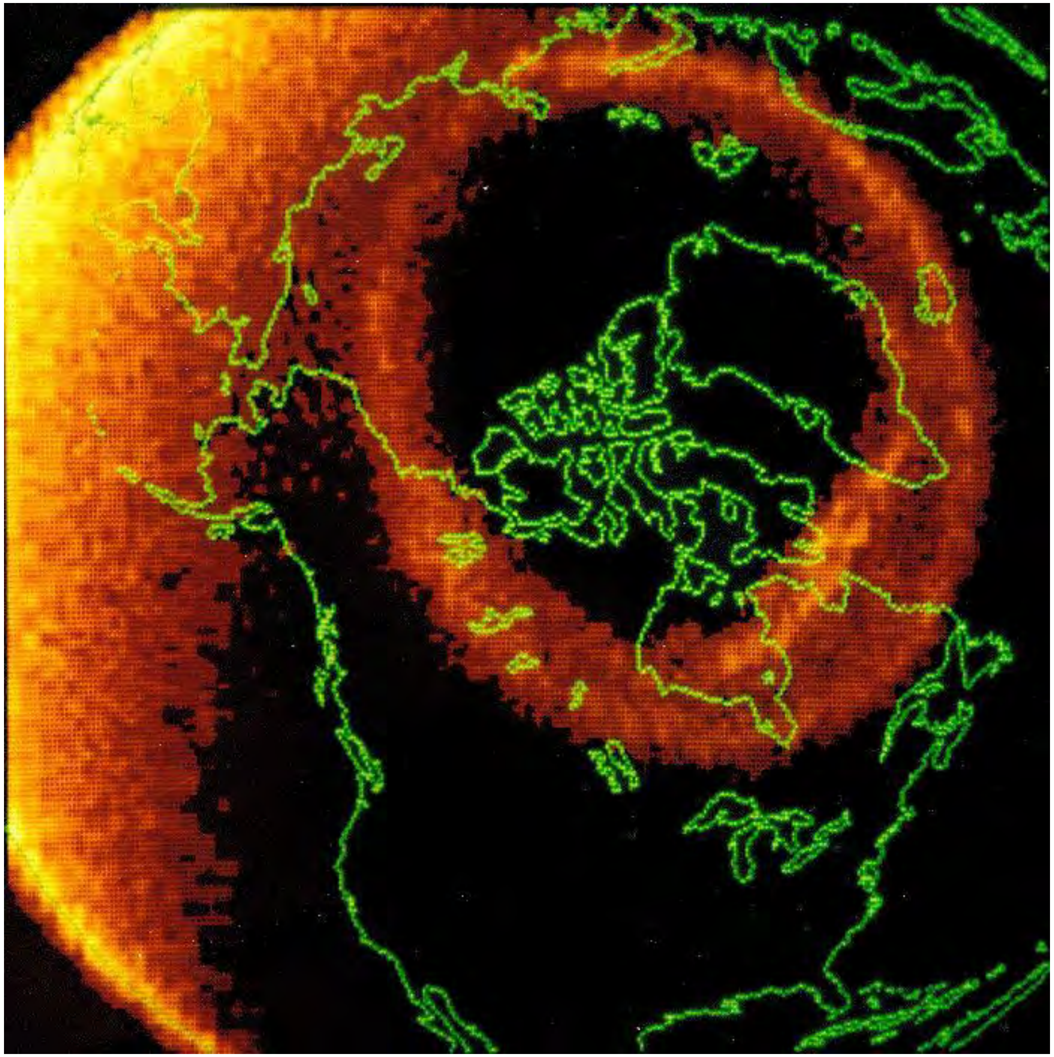
Properties of Earth's ionosphere

- At high latitudes precipitating particles can be the dominant source through impact ionization (i.e., aurora)

The Northern Auroral Oval Seen from Space

Image of auroral oval taken from the Dynamics Explorer 1 satellite on Nov. 8, 1981

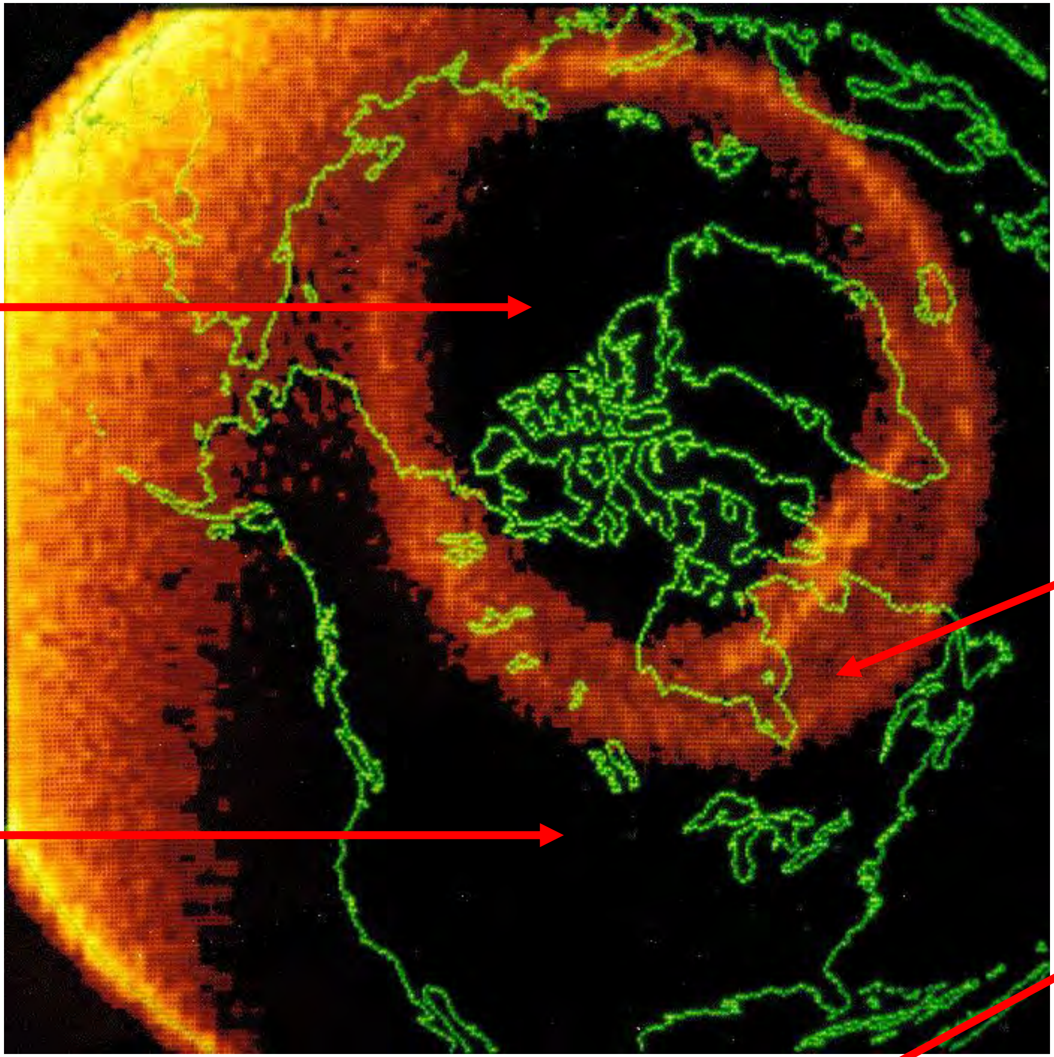
The auroral oval expands and contracts with the level of geomagnetic activity



Regions of the Ionosphere

The boundaries of the auroral oval define regions by geomagnetic latitude

Polar Cap

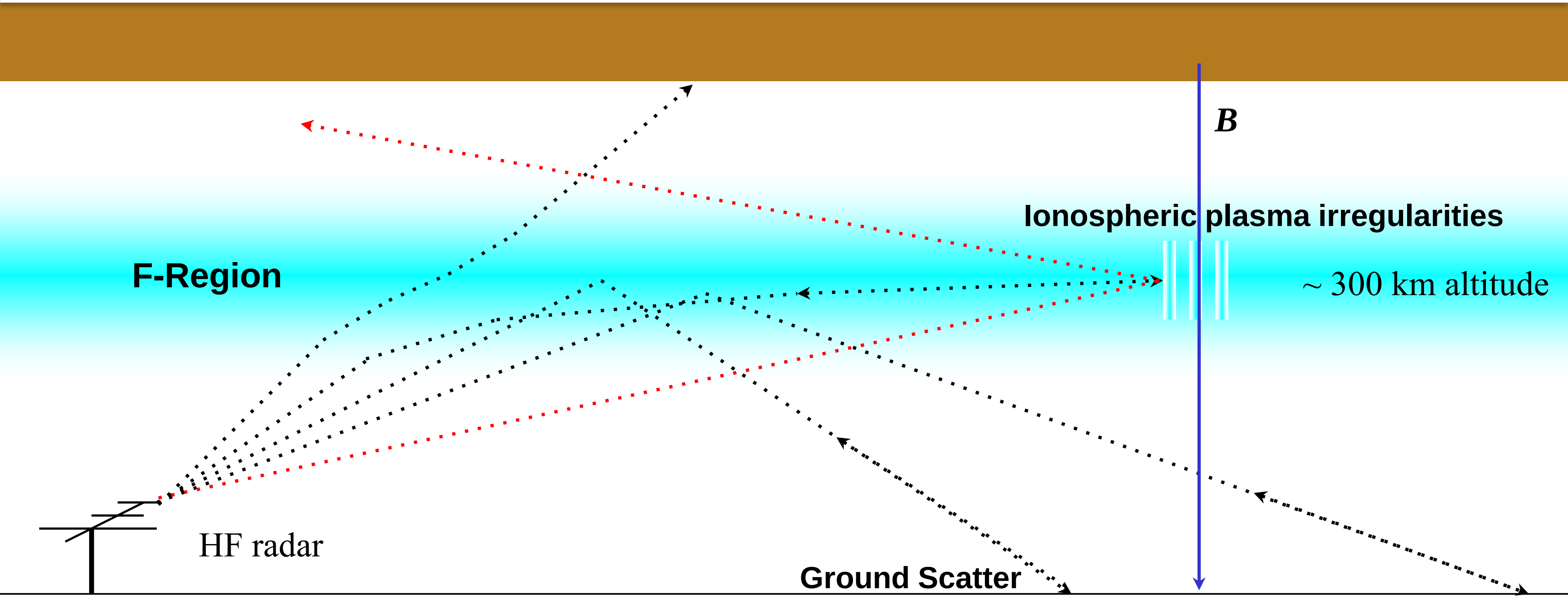


Auroral Zone / Oval

Mid-Latitude (Subauroral) Region

Equatorial Zone

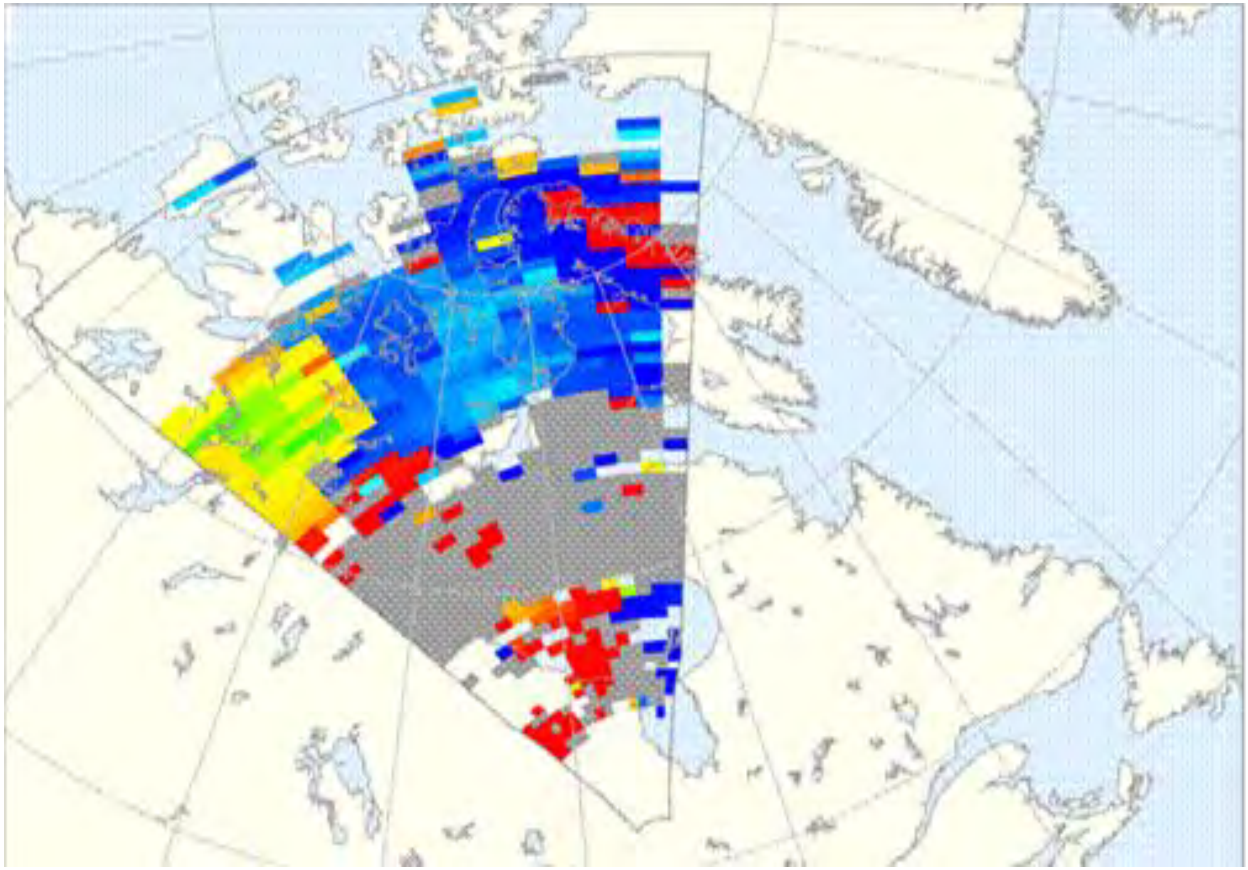
SuperDARN: Propagation and Scattering of HF Signal

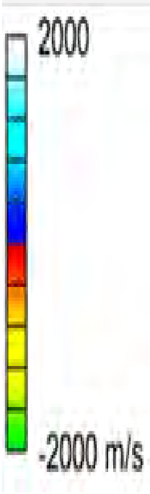


- HF rays are refracted in the ionosphere as they encounter density gradients
- Transmitted signals can be reflected back to the radar by:
    1) Ionospheric plasma irregularities (Field-Aligned Irregularities, or FAIs)
    2) Earth's surface ('ground scatter')
- Information about the reflectors is carried in returned signal, e.g., Doppler velocity

HF Backscatter from the Auroral Ionosphere

Map of Doppler velocity obtained from a single 2-min radar scan





Velocity magnitude

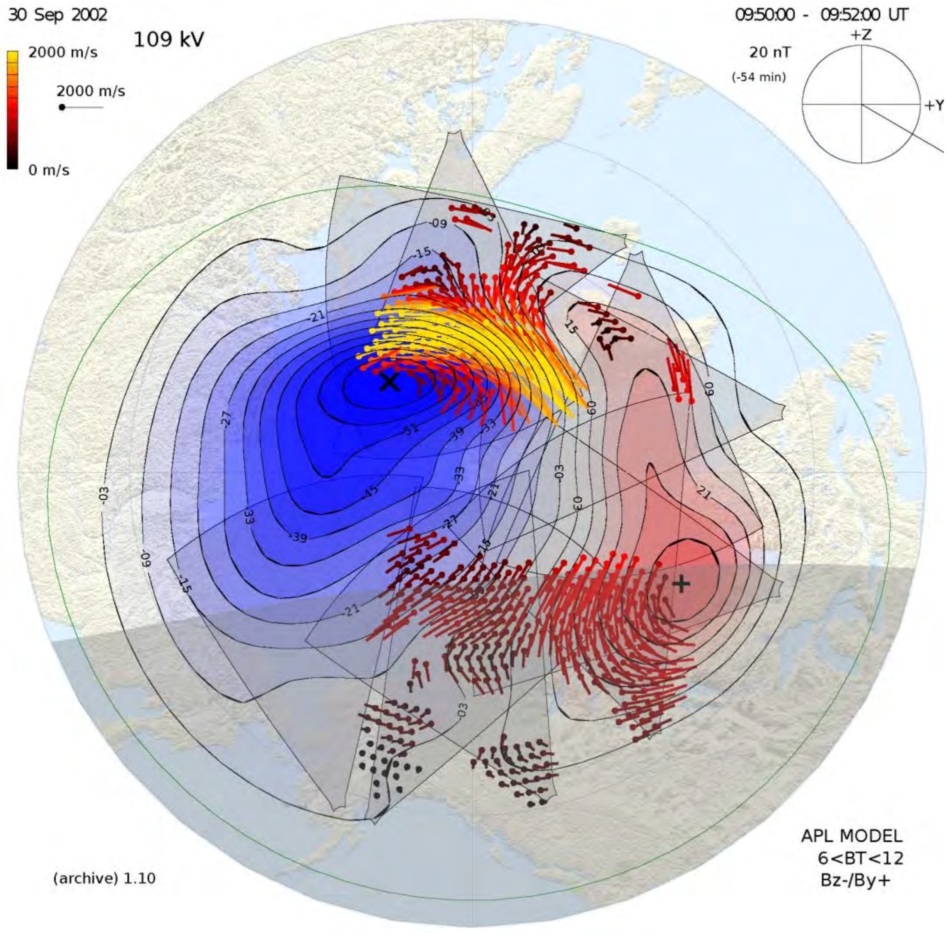
Blue - towards
Red - away

SuperDARN radar located at Kapuskasing, Ontario (Canada)

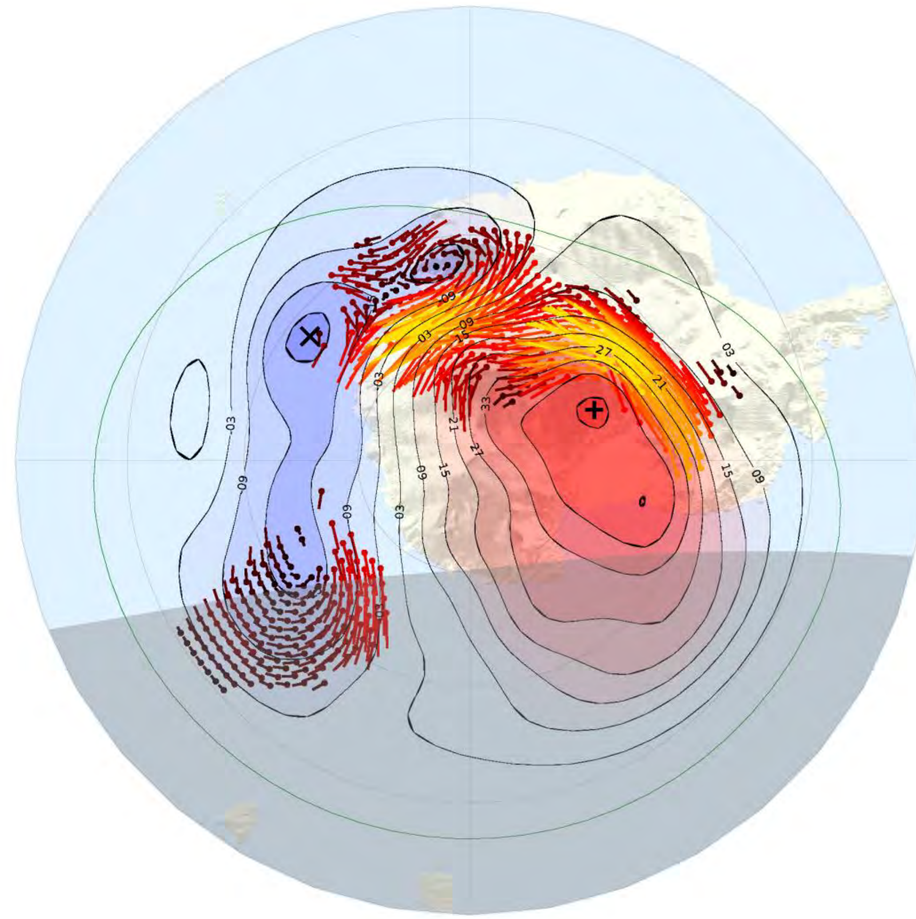
Global-Scale Mapping of High-Latitude Ionospheric Plasma Motion

Assimilation of observational and model data into maps [Ruohoniemi and Baker, 1998]

September 30, 2002: 09:50 – 09:52 UT

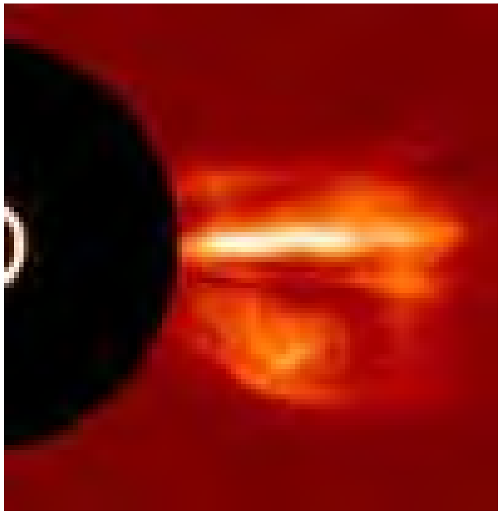


Northern Hemisphere



Southern Hemisphere

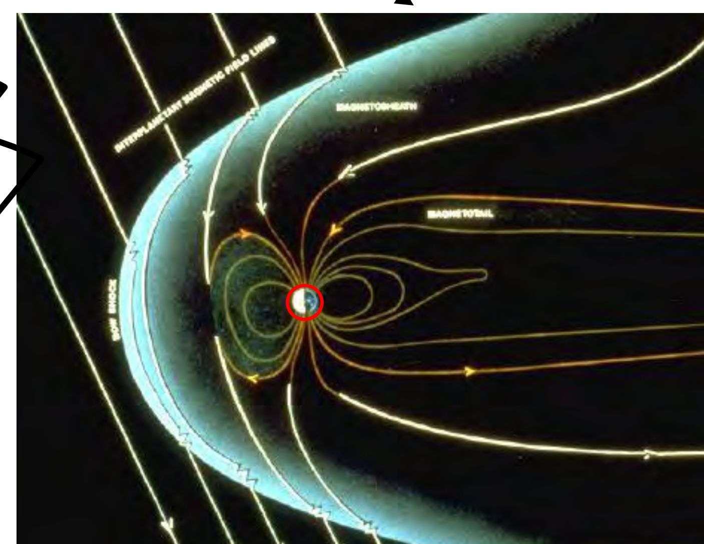
Origins of Visual Aurora and Plasma Motion in the Ionosphere



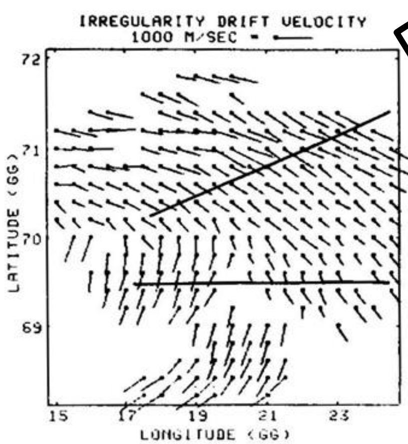
Solar wind plasma

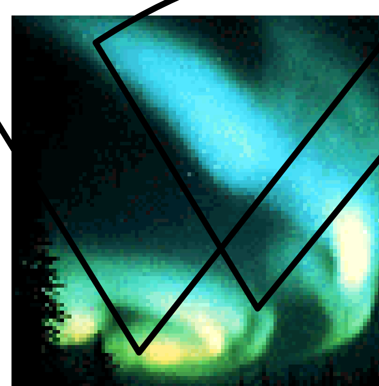
collides with Earth's magnetosphere

Causing currents to flow



And high-latitude effects





The midlatitude region versus the other zones

- The mid-latitude ionosphere has traditionally been thought of as a buffer zone lying between the high-latitude ionosphere (above 60º N) and the equatorial ionosphere (below 20º N to the equator)
- The situation with zones mirrors in the southern hemisphere (of course)
- High latitudes are known to be very ‘active’ with auroral processes, giving rise to electric fields, currents, plasma density structuring and irregularities, variable radiowave propagation, etc., in the ionosphere
- Equatorial latitudes have a special physics that also results in high levels of activity
- Leaving the midlatitude ionosphere to be neglected as lacking scientific and operational interest…

The midatitude region comes into its own!

- In the era of space weather (1990+) this view of the midlatitude ionosphere has changed dramatically
- Most of the world's population lives at midlatitudes and the harmful impacts of space weather are potentially the most damaging there
- And the mid-latitude ionosphere turns out to be far from 'quiescent' - much of its physics remains unexplained, even unexplored

(Phil and Angel and their colleagues at the MIT Haystack and Arecibo Observatories knew this all along of course)

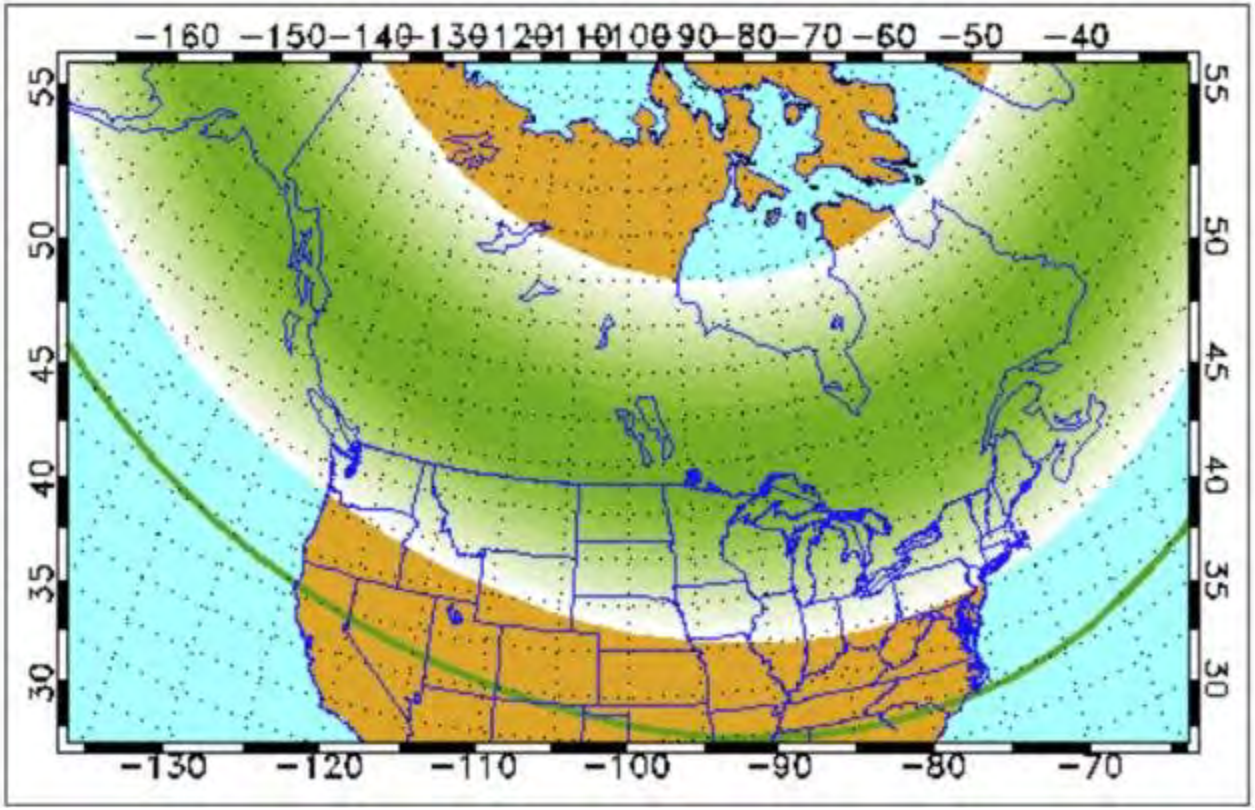
Diagnostic measurements with Incoherent Scatter Radar (ISR)

- The Millstone Hill Haystack Observatory (42.6ºN) with its fully steerable 46 meter antenna

- The Arecibo Observatory (18.3ºN) with its 305 m spherical reflector dish

The midlatitudes as an extension of the auroral zone

- The nominal midlatitudes can be the seat of auroral disturbances during large geomagnetic storms

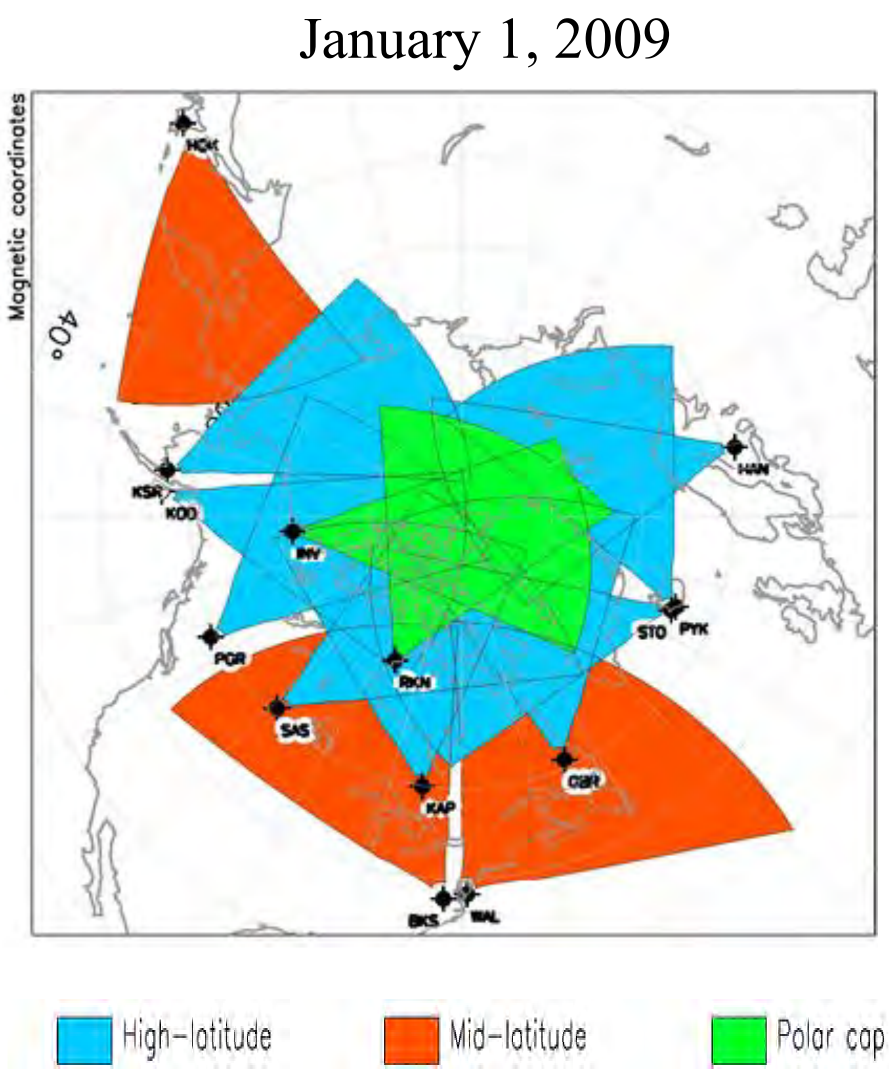


Map showing the predicted extent of the auroral zone during an anticipated event

The midlatitudes as an extension of the auroral zone

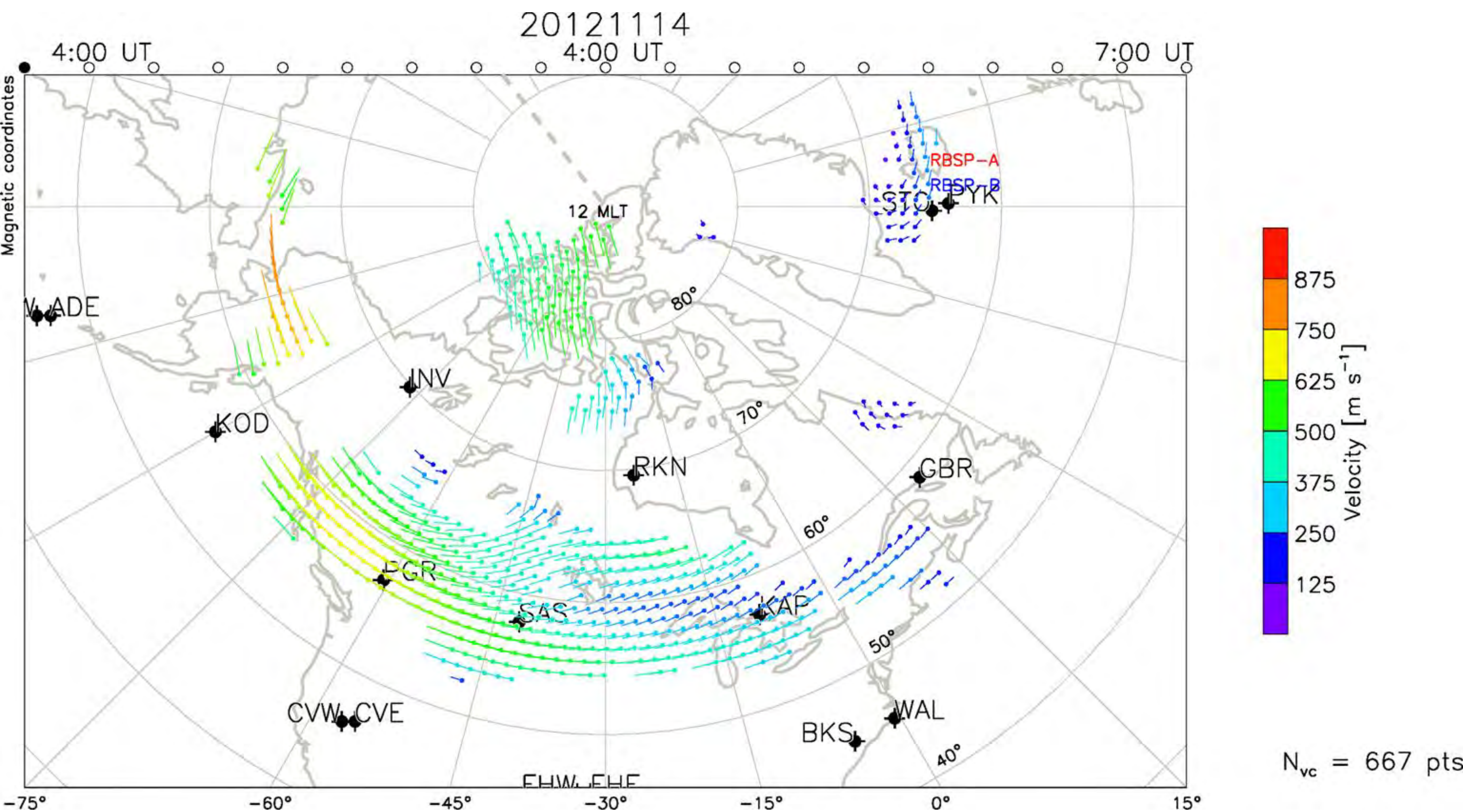
Observations of aurora from Blacksburg (37ºN) during the geomagnetic storm known as the St. Patrick's Day event (2015) – Photo credit: Alex Thornton

Expansion of SuperDARN to Mid-Latitudes



- SuperDARN was conceived of as a system of radars to operate at high latitudes (shown in blue)
- Later expanded to the polar cap (shown in green)
- Initial expansion to mid-latitudes was proposed as a way to observe the expansion of the auroral oval during storms
- Original name was 'StormDARN'

Expanded Observations of Plasma Convection during Storms



Fitted velocity vectors during storm: Nov. 14, 2012, 4 – 7 UT

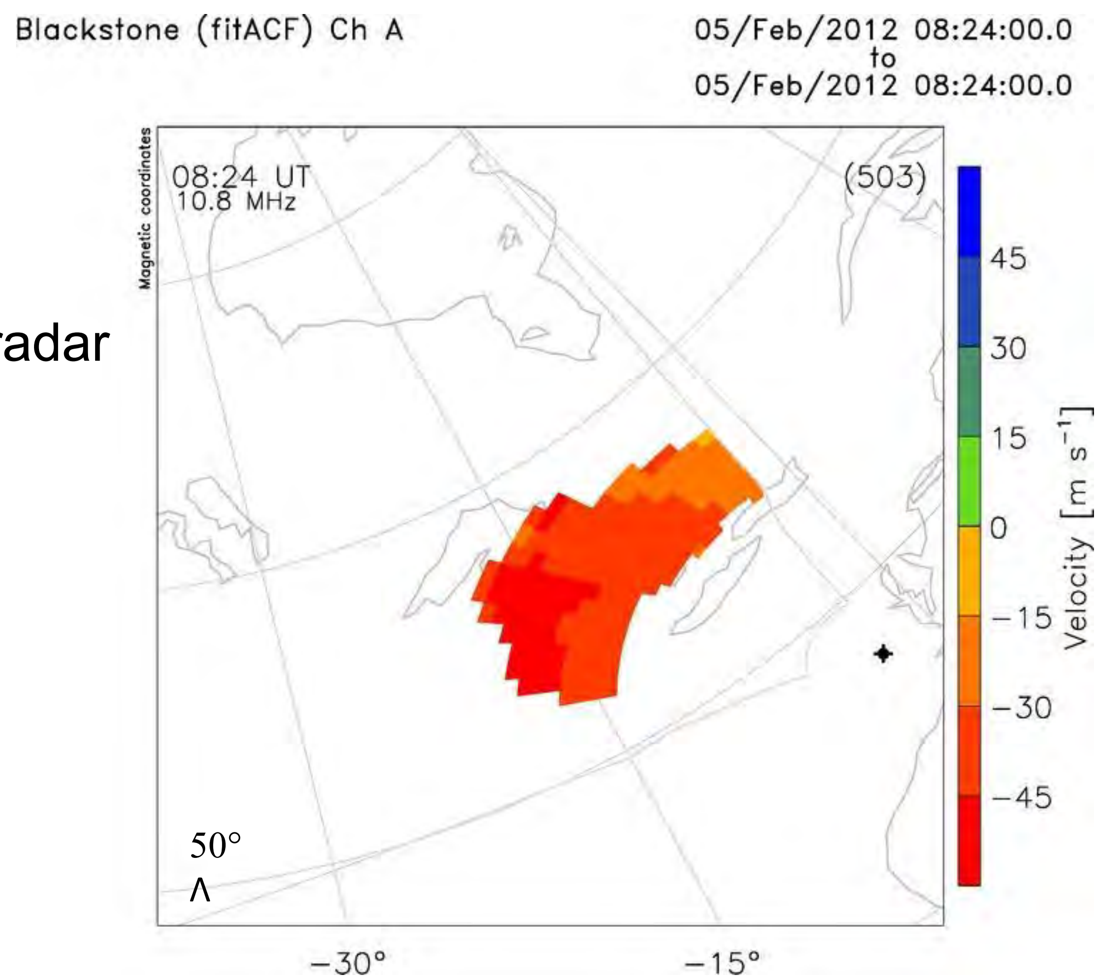
Expansion of SuperDARN to Mid-Latitudes

- With 'StormDARN' there was no expectation that we would observe interesting backscatter from the quiet-time midlatitude ionosphere
- But shortly after the first mid-latitude radar came into operation at NASA Wallops Flight Facility in Virginia we observed a new kind of ionospheric backscatter
- It occurs throughout the night during geomagnetically quiet conditions with low Doppler velocities (< 100 m/s)
- Described as *SubAuroral Ionospheric Scatter* (SAIS) by Ribeiro et al. [2012]

Map of Midlatitude Plasma Motion derived from SAIS

Blackstone radar

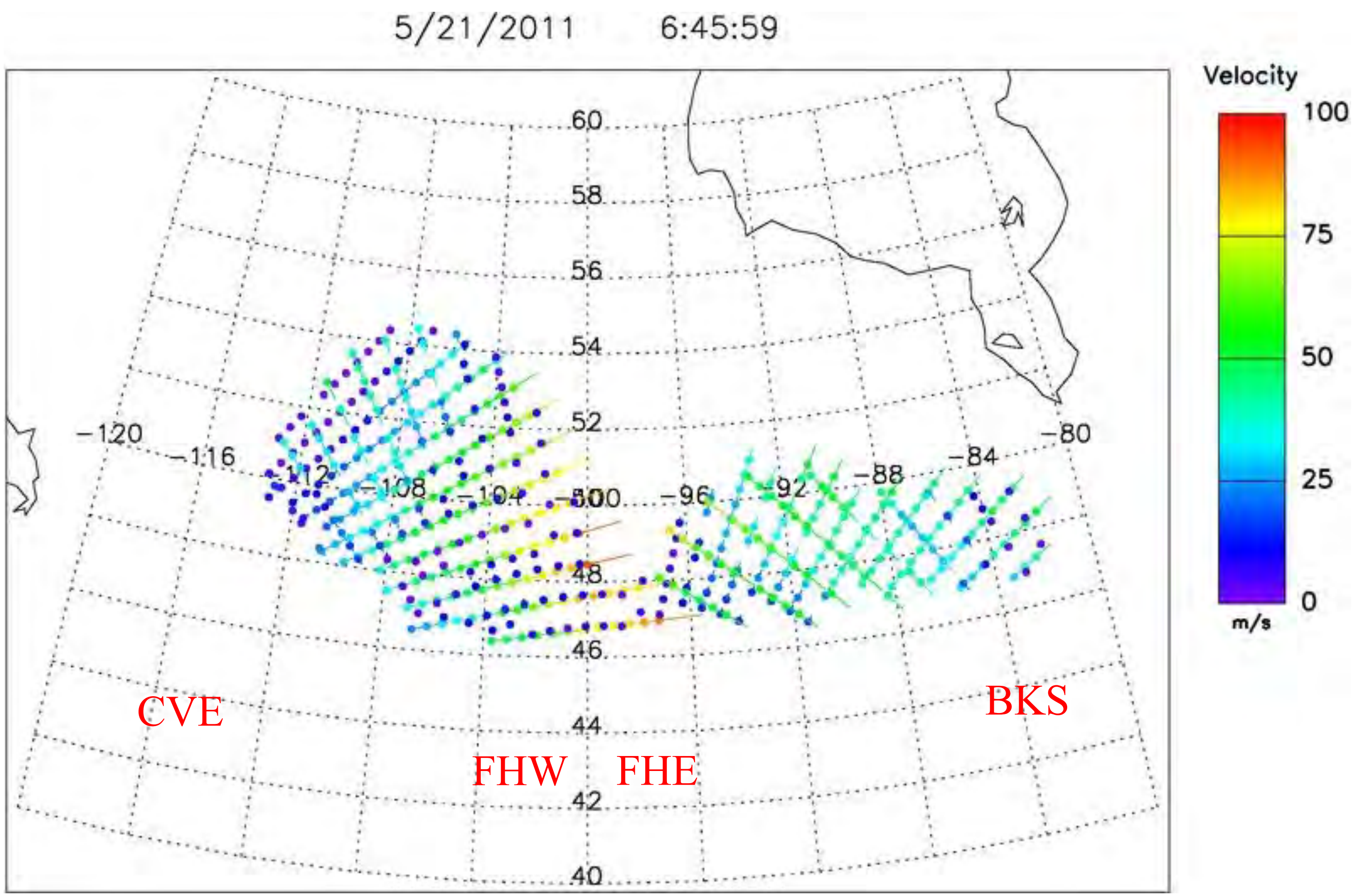
08:24 - 08:26 UT



Scan plot of SAIS showing variation in line-of-sight velocity with azimuth that is consistent with westward flow

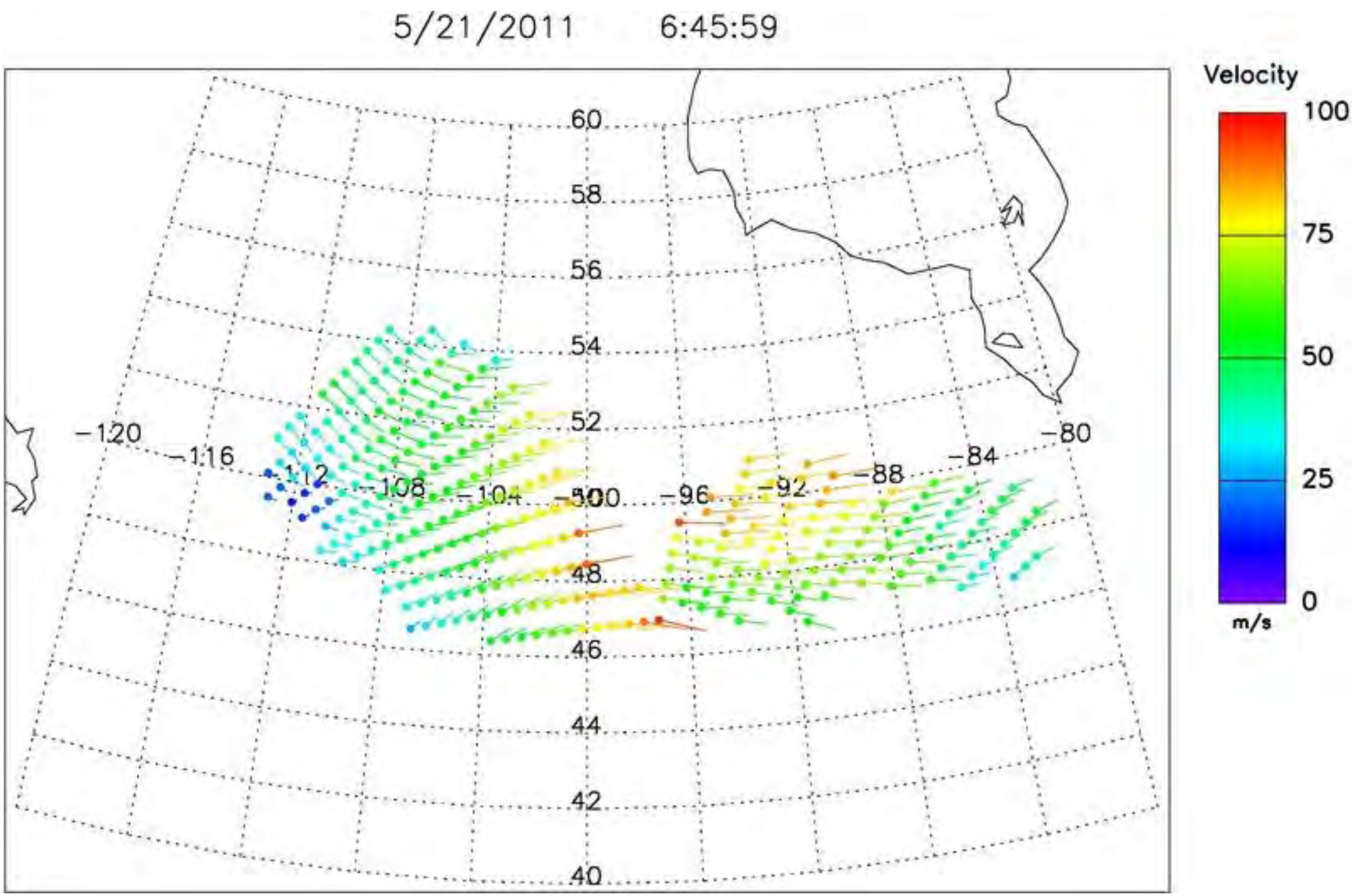
Expansion of SuperDARN to Mid-Latitudes

Overlapping line-of-sight velocity measurements from four midlatitude radars



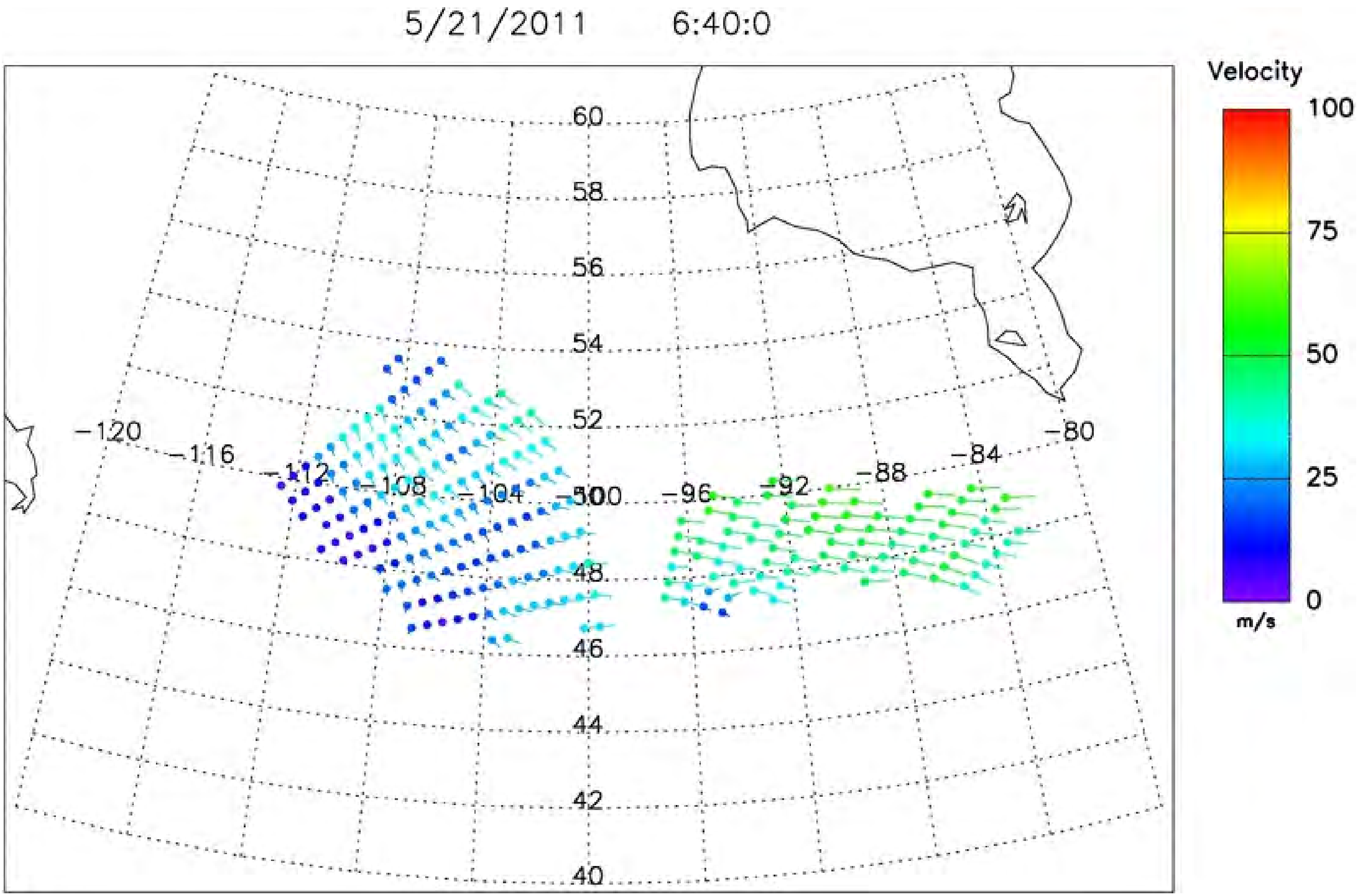
Expansion of SuperDARN to Mid-Latitudes

Map of merged plasma velocity vectors



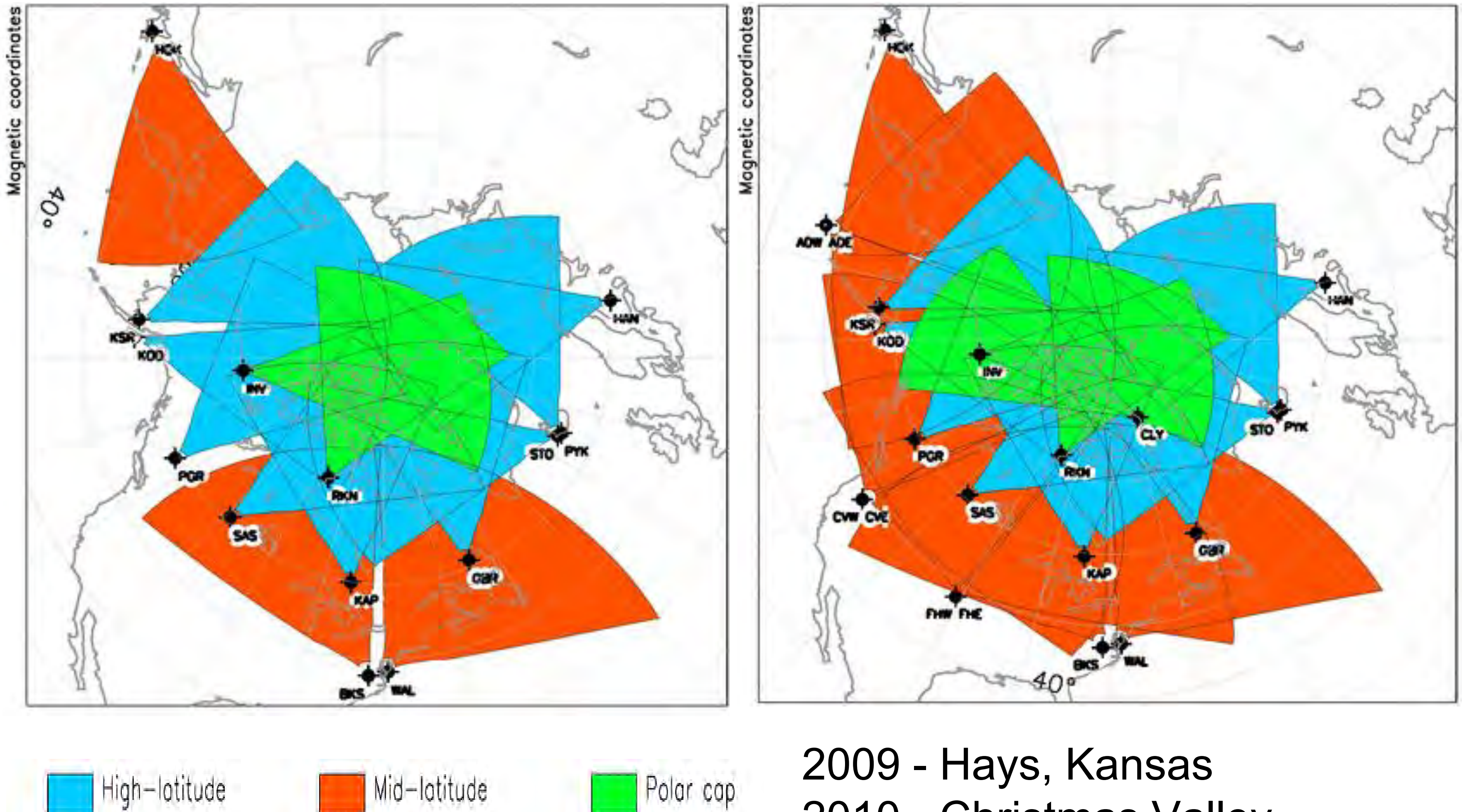
Expansion of SuperDARN to Mid-Latitudes

Twenty-minute movie showing a reversal in midlatitude plasma velocity



Expansion of SuperDARN to Mid-Latitudes

January 1, 2009 | January 1, 2013



2009 - Hays, Kansas
2010 - Christmas Valley, Oregon
2012 - Adak, Alaska

Two-radar SuperDARN site at Hays, Kansas

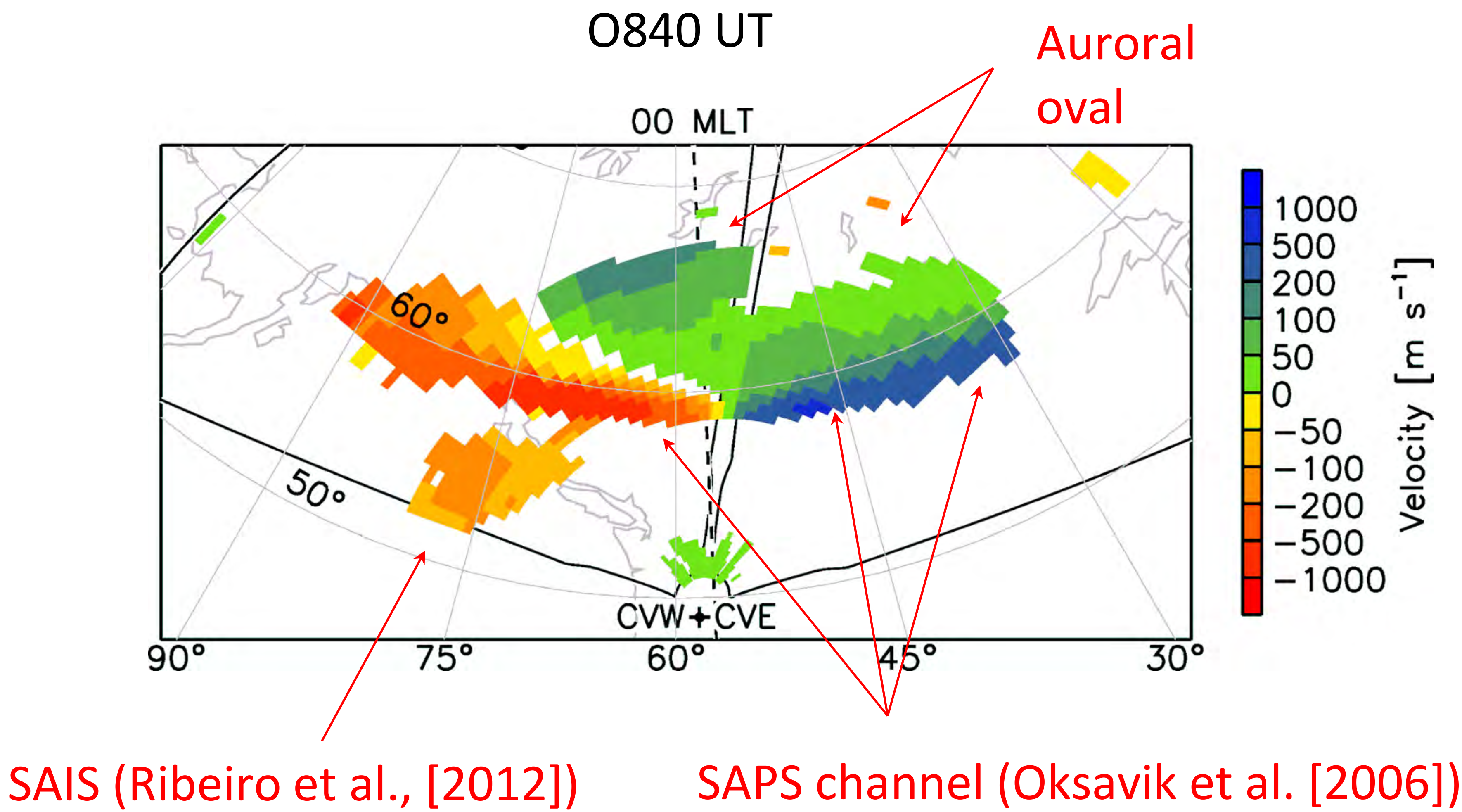
Aerial photo: one radar is oriented towards the NE, the other towards the NW

The Midlatitude ionosphere as an active region

- The deployment of the SuperDARN HF radar system to mid-latitudes has lead to new and exciting views of this part of the ionosphere, much is unexplained
- The value of observations from one system are greatly enhanced when they mesh with those from other systems
- For midlatitude SuperDARN collaborative measurements come from the MIT Haystack Observatory and GPS-derived records of Total Electron Content (TEC)
- Demonstrate here with observations of the *Subauroral Polarization Stream* (SAPS)

Observations of a SAPS from the Oregon radars

Line-of-sight velocity measurements

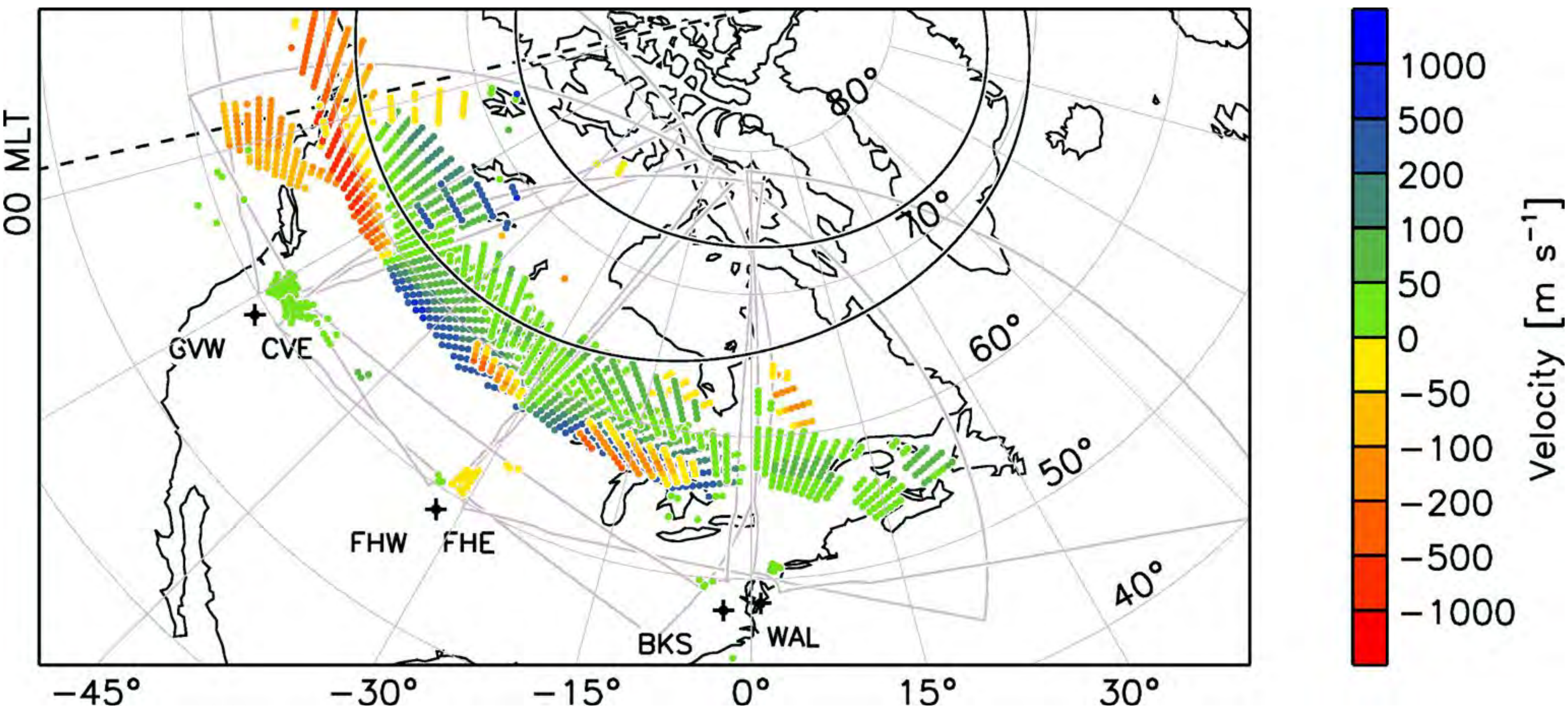


Fields of view of the Christmas Valley West and East radars (Oregon)

Large-Scale Map of SAPS Observations – April 9, 2011

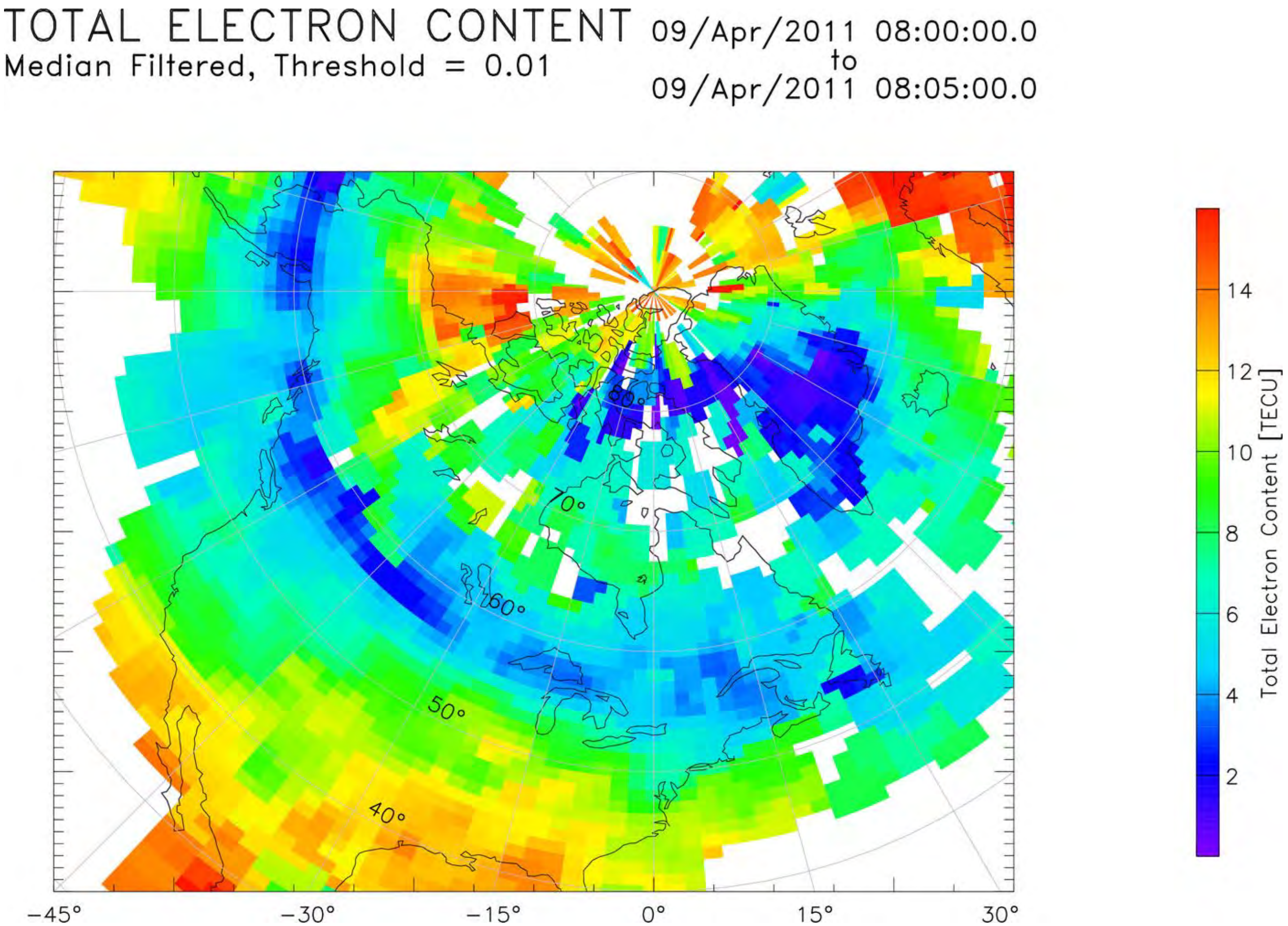
[From Clausen et al., 2012]

0840 UT



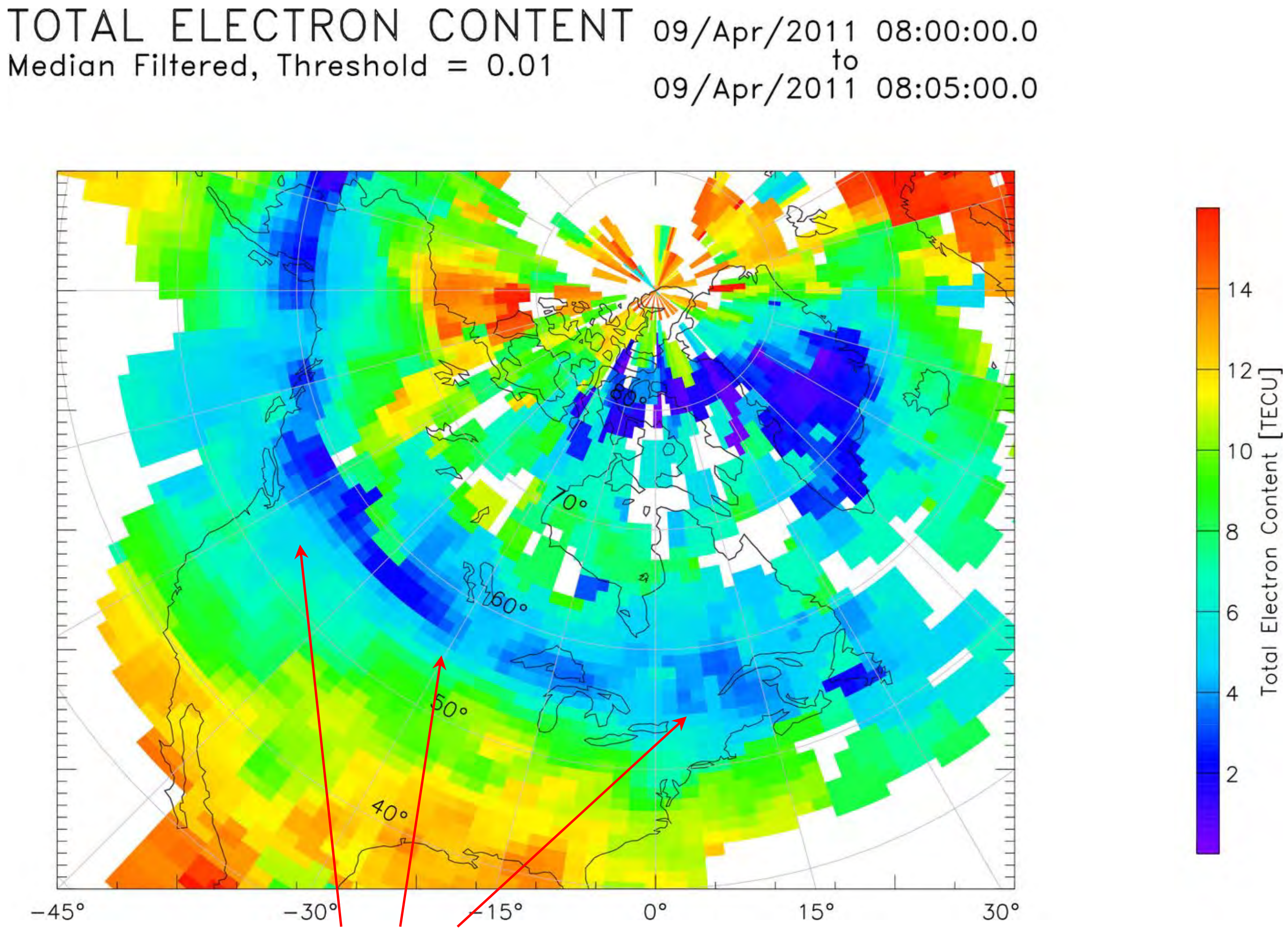
CVW/CVE – Christmas Valley E/W FHW/FHE – Fort Hays BKS/WAL – Blackstone/Wallops

Mid-Latitude Ionosphere: SAPS and the TEC Trough



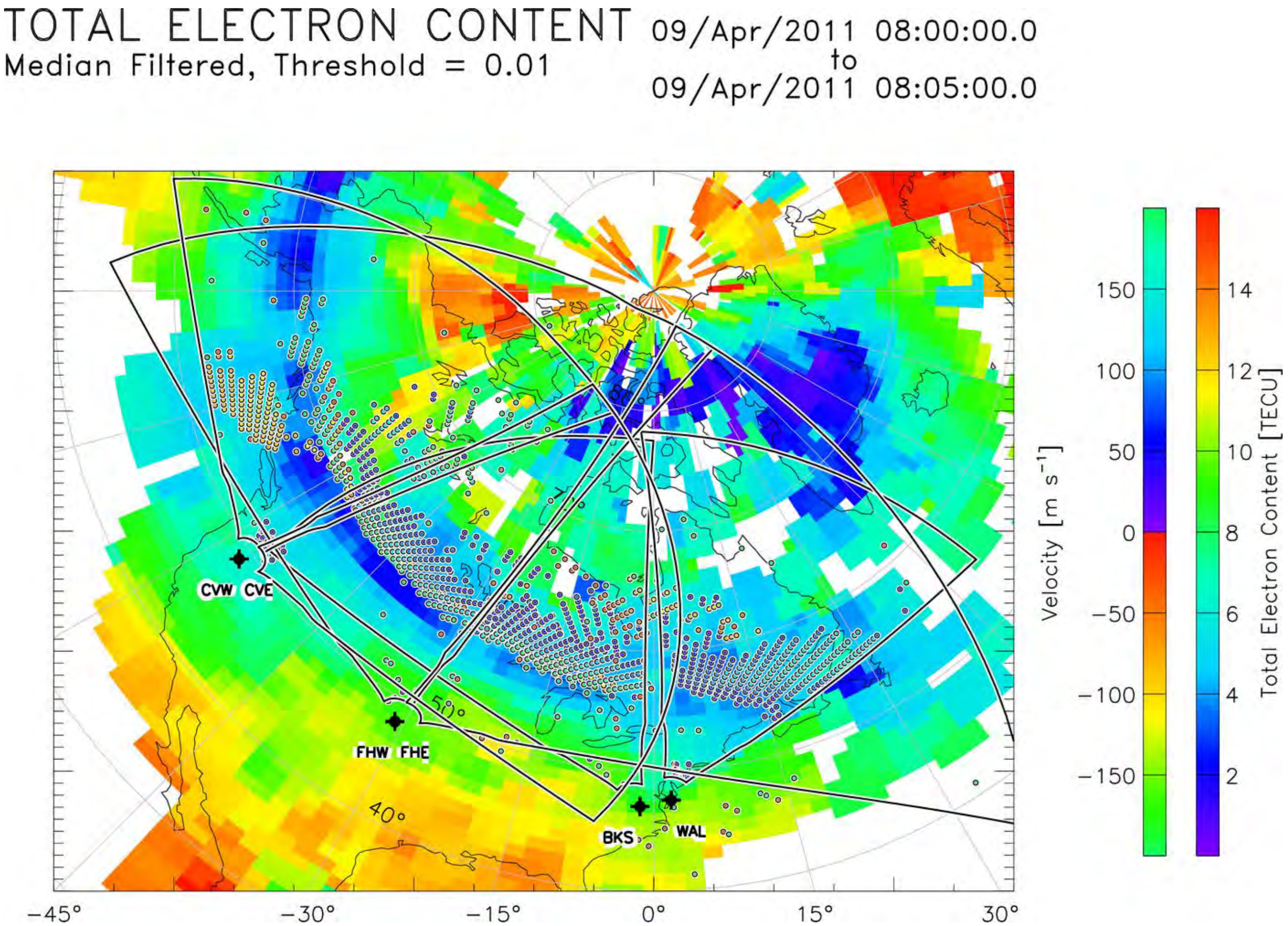
Map of the 'thickness' of the ionosphere measured by GPS satellites as the total count of electrons in a column of standard area

Mid-Latitude Ionosphere: SAPS and the TEC Trough



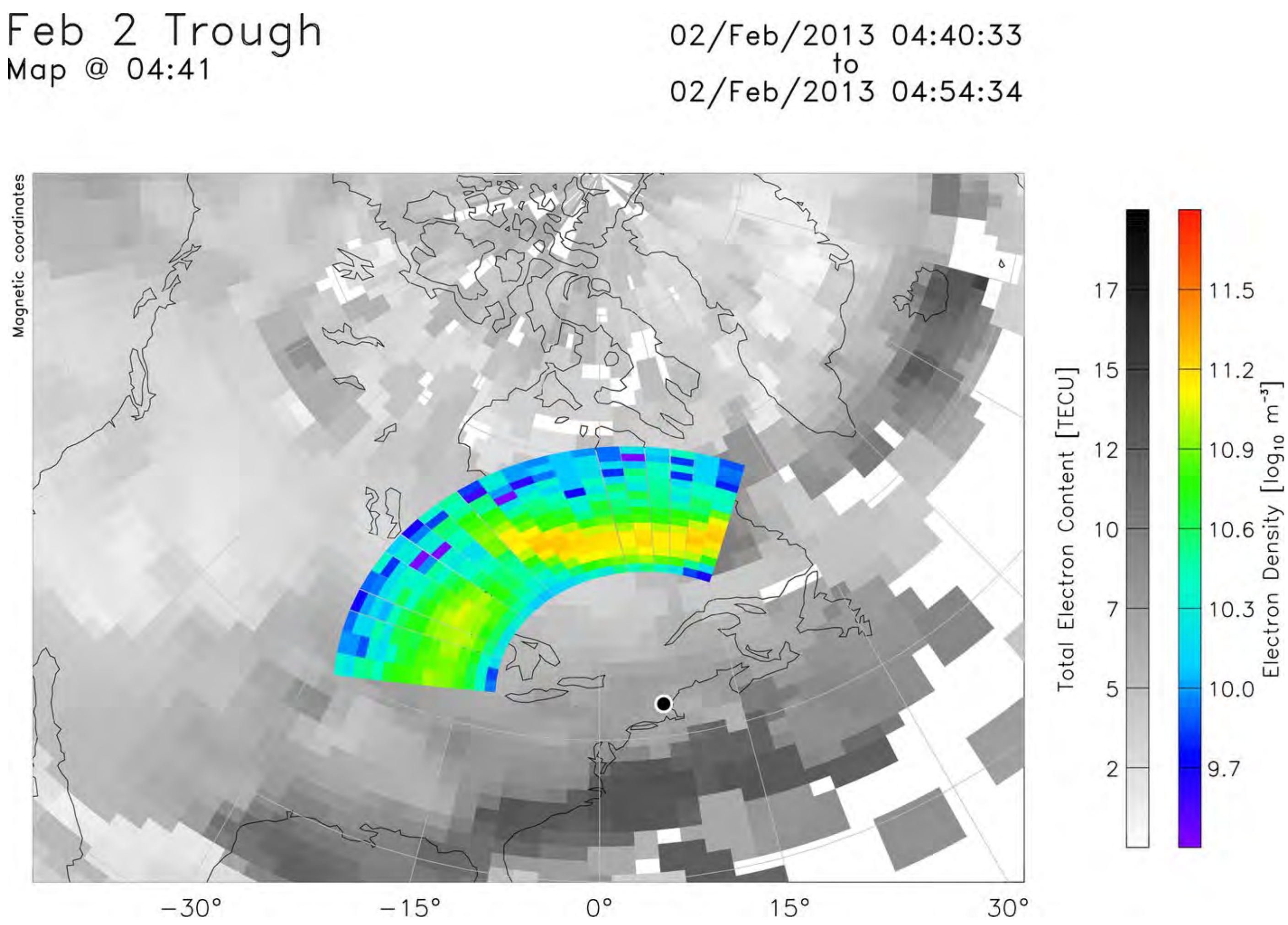
A mid-latitude 'trough' of very low plasma density as imaged in the TEC data across North America

Mid-Latitude Ionosphere: SAPS and the TEC Trough



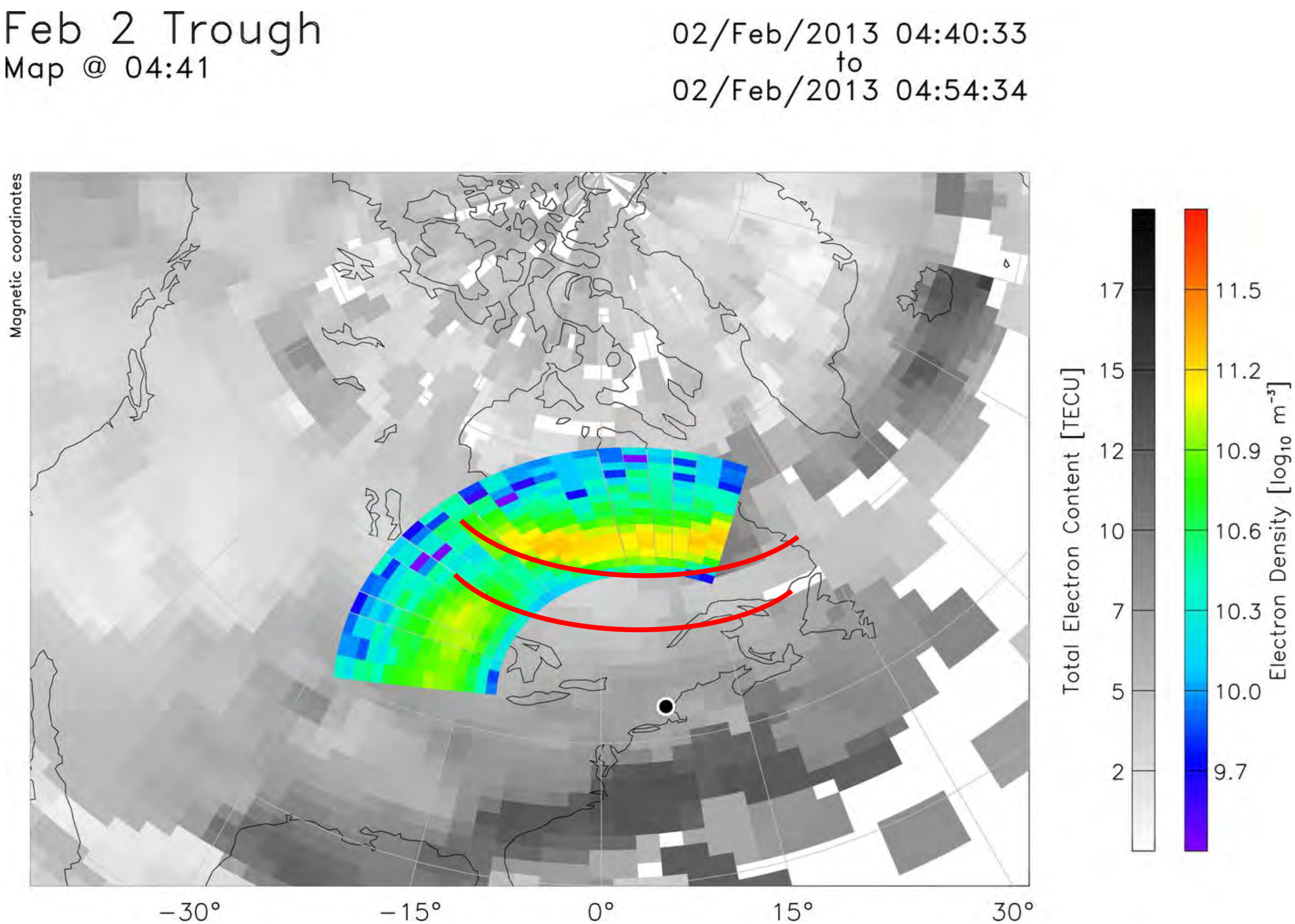
Superimposed radar data show that the SAPS feature is associated with the TEC trough

Scanning across the SAPS region with the Millstone Hill IS radar



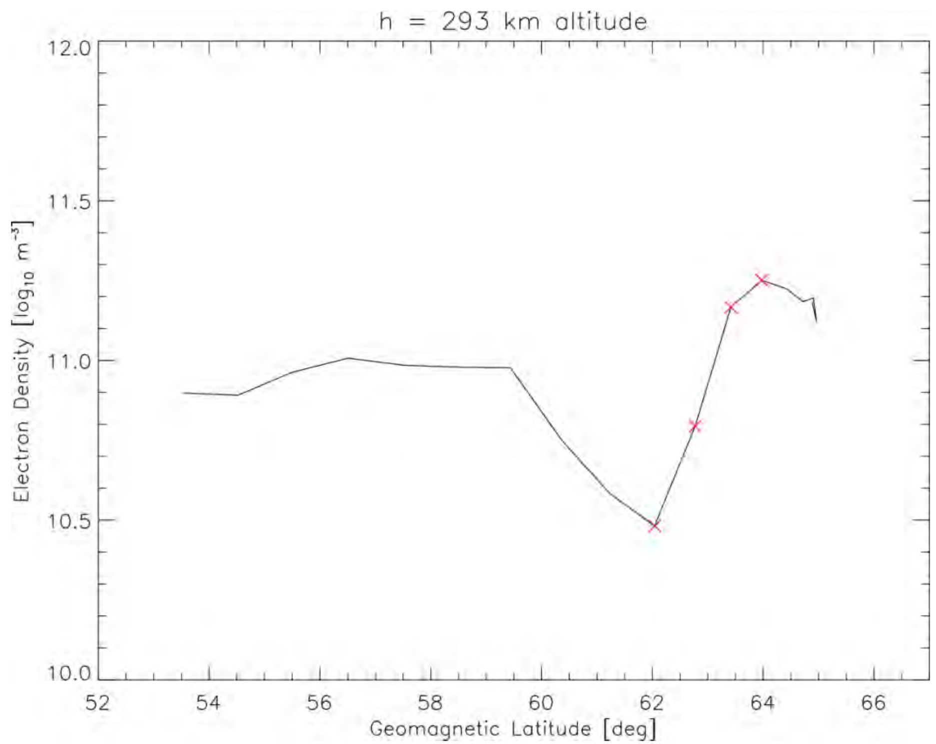
During this experiment the ISR performed azimuth scans and measured density and other plasma parameters

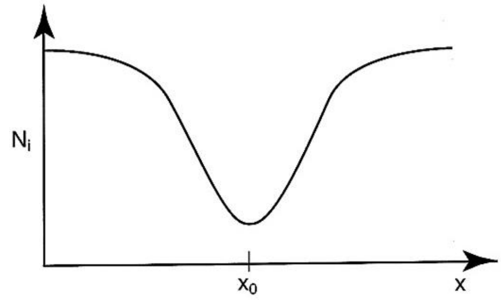
Scanning across the SAPS region with the Millstone Hill IS radar



During this experiment the ISR performed azimuth scans and measured density and other plasma parameters

What is the cause of HF radar backscatter from SAPS?





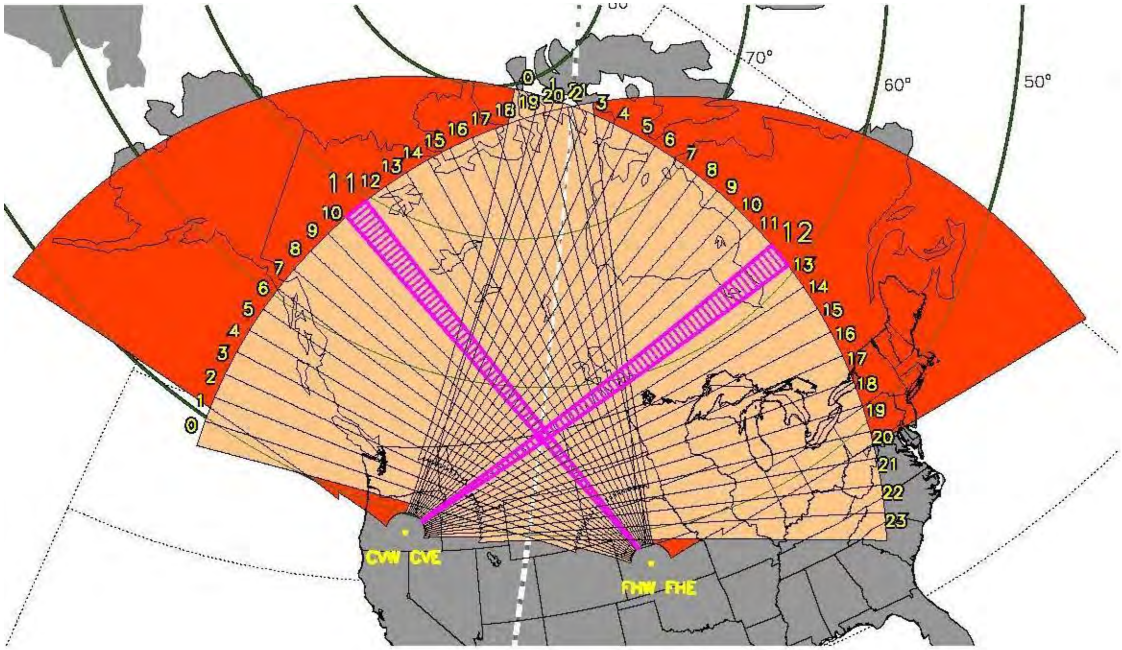
The ISR data indicated a classic plasma density trough with a very steep gradient at the poleward wall.

A component of plasma velocity in this direction would be favorable for an instability known as GDI.

But: it doesn't work!

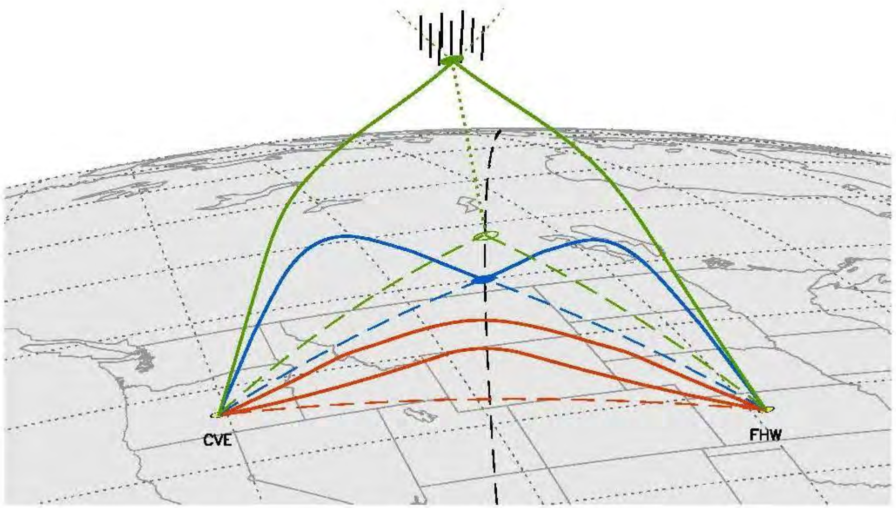
Still searching…

First bistatic SuperDARN radar observations



- Experiments have been conducted to analyze propagation path with the Fort Hays site transmitting and the Christmas Valley site receiving [Shepherd et al., 2020]

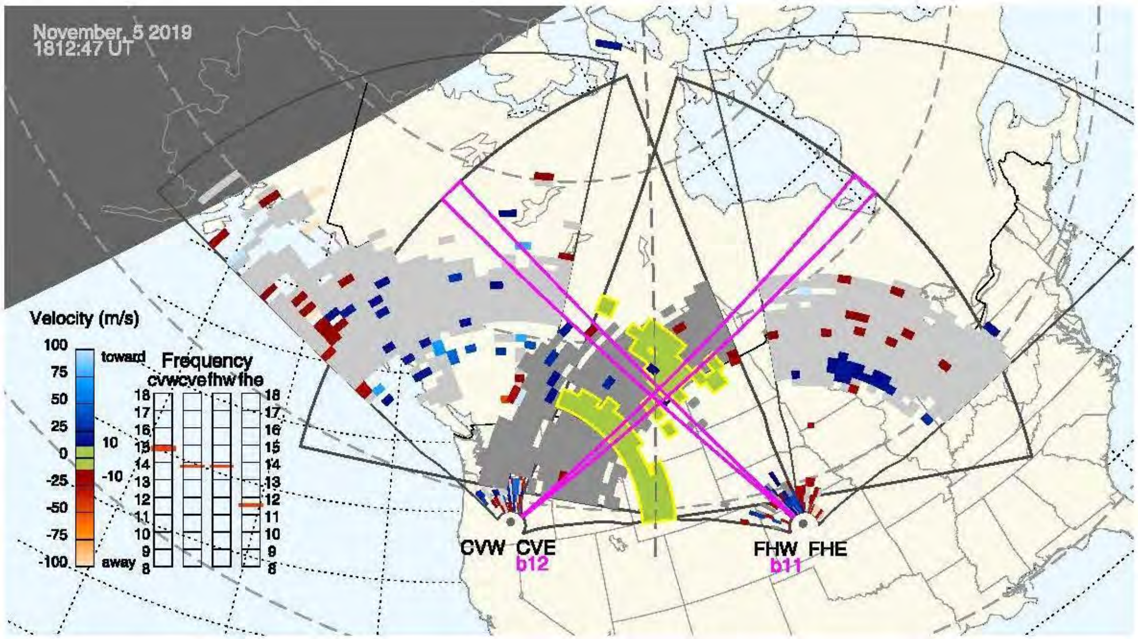
First bistatic SuperDARN radar observations



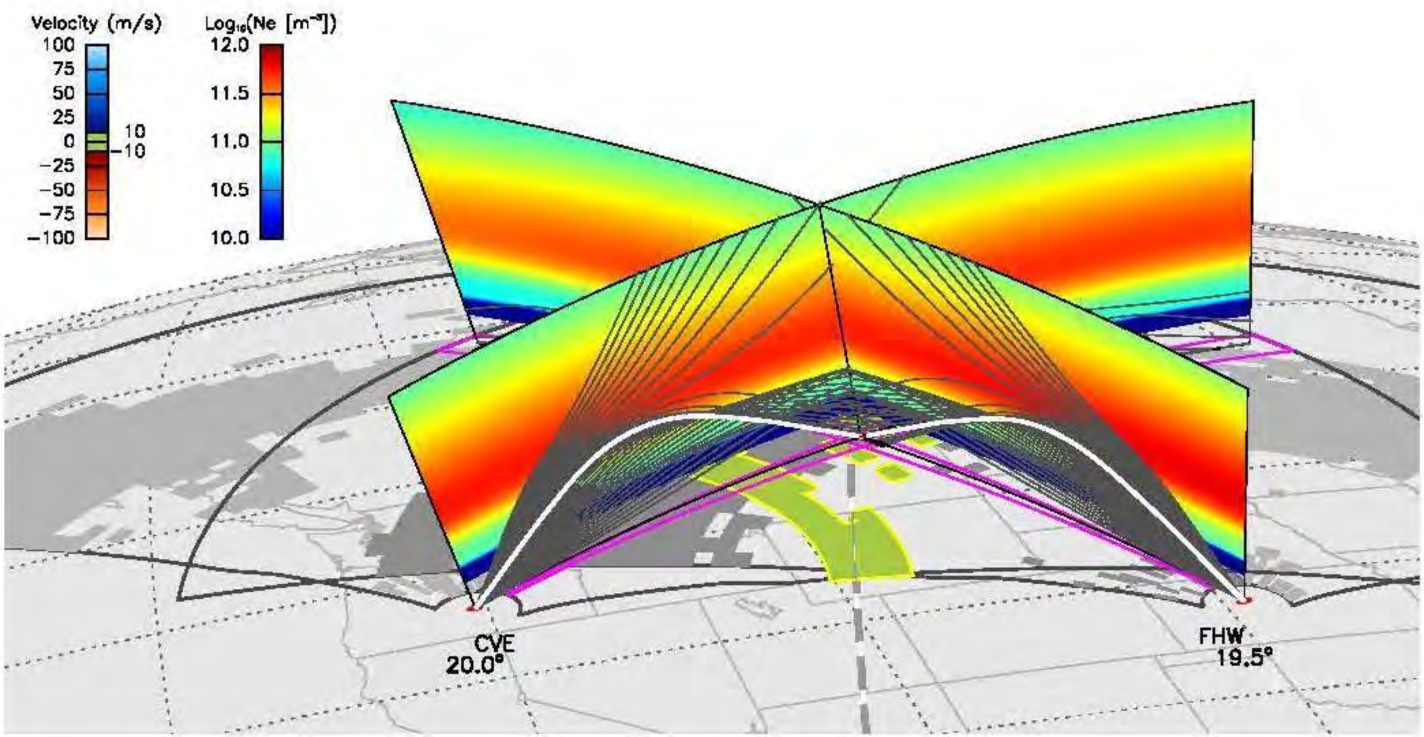
- Several possible propagation modes are indicated that can establish a link

- Normal monostatic radar scatter is shown in standard grey outline with colored speckles

- Bistatic scatter is shown in yellow highlight



First bistatic SuperDARN radar observations



- Ray tracing through a model ionosphere (based on the IRI) indicates the viability of two propagation modes, including bistatic observations via reflections from Earth’s surface (ground scatter)

Some HamSCI-related Open Research Questions

- Does the occurrence of ionospheric irregularities (SAIS, SAPS) in the nightside mid-latitude ionosphere enable reception for Hams?
- Can we account for the formation of midlatitude ionospheric irregularities?
- Can we realistically model the mid-latitude ionosphere (especially plasma density) on the basis of HF observations?
- What are the sources of variability in the mid-latitude ionosphere especially with regards to atmospheric winds, tides, waves, TIDS?
- Can HF observations be applied to test and develop models of ionospheric physics?
- Can we connect disturbances on HF propagation paths in the midlatitude ionosphere to other forms of space weather?

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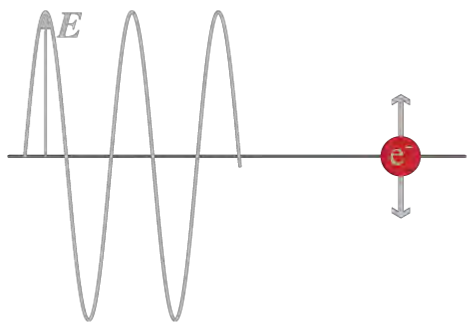
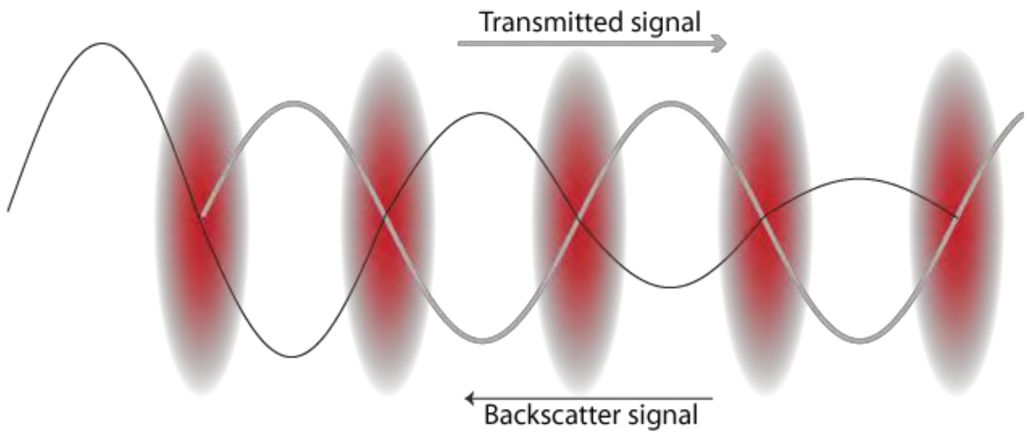
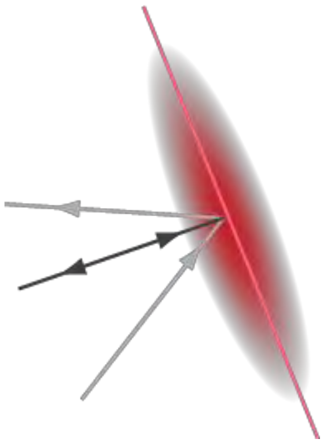
Conditions required to observe ‘coherent’ ionospheric backscatter



EM backscatter generated by free electrons in the ionosphere accelerated by a transmitted signal.



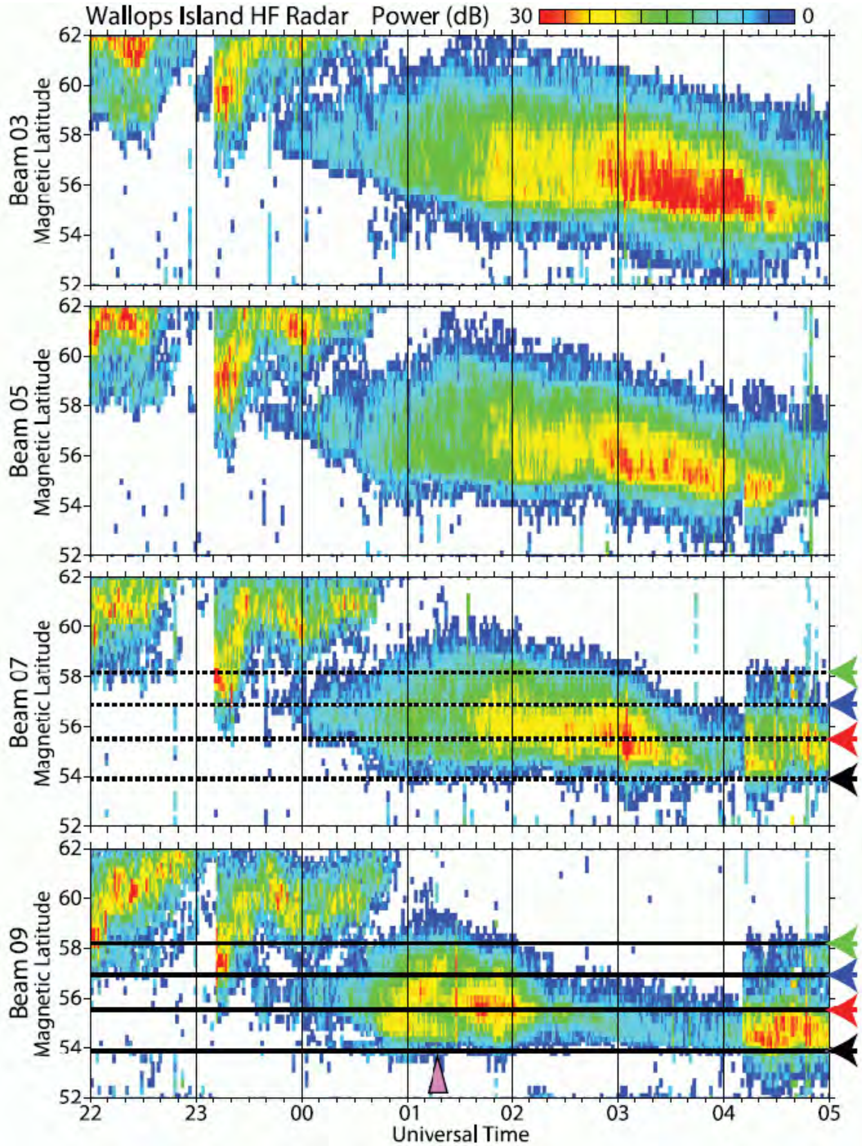


Backscatter is amplified under Bragg conditions by density fluctuations with scale sizes on the order of half the transmitted wavelength.

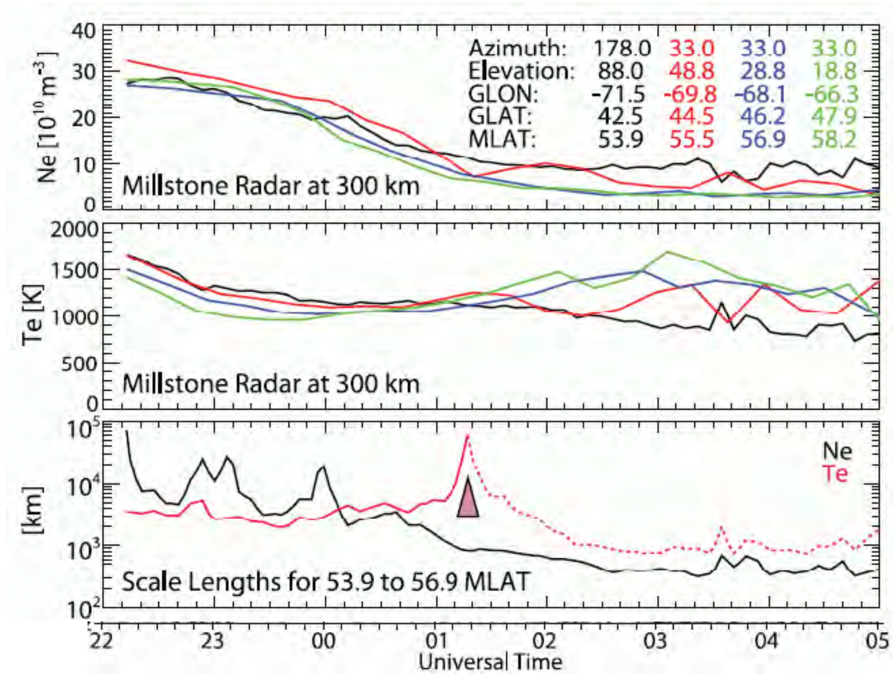
Orthogonality of the transmitted signal with the background magnetic field (aspect condition) provides maximum returned power.

Success in finding a possible cause of SAIS backscatter

Wallops SuperDARN HF radar

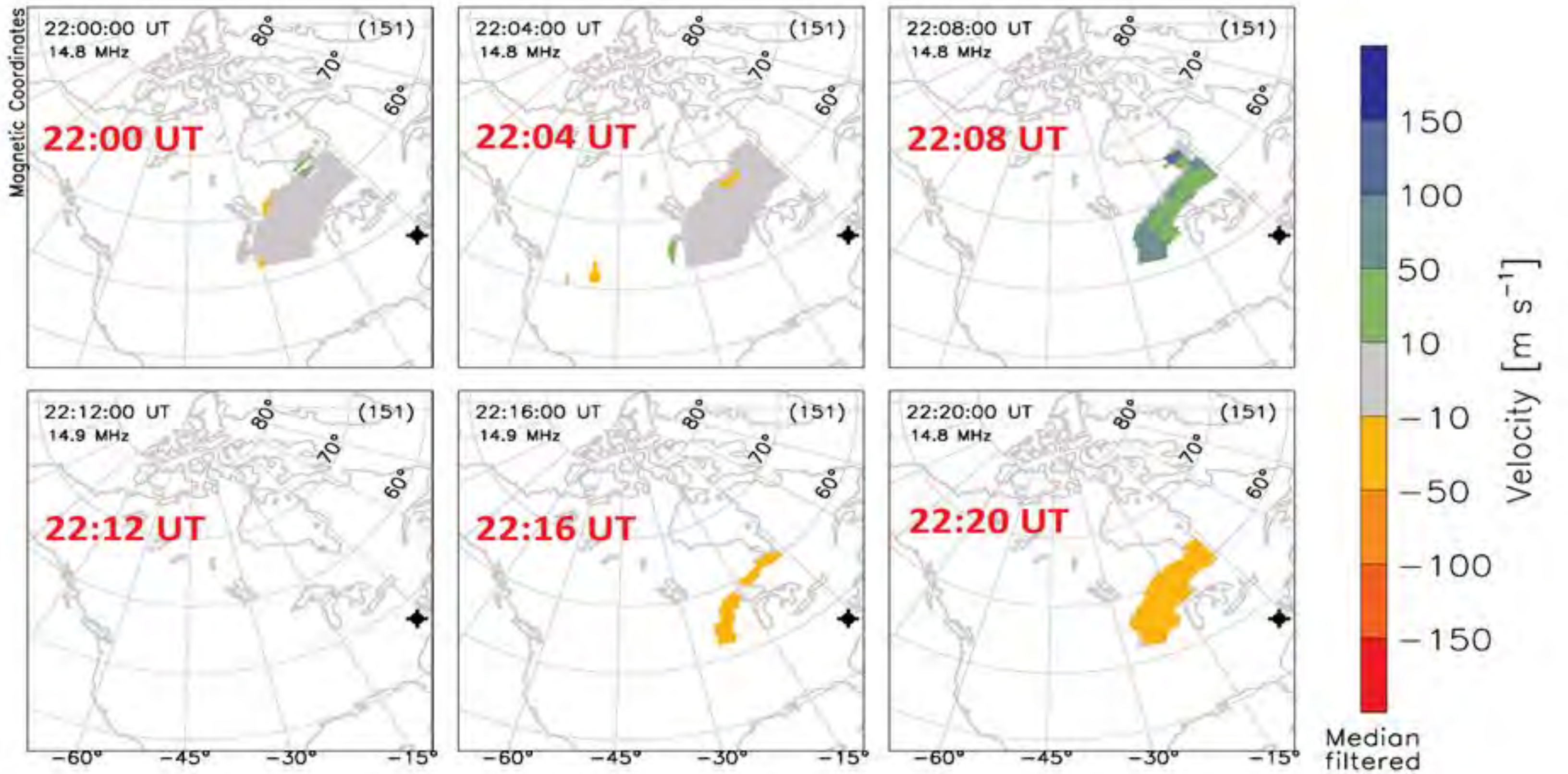


Millstone Hill Observatory ISR



- Good evidence for a certain plasma instability in MHO radar observations of density and temperature variations during a SAIS event [Greenwald et al., 2006]

Solar Flare Effects – ShortWave Fadeout (SWF)



- Observations with the Blackstone SuperDARN radar of the impact of a solar flare – suppression of daytime HF groundscatter and a sudden frequency deviation or 'Doppler flash' [Chakraborty et al. , 2018]