SuperDARN – A Primer on the coherent-scatter HF radar system

(Based on the Buonsanto lecture of November 1, 2012)

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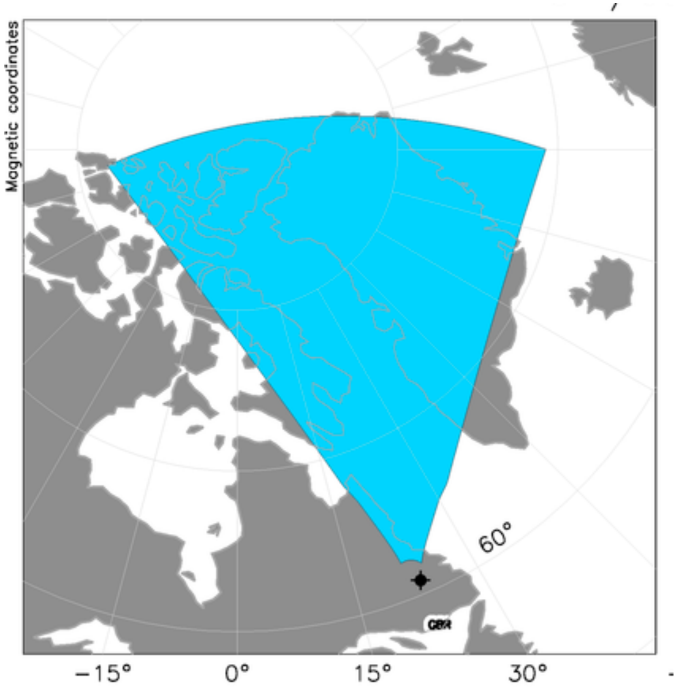
Themes of Lecture

- Origins of SuperDARN as an international collaboration
- Discussion of the HF radar technique
- Mapping of ionospheric plasma convection, TIDs / AGWS
- Collaborations with ISR, GPS/TEC, Van Allen Probes

Origins of SuperDARN

HF Radar Coverage - 1986

First radar located at Goose Bay, Labrador, Canada

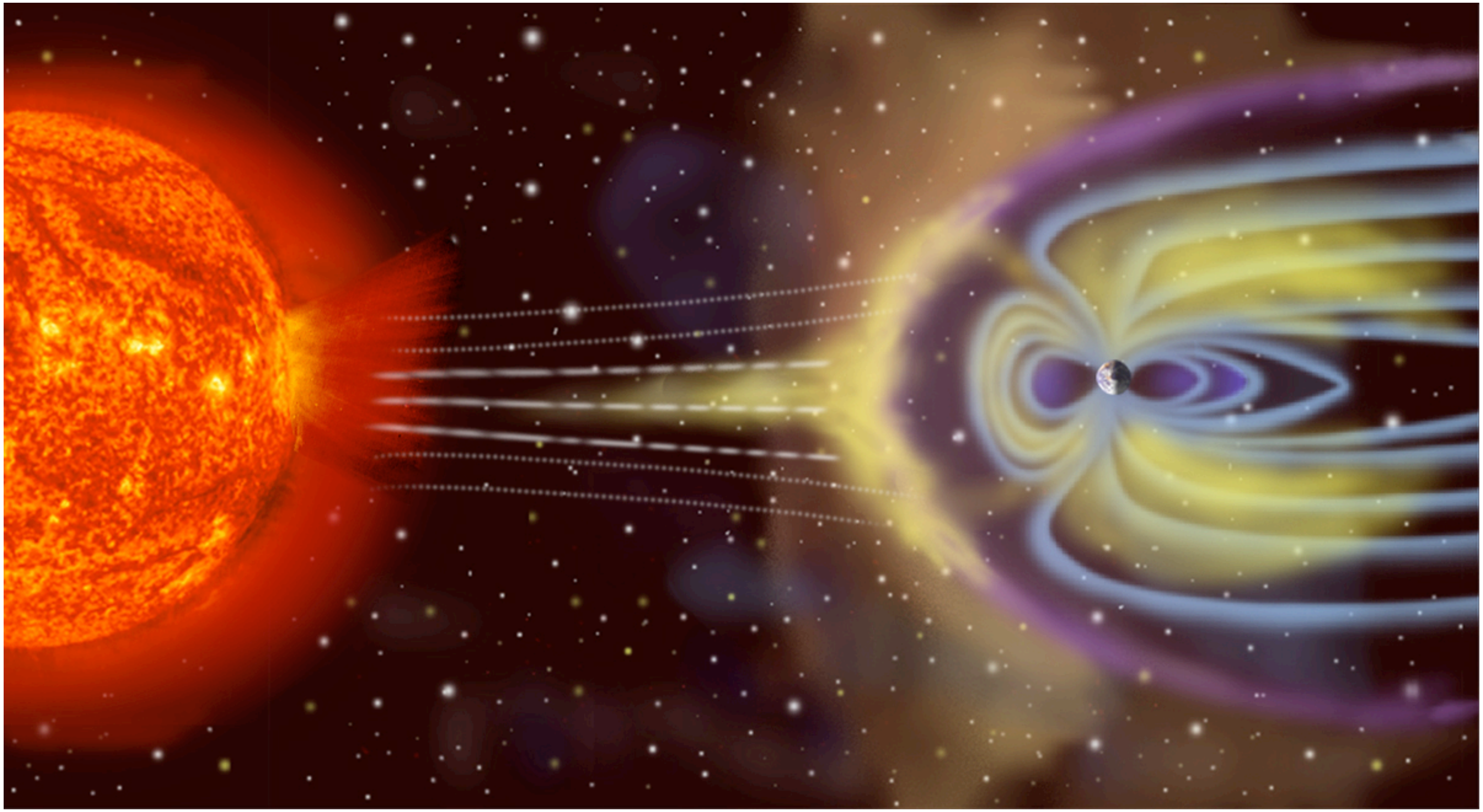


Origins of SuperDARN

- In 1986 a single HF radar operated out of Goose Bay, Labrador
- Build in 1983 by a group out of JHU/APL led by Ray Greenwald that included Kile Baker and J.-P. Villain
- The aim was to demonstrate the viability of using coherent backscatter from the auroral *F* region to study the ionosphere, magnetosphere, and coupling to the solar wind
- Followed by collaborative radar builds with French scientists at Schefferville, Quebec and U.K. scientists at Halley Bay, Antarctica (<1990)
- In the early 1990's discussions led to the founding of the international SuperDARN collaboration (U.S., U.K., Canada, France, Japan, South Africa)

Space weather arises from collision of the Solar Wind with Earth's Magnetosphere

Artist's rendering of a solar flare event

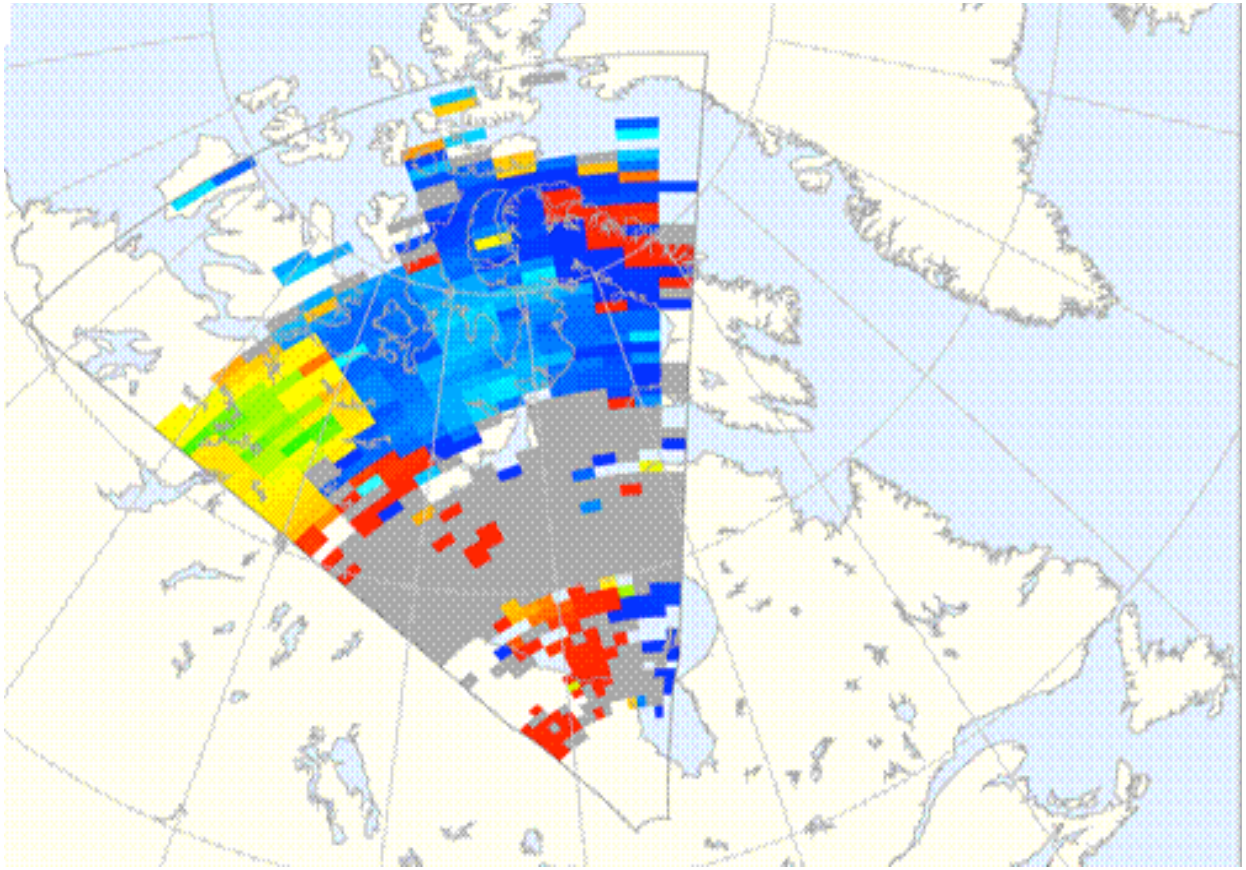


Space weather funnels energy into Earth’s Upper Atmosphere

Photograph of a display of aurora borealis (northern lights)

Mapping the ‘Radar’ Aurora

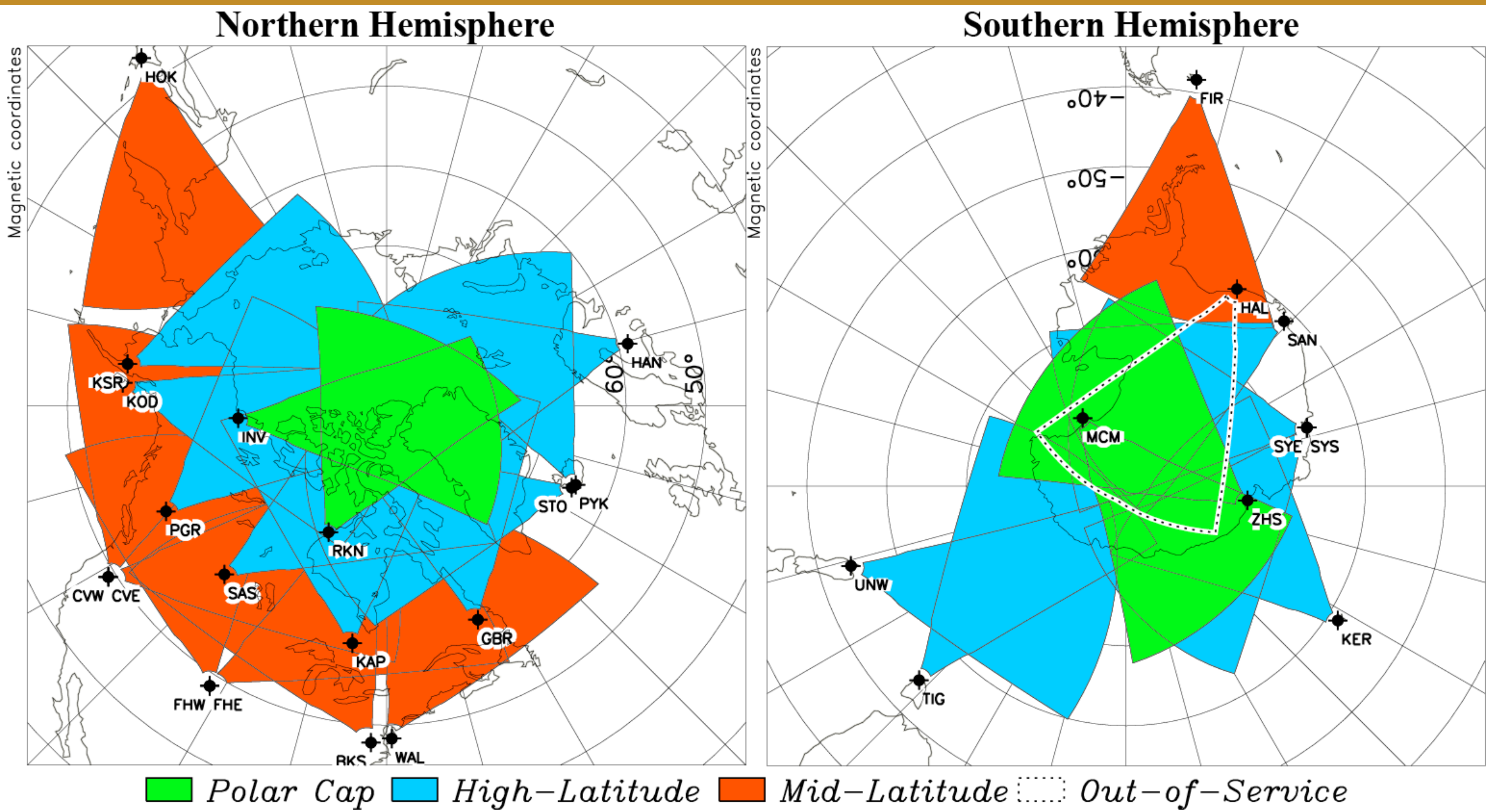
Doppler velocity map obtained form a single 2-min radar scan



Blue - towards
Red - away

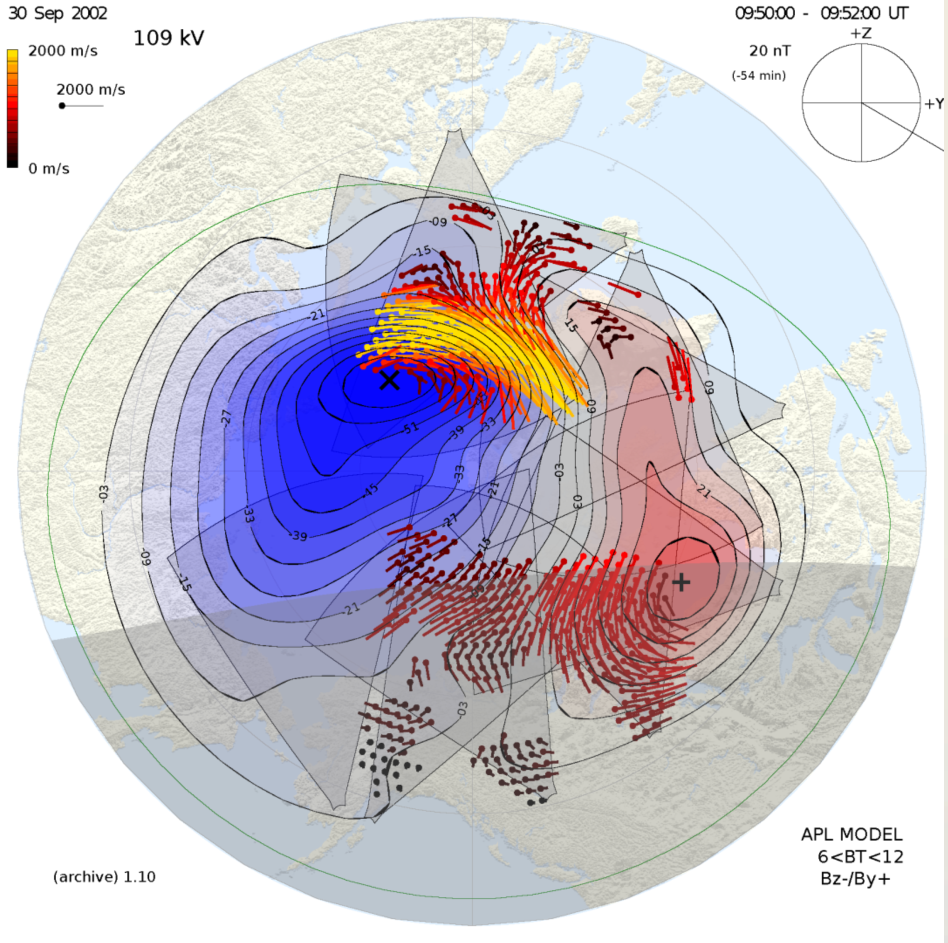
Coverage by the SuperDARN radars

As of September 1, 2011

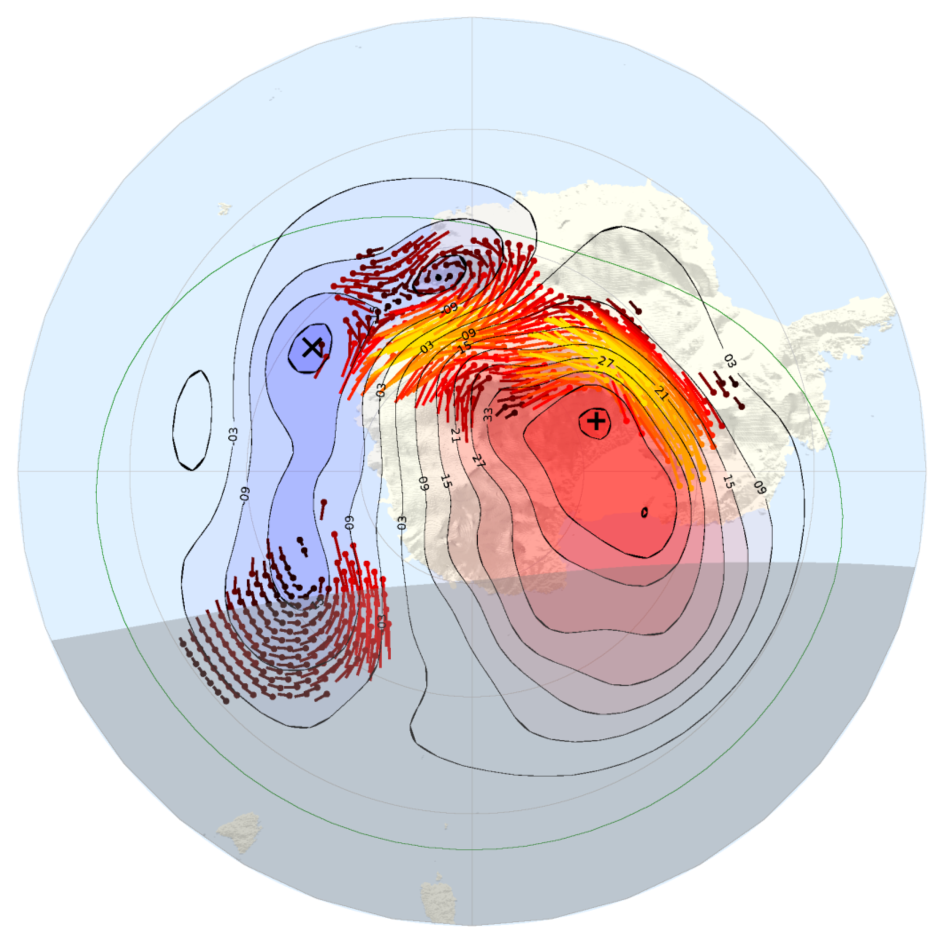


Large-Scale Mapping of Ionospheric Plasma Convection

September 30, 2002: 09:50 – 09:52 UT



Northern Hemisphere



Southern Hemisphere

SuperDARN: A funny name

- Stands for:

  Super Dual Auroral Radar Network

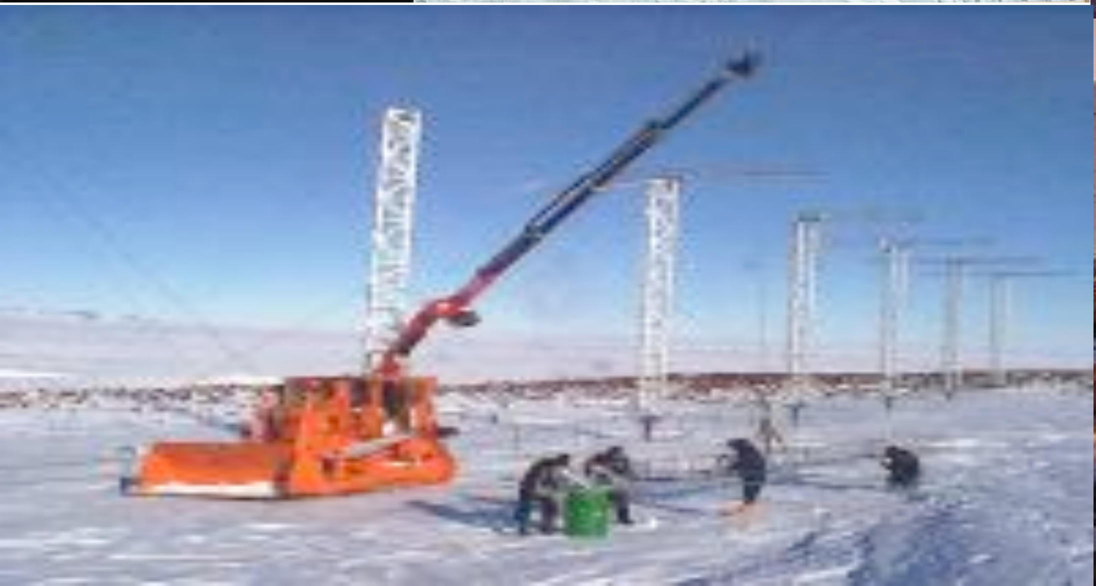
- The radars are oriented in pairs, hence dual, and the network is super because it covers both the northern and southern hemispheres
- SuperDARN is a large international collaboration involving ten countries and 35 radars
- The radars are relatively cheap and operate automatically and all the time
- They monitor the weather in the near-space environment, including the effects of large geomagnetic storms that are due to solar flares

SuperDARN PI Institutions

- Johns Hopkins University Applied Physics Laboratory, USA (1983)
- British Antarctic Survey, UK (1988)
- University of Saskatchewan, Canada (1993)
- Centre National de la Recherche Scientifique, France (1994)
- National Institute for Polar Research, Japan (1995)
- University of Leicester, UK (1995)
- University of KwaZulu-Natal, South Africa (1997)
- La Trobe University, Australia (1999)
- University of Alaska Fairbanks, USA (2000)
- National Institute of Information and Communications Technology , Japan (2001)
- Nagoya University, Japan (2008)
- Virginia Tech, USA (2008)
- Polar Research Institute of China (2010)
- Dartmouth College, USA (2010)
- Institute of Solar Terrestrial Physics, Russia (2012)

Northern Hemisphere Radars, circa 2004

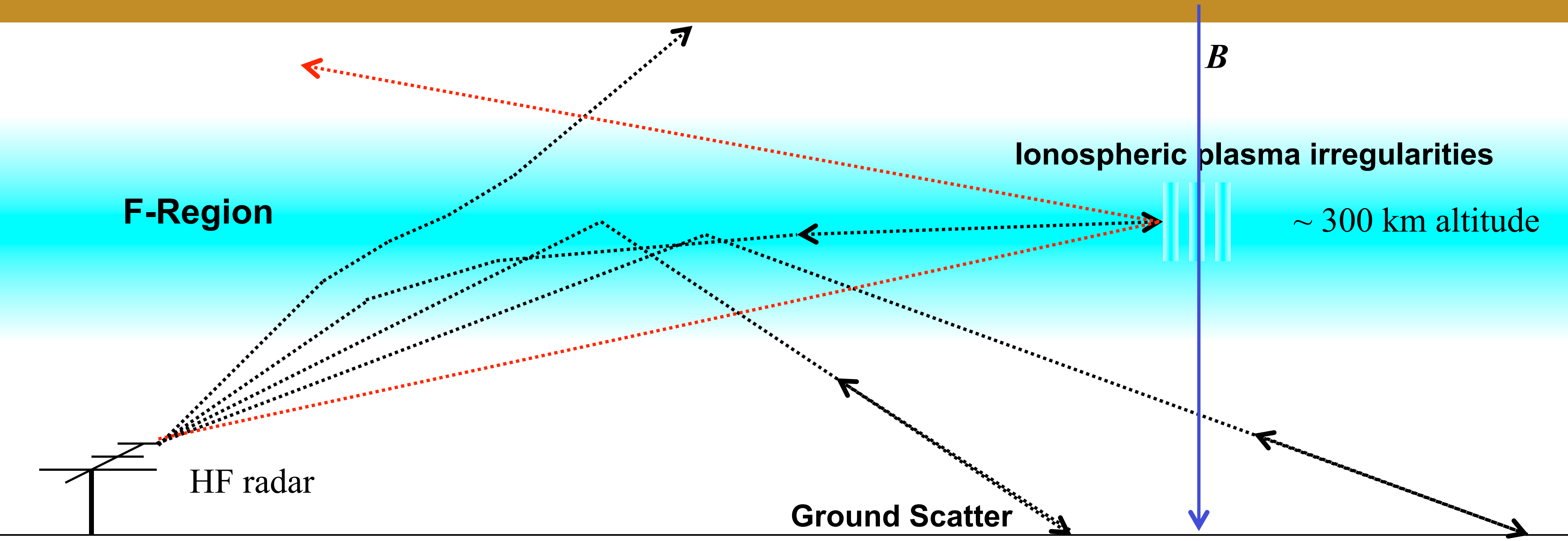
Southern Hemisphere Radars, circa 2004



Primer on Remote Sensing with HF Radar

- High Frequency (HF) radars operate at ~10 MHz (wavelengths of ~30 m)
- An early success of HF radar as a remote sensing device was the discovery of the ionosphere (from reflections)
- The ionosphere is the layer of the atmosphere that contains weakly ionized plasma and extends upwards from about 90 km
- HF rays are bent, or refracted, by the ionosphere and can propagate to great distances leading to:
  - Short wave radio propagation
  - Over-The-Horizon (OTH) radar
- An HF radar can detect scatter from blobs, or irregularities, in the ionosphere and from structure on Earth's surface

Propagation and Reflection of HF Signal



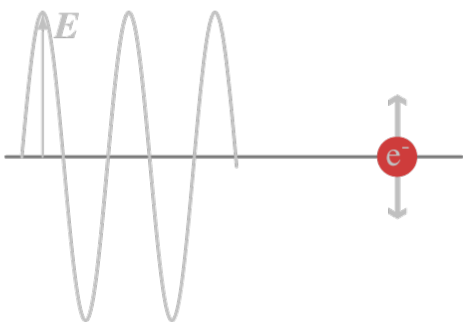
- HF rays are refracted in the ionosphere as they encounter gradients in electron density.
- Transmitted signals can be reflected back to the radar by:

  1) Ionospheric plasma irregularities

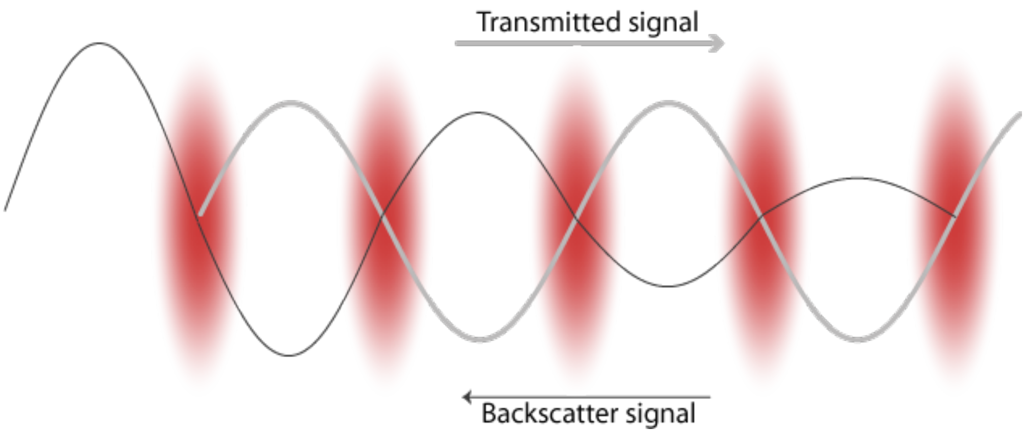
  OR 2) Earth's surface
- Information about the reflectors is carried in the returned signal, e.g., Doppler velocity

Coherent ionospheric scatter

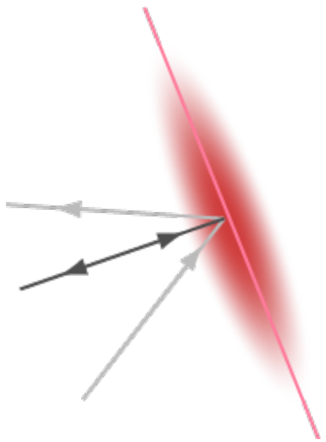
- Conditions required to observe ionospheric scatter with SuperDARN radars



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



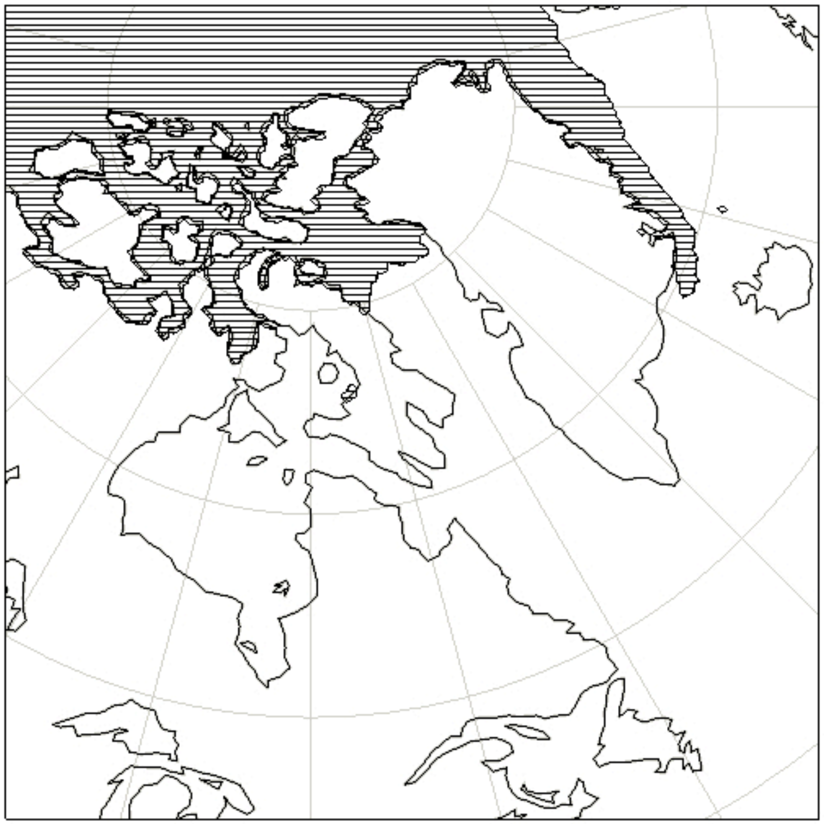
Backscatter is amplified under Bragg conditions by density fluctuations with scale sizes on the order of half the transmitted wavelength.



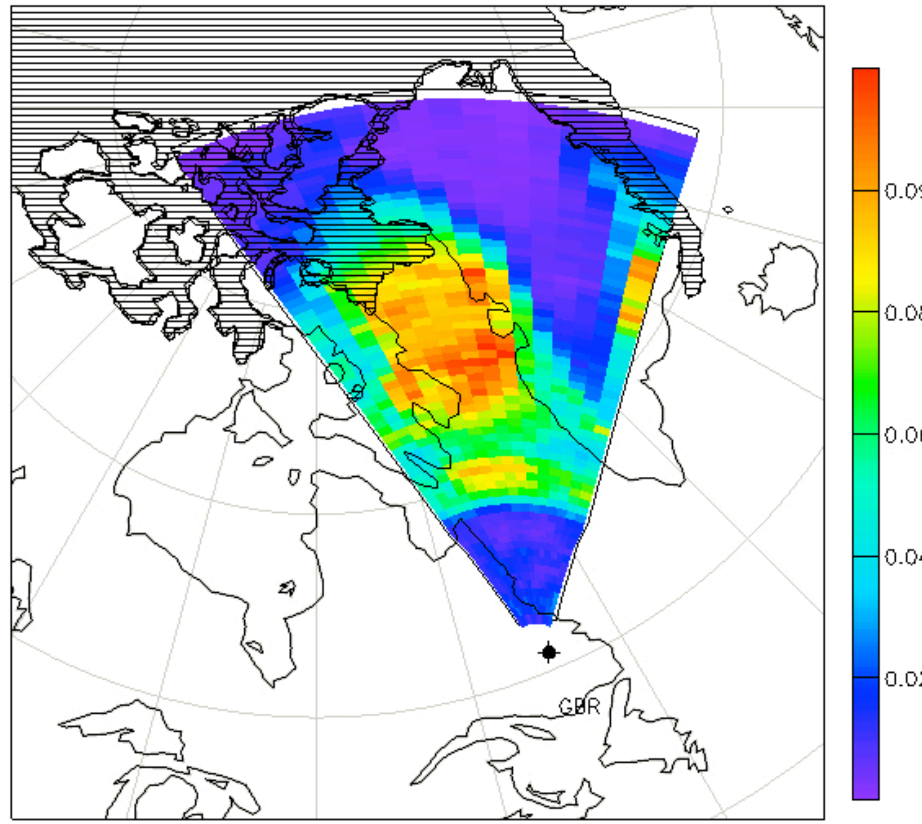
Orthogonality of the transmitted signal with the background magnetic field (aspect condition) guarantees maximum returned power.

Mapping the Roughness of Earth's Surface

Comparison of sea ice cover and HF radar observations



- Furthest extent of sea ice cover during month of October 2000 (National Snow and Ice Data Center, Boulder, CO).

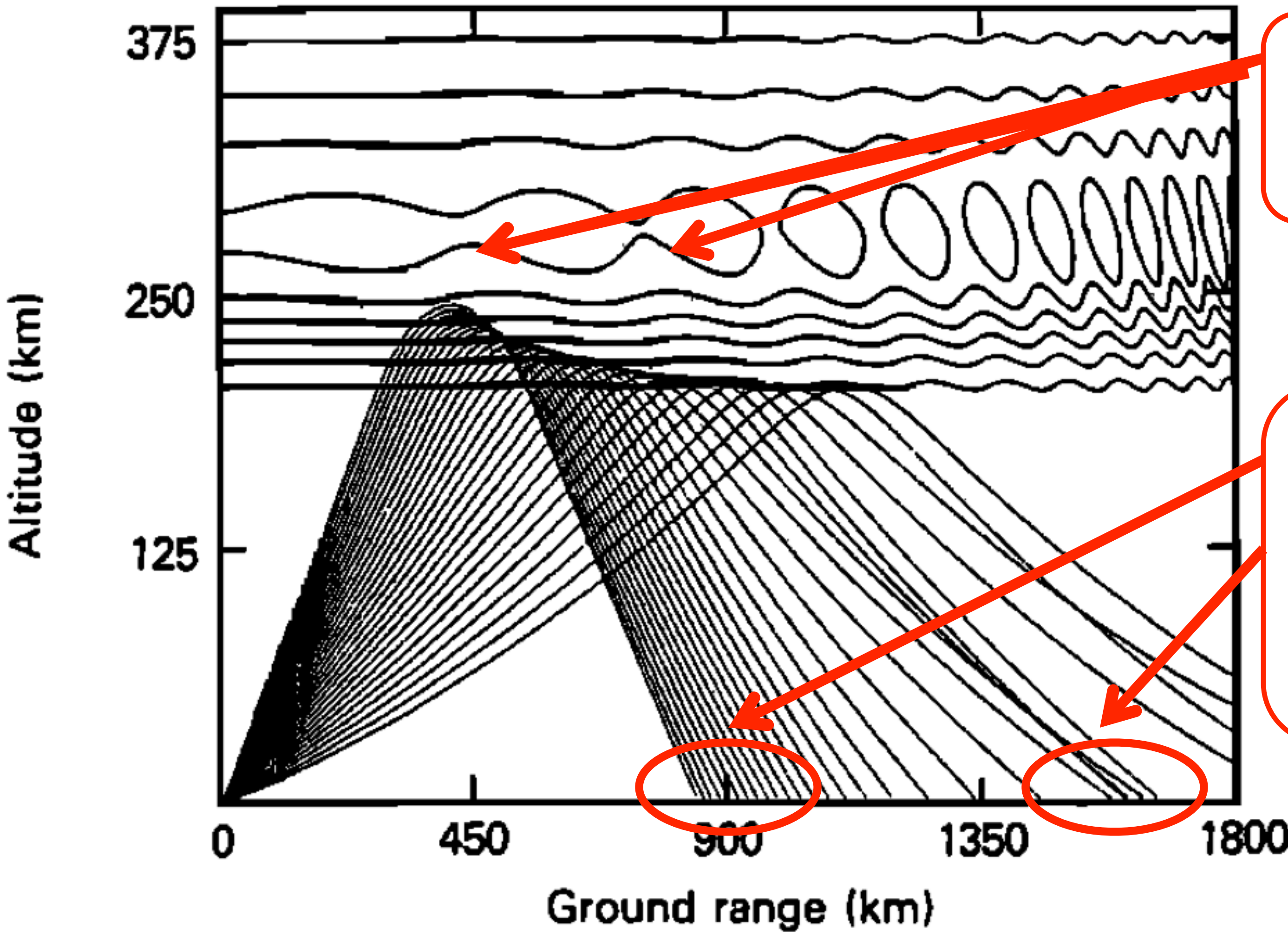


- Ground scatter occurrence rate observed by the radar at Goose Bay during daytime over the month of October 2000.

Waves in Earth's Atmosphere

Time lapse of gravity wave action from the Tama, Iowa KCCI-TV webcam on 6 May 2007.
[*http://www.youtube.com/watch?v=yXnkzeCU3bE*]

HF Ray Paths during Gravity Wave Events



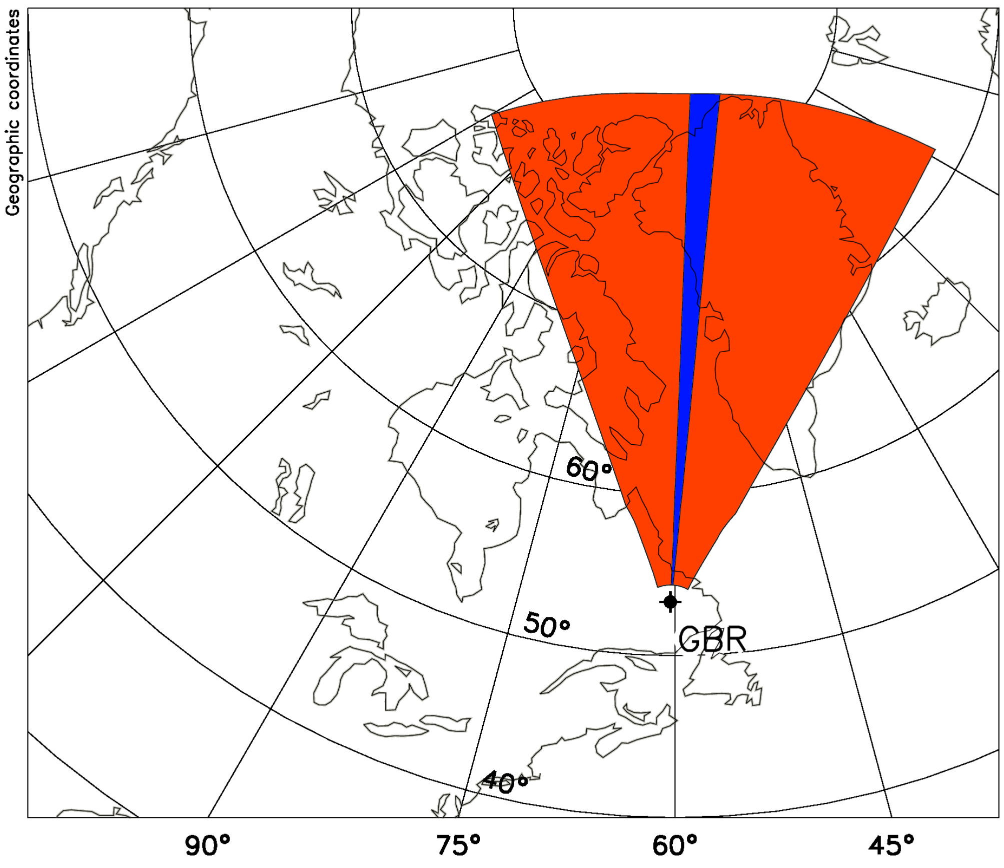
Gravity Wave Causes Moving Ionospheric Concavities

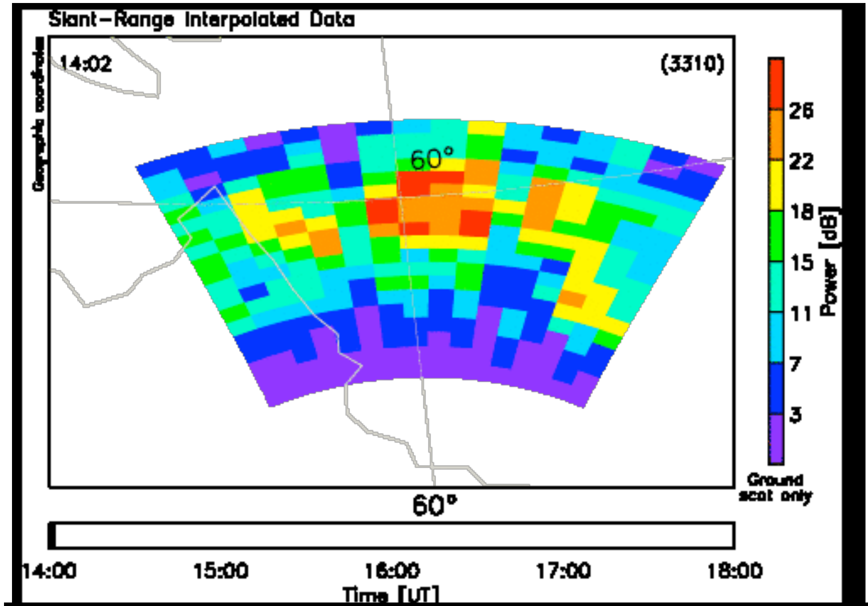
Concavities focus radar beams, therefore resulting in stronger backscatter at these locations.

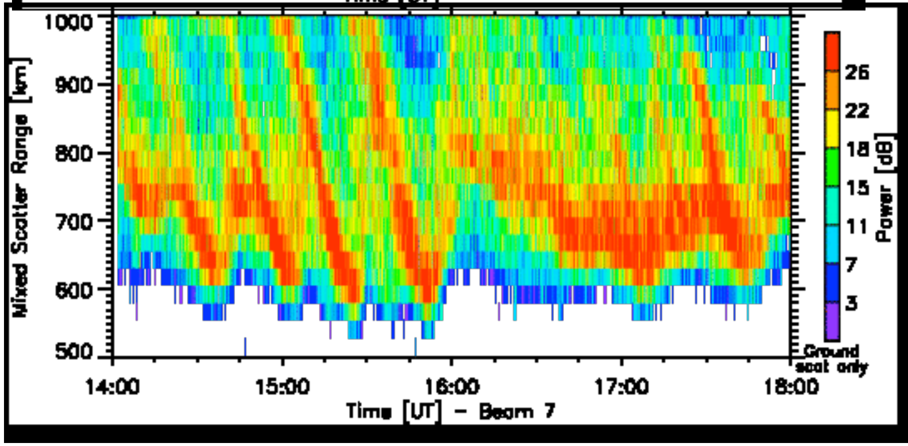
[*Bristow et al.*, 1994]

HF Radar Observations of Atmospheric Gravity Waves

Goose Bay Radar (GBR)
19 November 2010



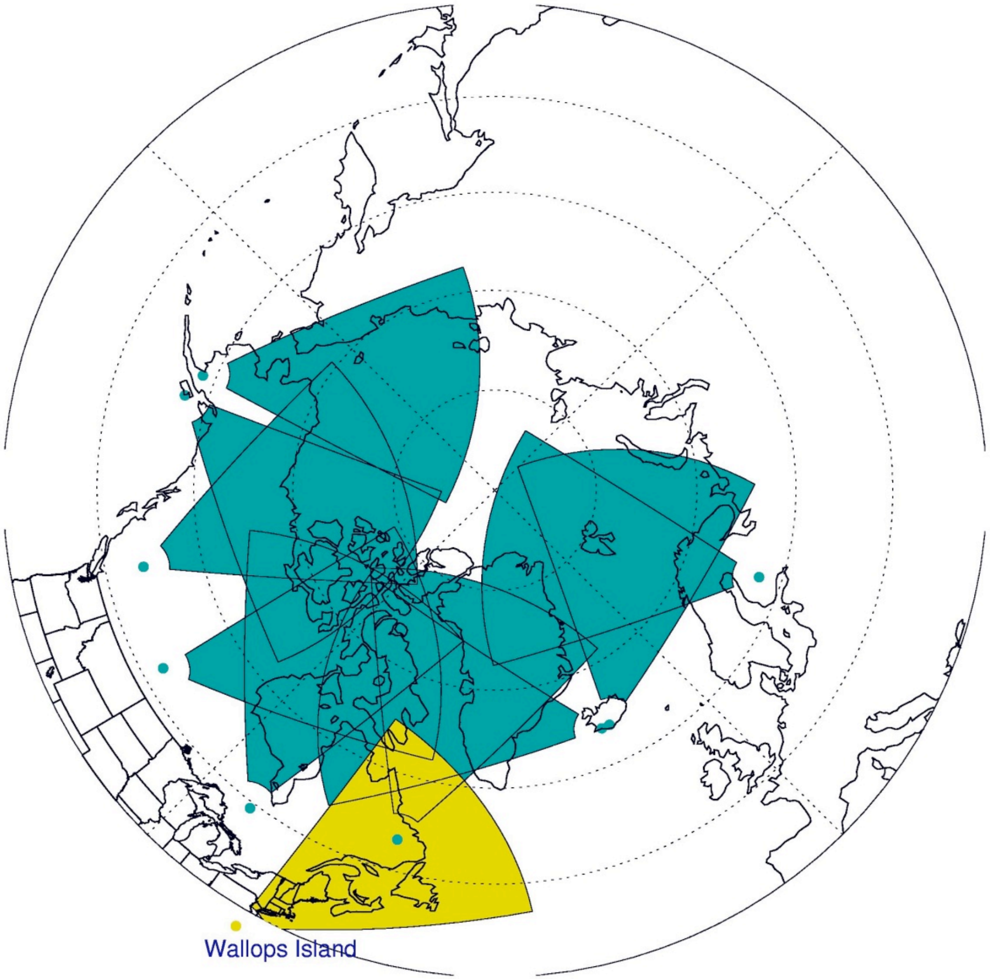




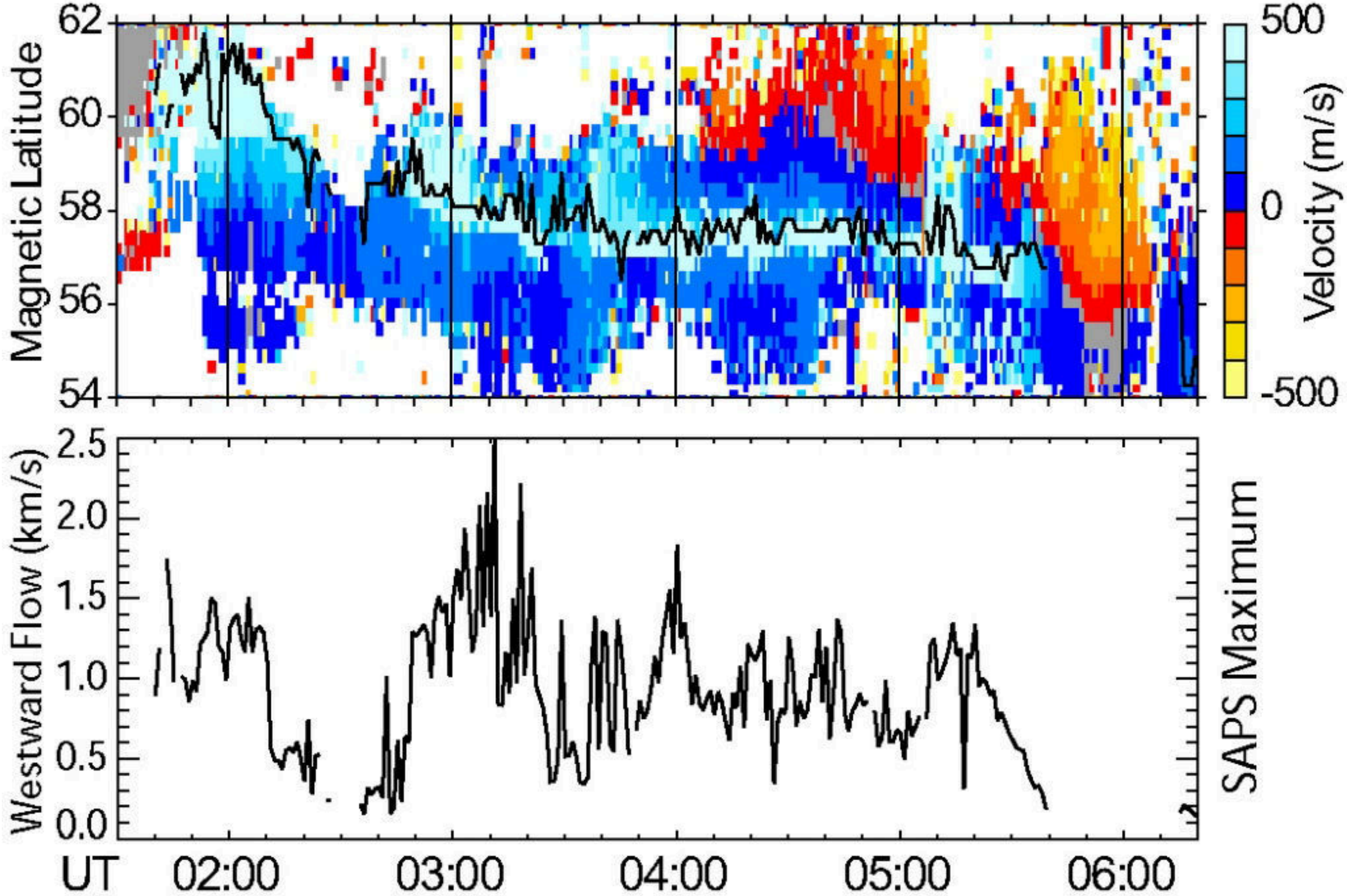
SuperDARN radar at mid-latitudes

- First radar was built at NASA Wallops Flight Facility in 2005, a collaboration between JHU/APL and NASA/GSFC
- Demonstrated the viability of the HF technique at mid-latitudes
- Observed storm effects such as SAPS (expected)
- Observed backscatter from the quiet–time nightside ionosphere (unexpected)
- Second radar was built at Blackstone, Virginia, a collaboration between JHU/APL, Virginia Tech, and Leicester University (U.K.)
- Joint observations have been conducted between these radars and MIT/Haystack radars

Wallops Island: First SuperDARN mid-latitude radar

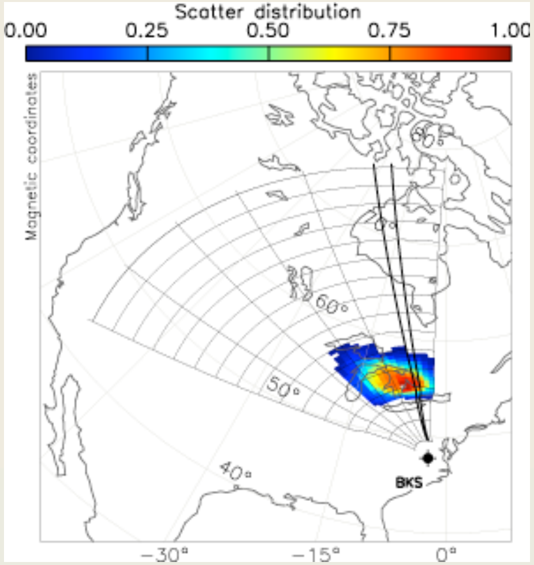


StormDARN: Example of subauroral (SAPS) flow from Wallops observations

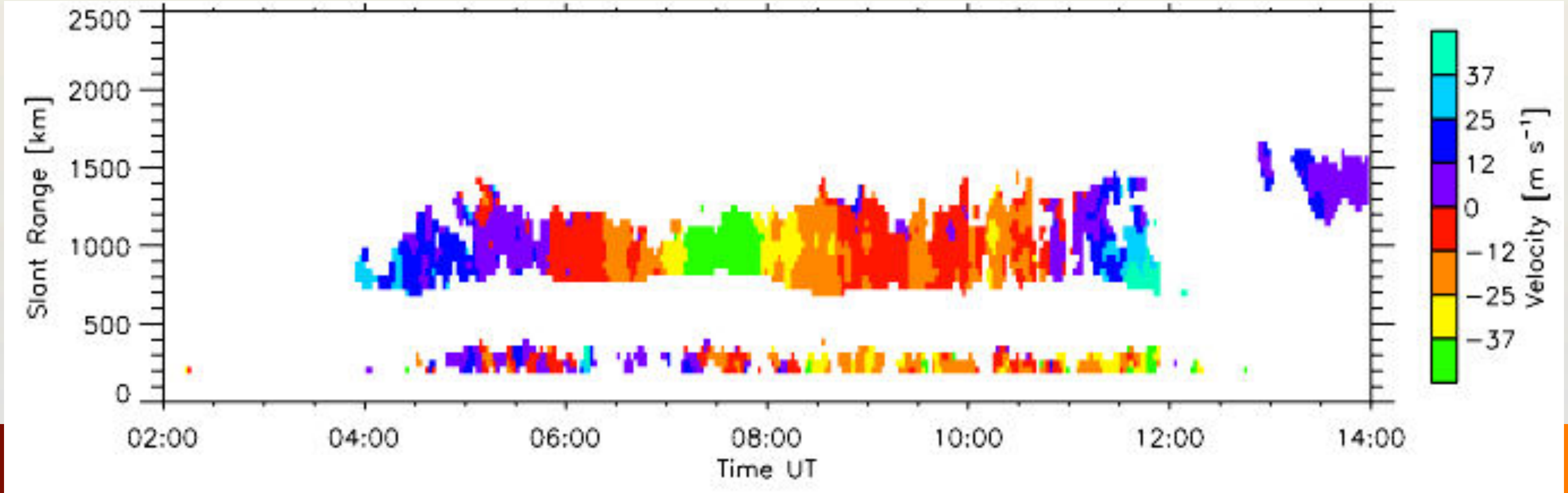


(after *Oksavik et al.* [2007])

A Surprise! HF backscatter during quiet times from the nightside subauroral ionosphere



- Backscatter is common and indicates that the nightside subauroral ionosphere is full of irregularities
- Low velocity and narrow spectral width
- Provides views of the electric fields in the conjugate region of the inner magnetosphere
- Plot of 1-night backscatter occurrence (*left*) and velocity time series (*below*) along indicated beam for a night of observations from Blackstone



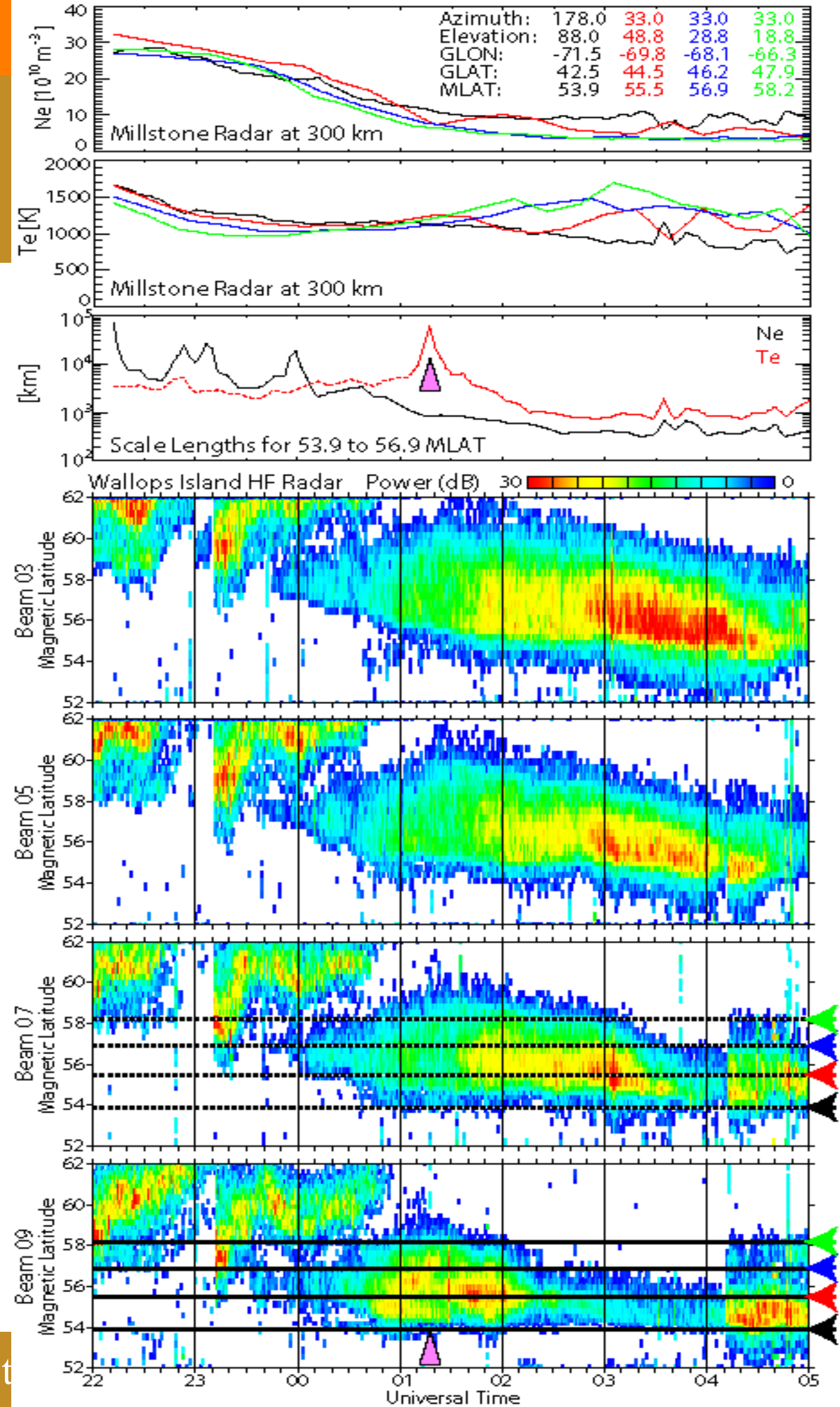
Joint Radar studies of the Causes of Mid-Latitude Ionospheric Irregularities

An early coordinated experiment between Millstone Hill Observatory and Wallops indicated that the temperature gradient instability (TGI) as a primary factor

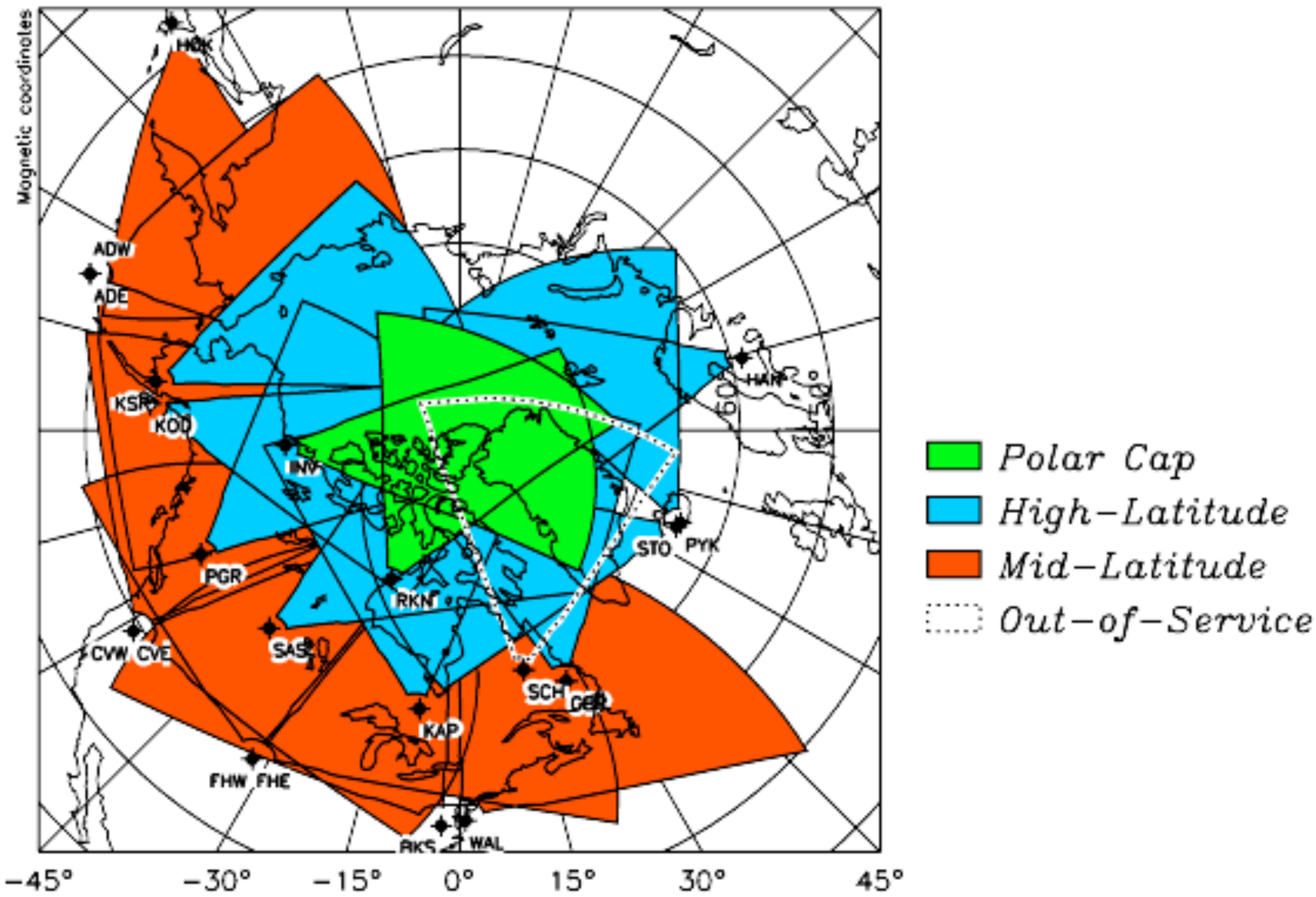
Plots show time series of HF backscatter power and MHO density and temperature gradients

2200 – 0500 UTC 2006-02-22
2200 – 2340: Ground refracted scatter
2340 – 0140: GDI or trough wall or zonal gradient (seen before). TGI not active yet.
0140 onwards: TGI conditions present as Te gradient changes sign.

(after *Greenwald et al.* [2007])



Expansion of SuperDARN to Mid-Latitudes



Aerial view of the Fort Hays SuperDARN radar site located near Hays, Kansas

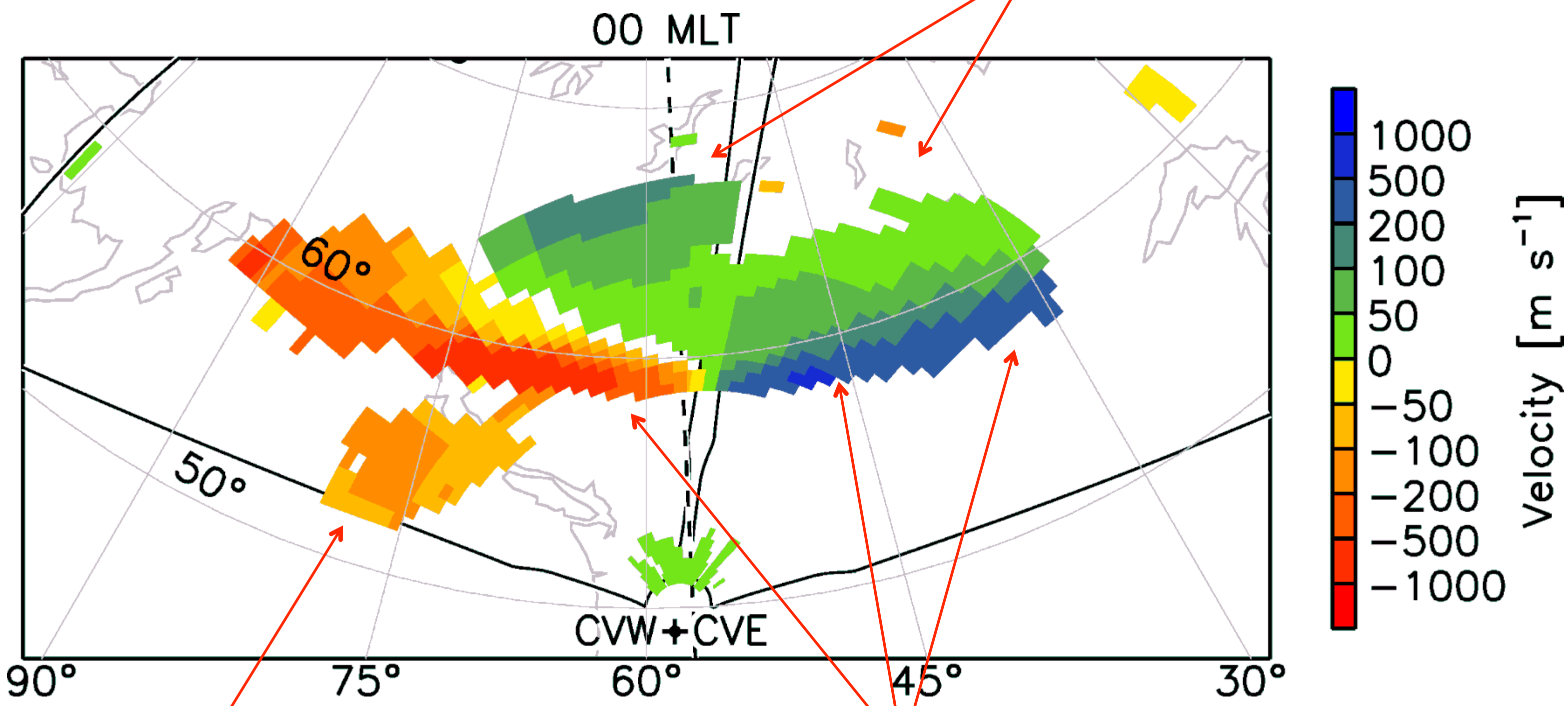
Each of the two radars is associated with a pairing of longer and shorter antenna arrays.

The transmitters and control electronics for both radars are housed in the centrally located shelter.

Line-of-sight velocity measurements

O840 UT

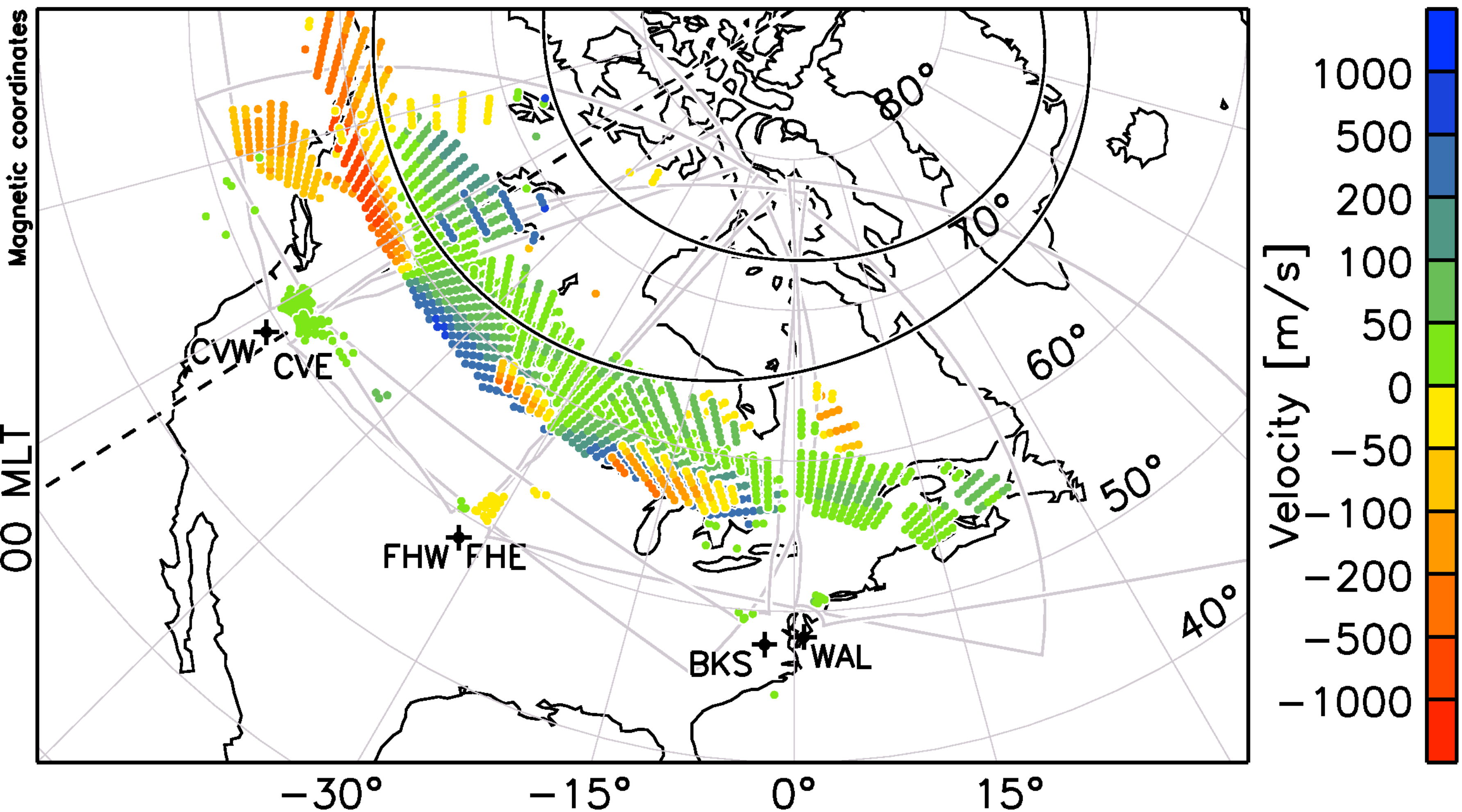
Auroral oval



Subauroral region (*Riberio et al.* [2011])

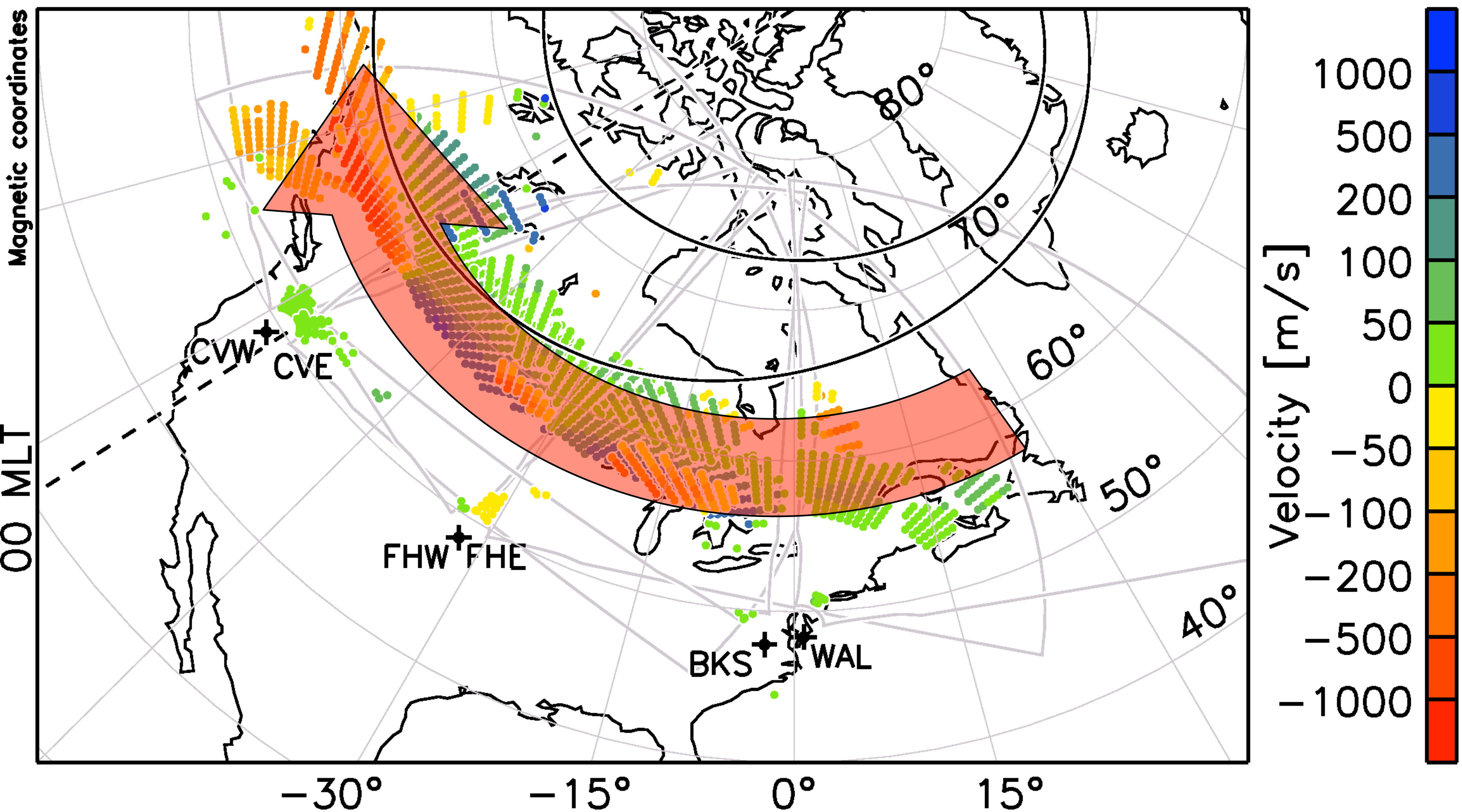
SAPS channel (*Oksavik et al.* [2006])

MSI SuperDARN: First Extended, Instantaneous Image of a SAPS Flow Channel



Map of Line-of-Sight Velocities for 08:40 UT, March 9th, 2011 (after *Clausen et al.* [2012])

MSI SuperDARN: First Extended, Instantaneous Image of a SAPS Flow Channel

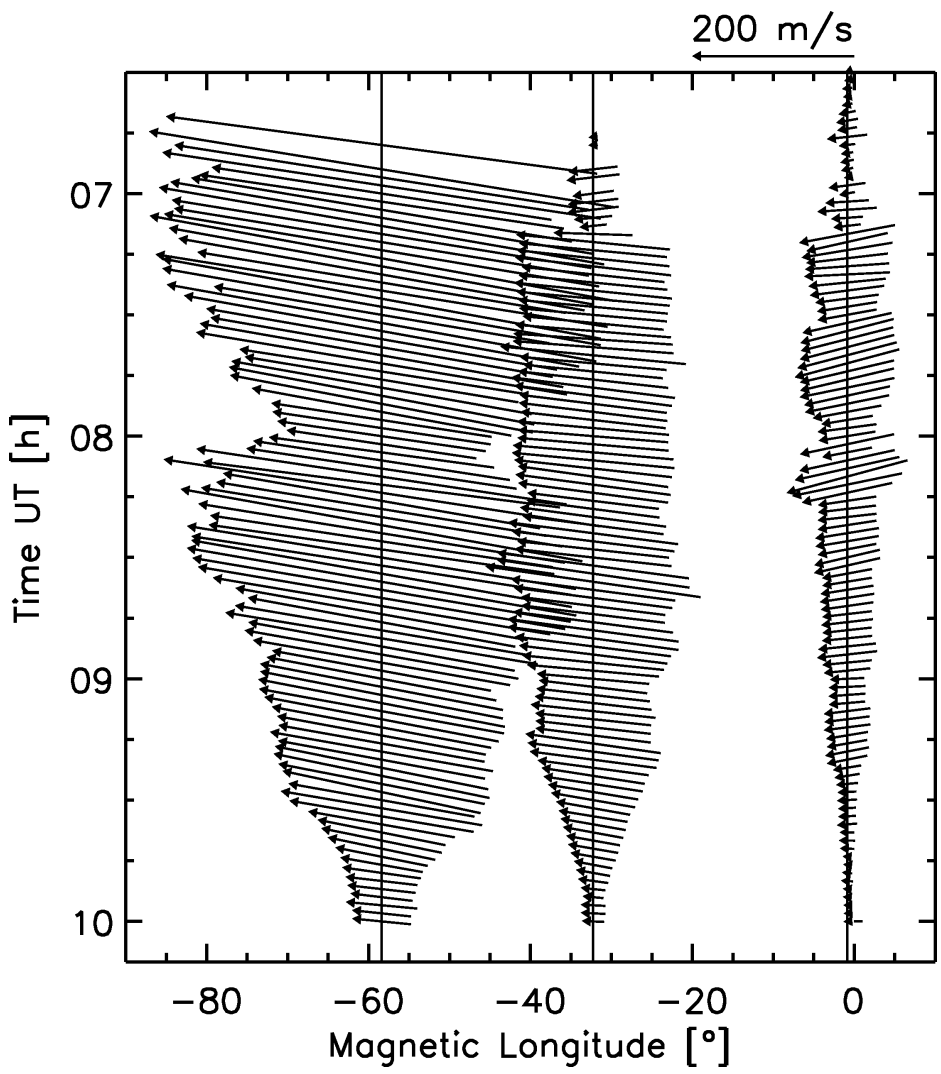


Map of Line-of-Sight Velocities for 08:40 UT, March 9th, 2011 (after *Clausen et al.* [2012])

April 9, 2011 - Inferred SAPS Velocities versus UT

Analysis of the peak velocities seen across pairs of radar observations produces estimates of SAPS velocity versus time and MLT

Storm-time SAPS in the SuperDARN observations span many hours of MLT for long periods of UT



Summary of SAPS Observations (Clausen event)

- A high-speed SAPS feature covered about 3 deg of latitude and extended continuously across the fields of view of the mid-latitude radars through 6 hours of MLT.

- Simultaneous POES-18 satellite data indicate that the band was located 2-3 deg equatorward of the electron precipitation boundary (auroral oval).

- The plasma velocities within the band were westward; the velocity magnitudes exceeded 1 km/sec near midnight MLT and decreased through the morning sector.

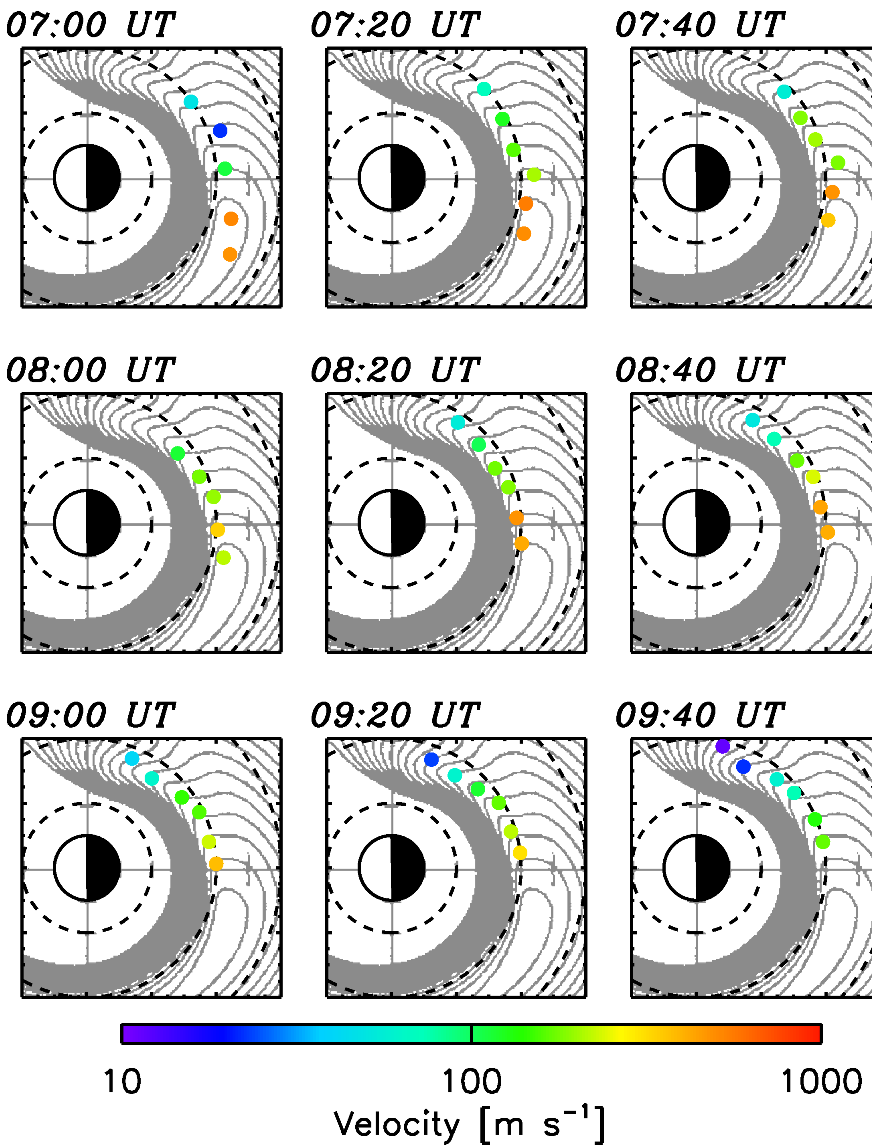
- Consistent with known statistical properties of SAPS, e.g., *Foster and Vo* [2002], *Erickson et al.* [2011].

Projection of the SAPS into the Equatorial Plane

Locations of SAPS velocity maxima were mapped using T95 (colored dots).

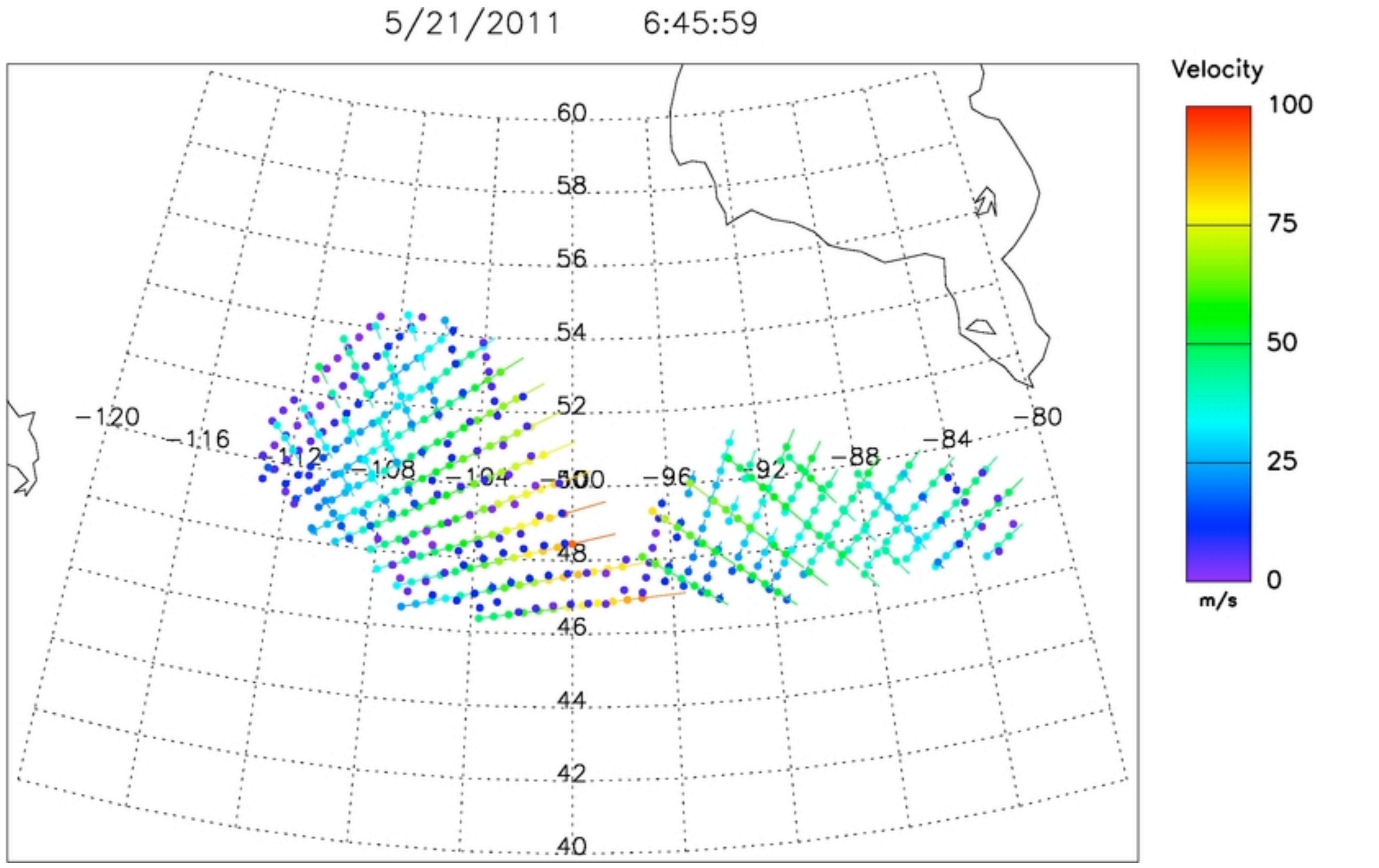
The variation in geocentric distance with MLT is consistent with *Erickson et al.* [2011].

Contours of constant plasma pressure are taken from an RCM run by *Toffoletto et al.* [2003] with Dst ~ -100 nT. Note similarity of trends with MLT.



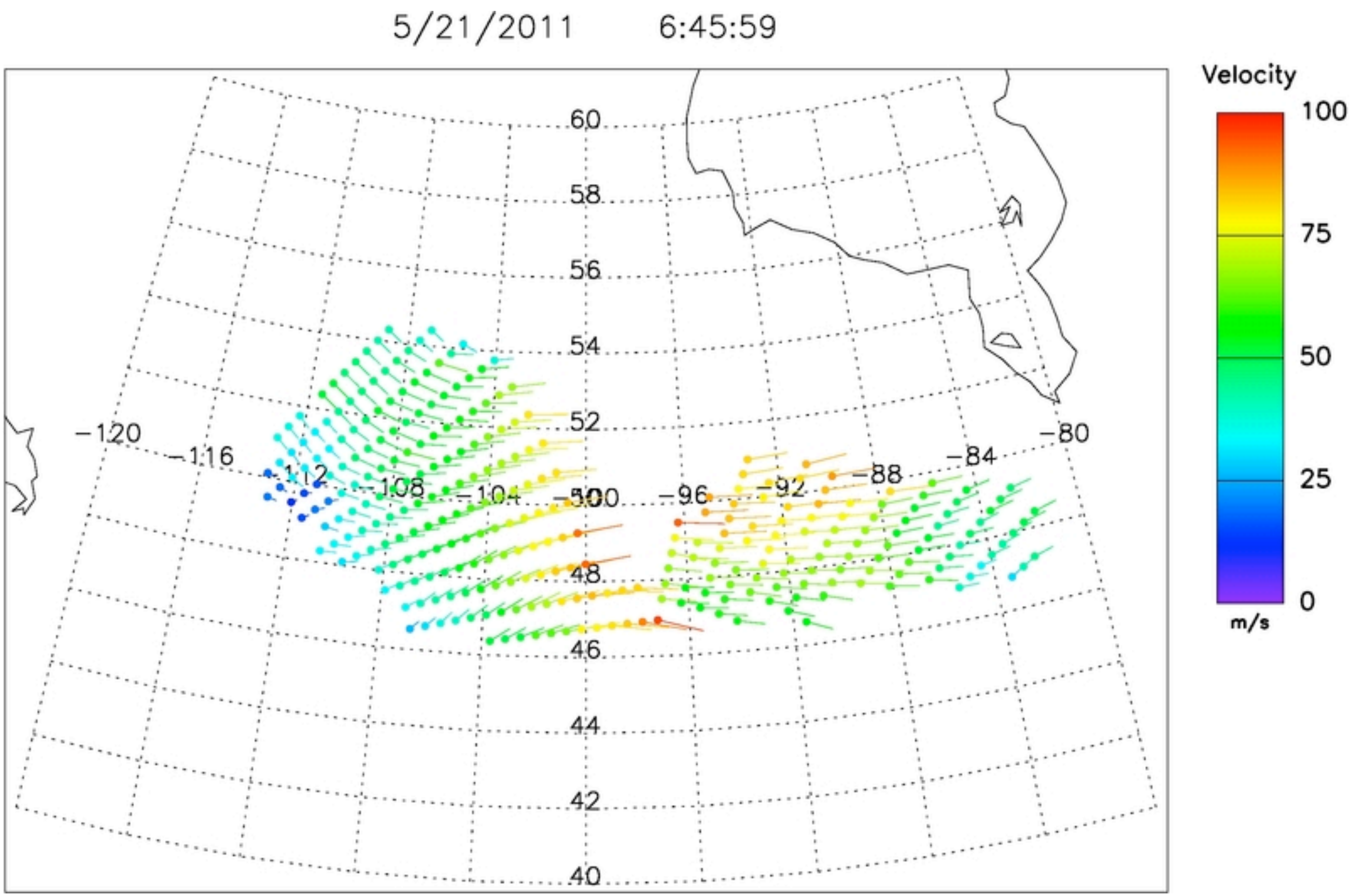
Extended Observations of Mid-Latitude Plasma Convection

Common-volume line-of-sight velocities measured by radars in Oregon and Kansas



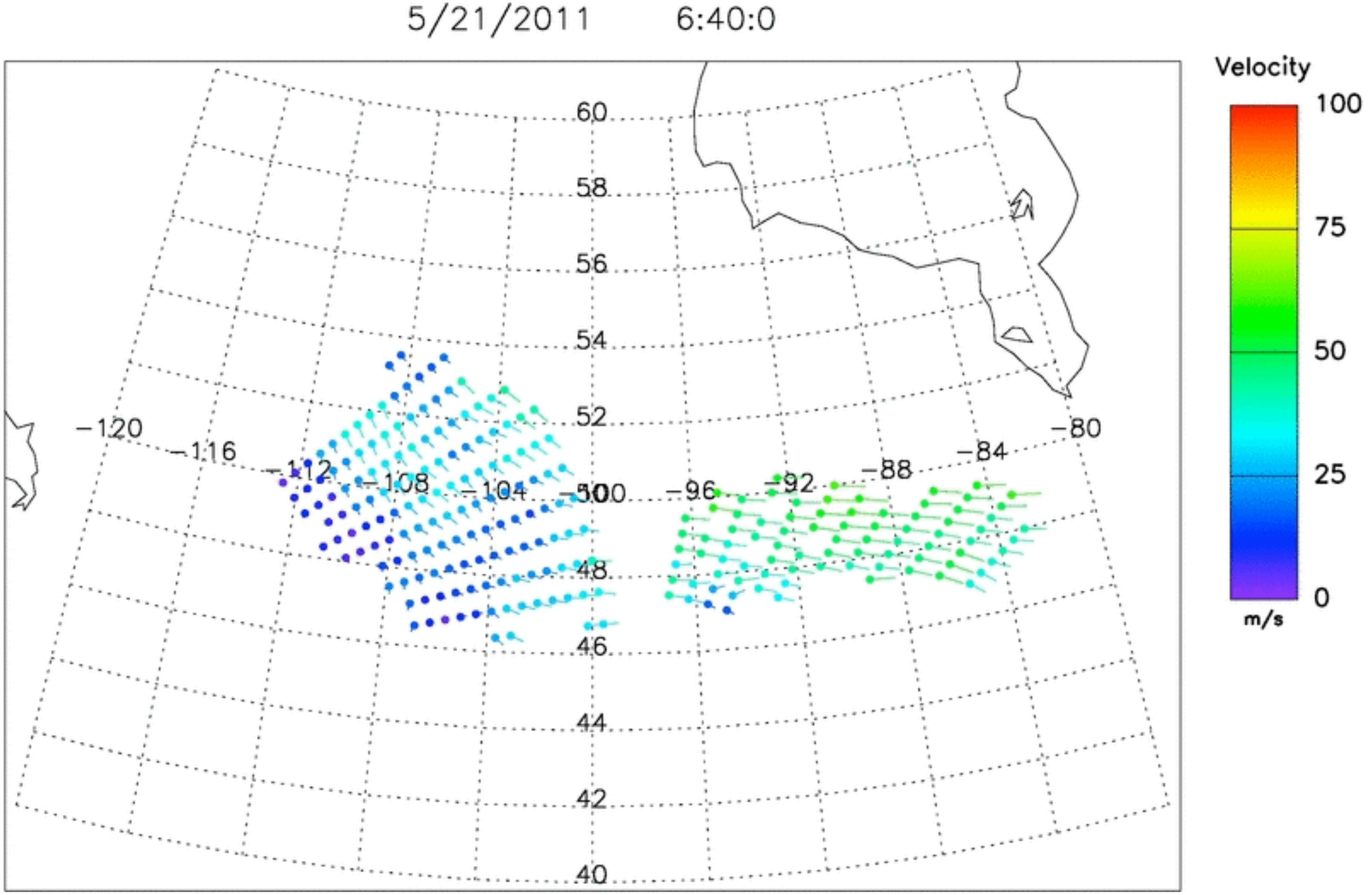
Mapping Plasma Motion in the Ionosphere

Map of merged two-dimensional plasma velocity vectors

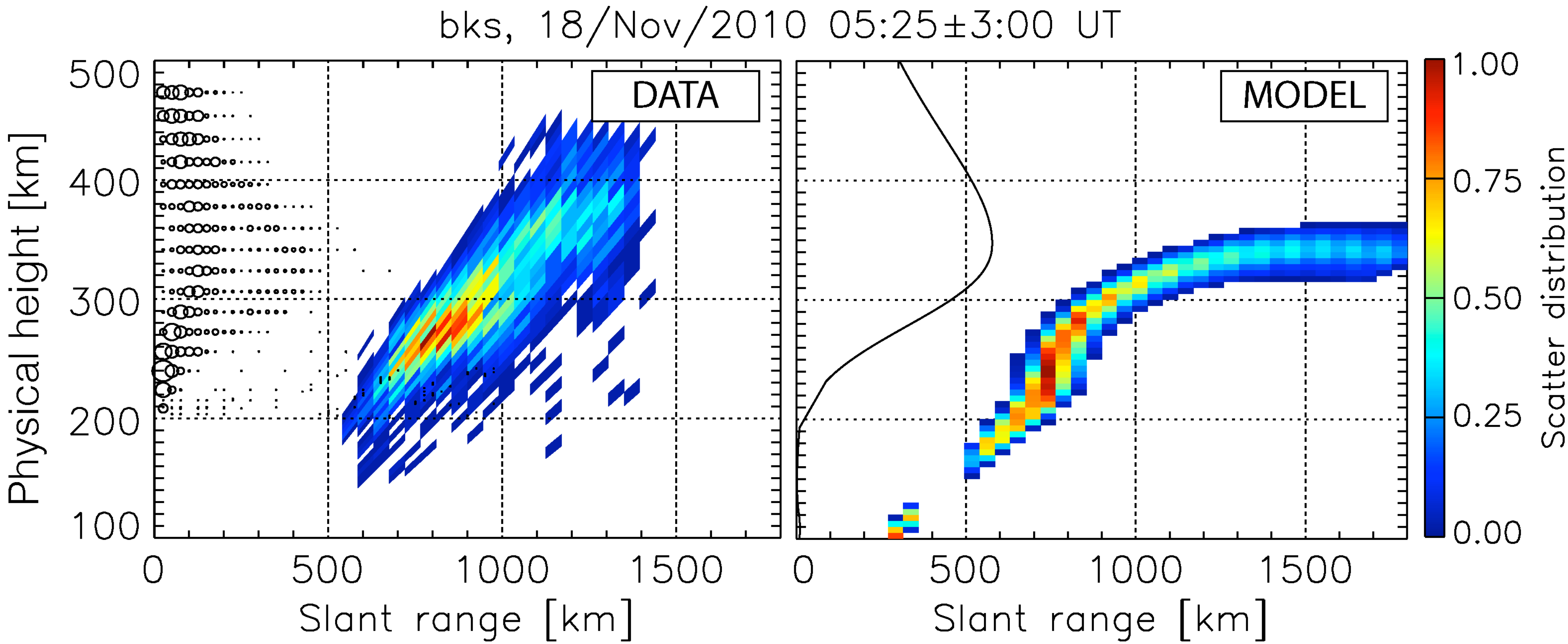


Mapping Plasma Motion in the Ionosphere

Twenty-minute movie of ionospheric plasma 'winds'



Studies of Mid-Latitude Irregularities with



Altitude versus slant range plots of quiet –time subauroral backscatter from SuperDARN (color) and of electron densities from MHO (bubbles) and from the IRI model (line). As suggested by the comparison to the model, the observations with MHO indicate that the irregularities occur mostly below the F-region peak.

VT-MIT Collaboration on GPS/TEC

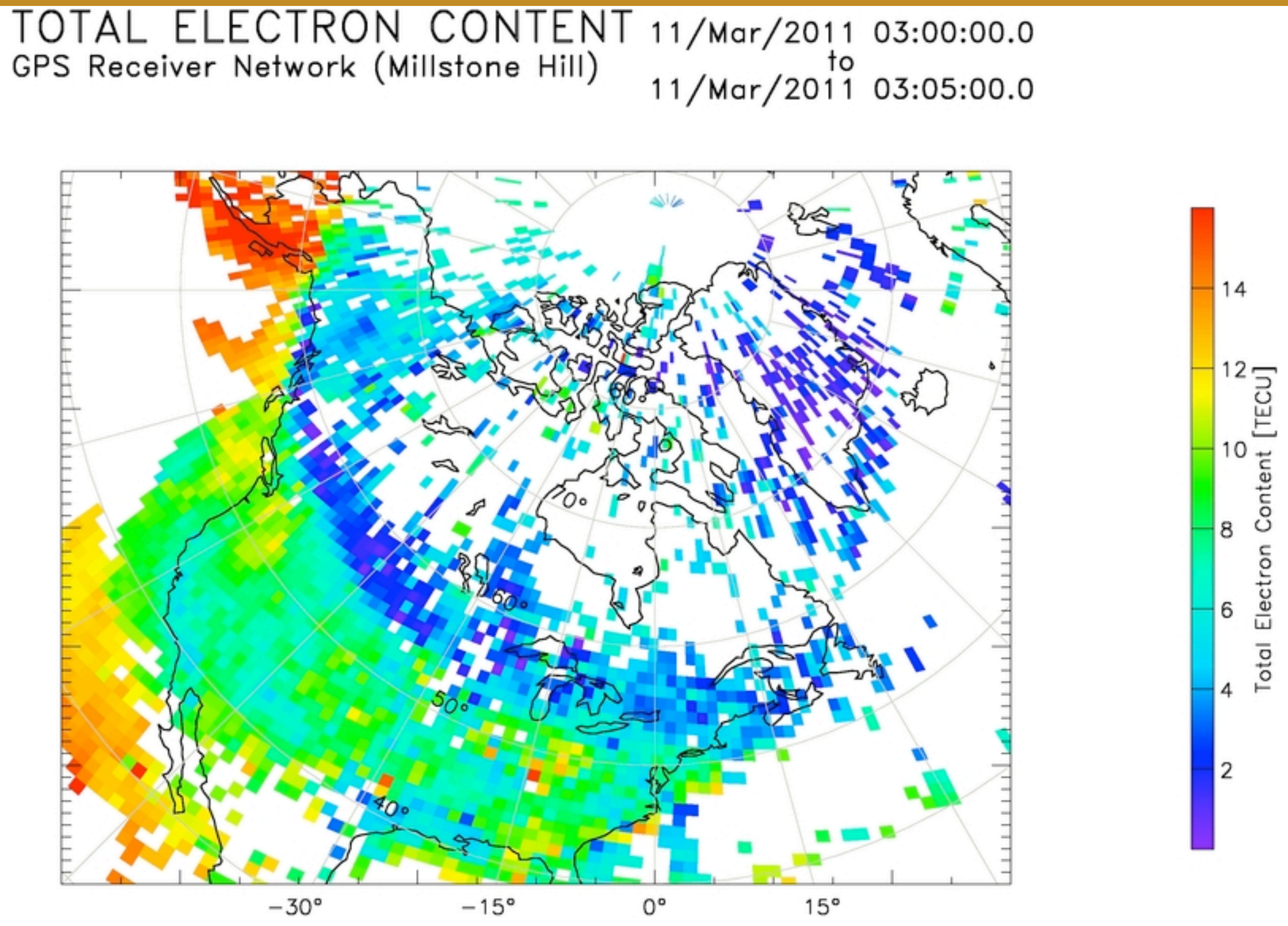
- The Virginia Tech effort to integrate GPS Total Electron Content data with SuperDARN began after a conversation between graduate student Evan Thomas and Dr. Anthea Coster at the 2010 AMISR Student Workshop, hosted at MIT Haystack Observatory.

- After returning to Virginia Tech, Evan began writing a new set of software tools to download and plot the GPS TEC data with valuable support from Anthea and Bill Rideout.

- The first online interactive TEC/SuperDARN plotting tool went live in November 2010 and first results were presented at the 2011 Joint CEDAR-GEM Workshop in Santa Fe, NM.

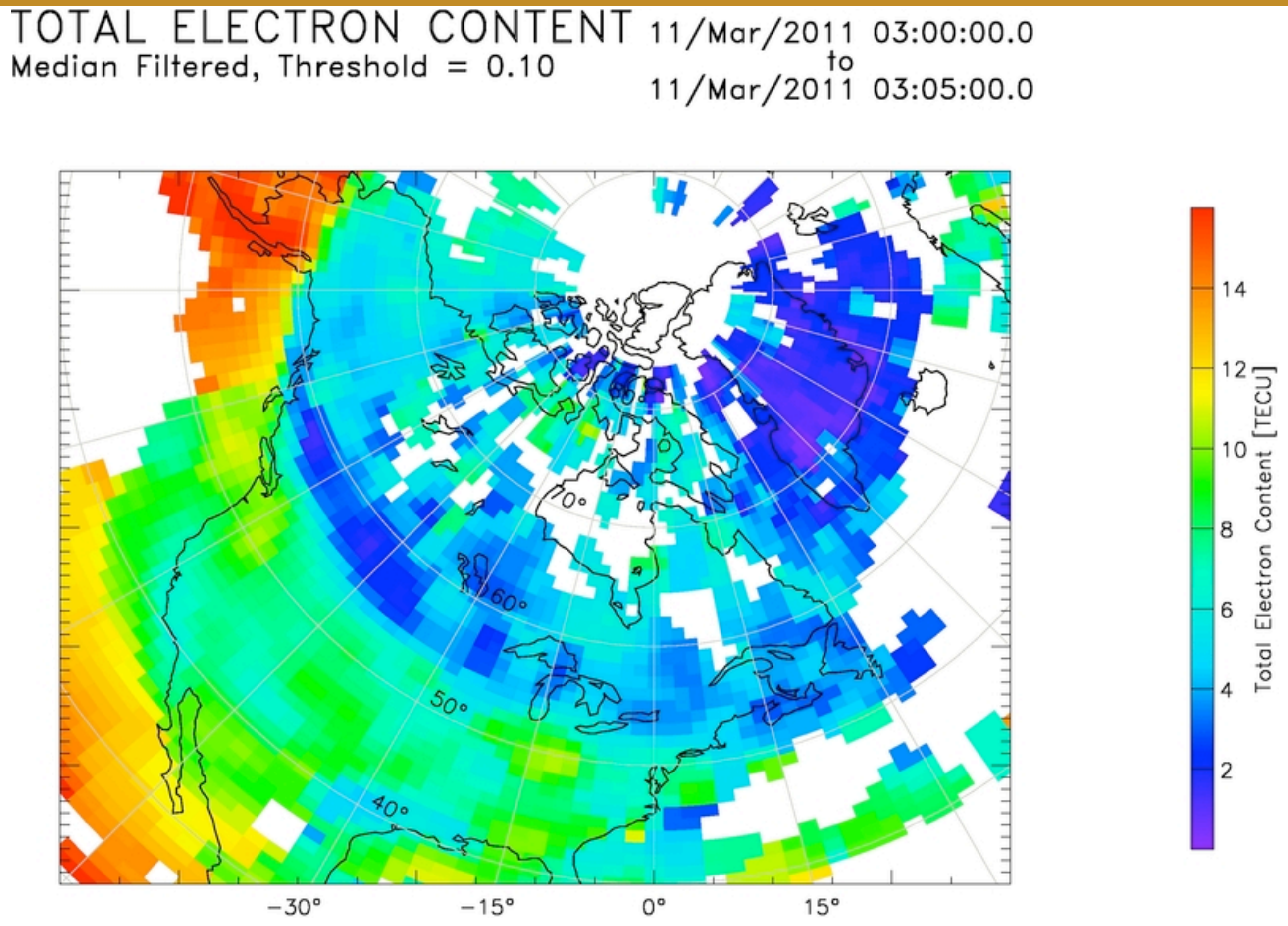
GPS/TEC Plotting

VirginiaTech
Invent the Future®



Plot of unfiltered TEC values over North America for March 11th, 2011 created on the GPS/TEC Plot page of the VT website.

GPS/TEC Plotting



Plot of median filtered TEC values over North America for March 11th, 2011 created on the GPS/TEC Plot page of the VT website.

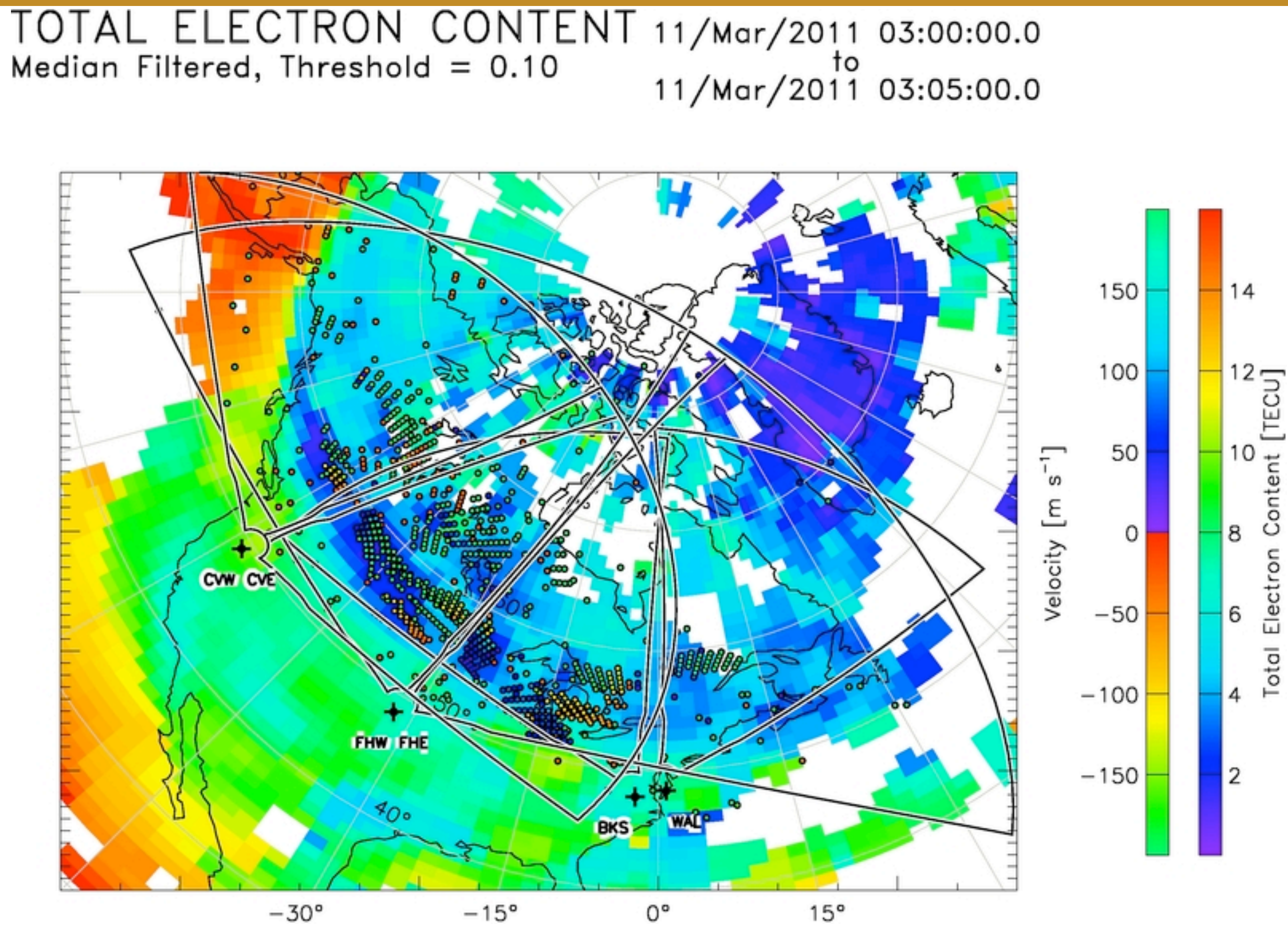
GPS/TEC Plotting

- Our goal is to make large-scale observations of ionospheric irregularities utilizing the new chain of mid-latitude radars in conjunction with global total electron content (TEC) data.

- TEC data has been downloaded from the Madrigal website at Millstone Hill for all processed days from Jan. 1st, 2007 to present.

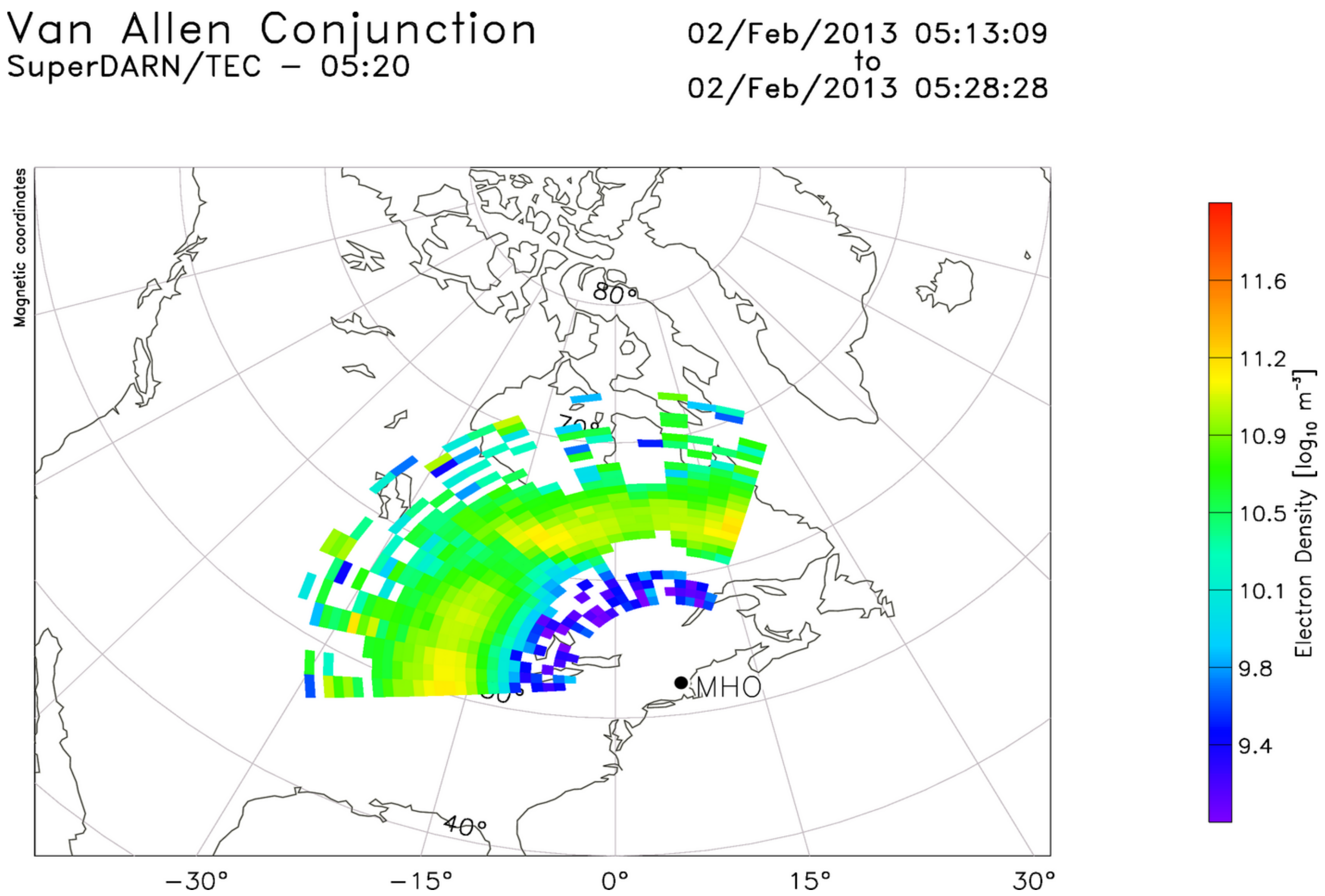
- This TEC data is now available for plotting on the VT SuperDARN website with overlays of radar measurements in a variety of formats (e.g. contours of electrostatic potential).

GPS/TEC & SuperDARN

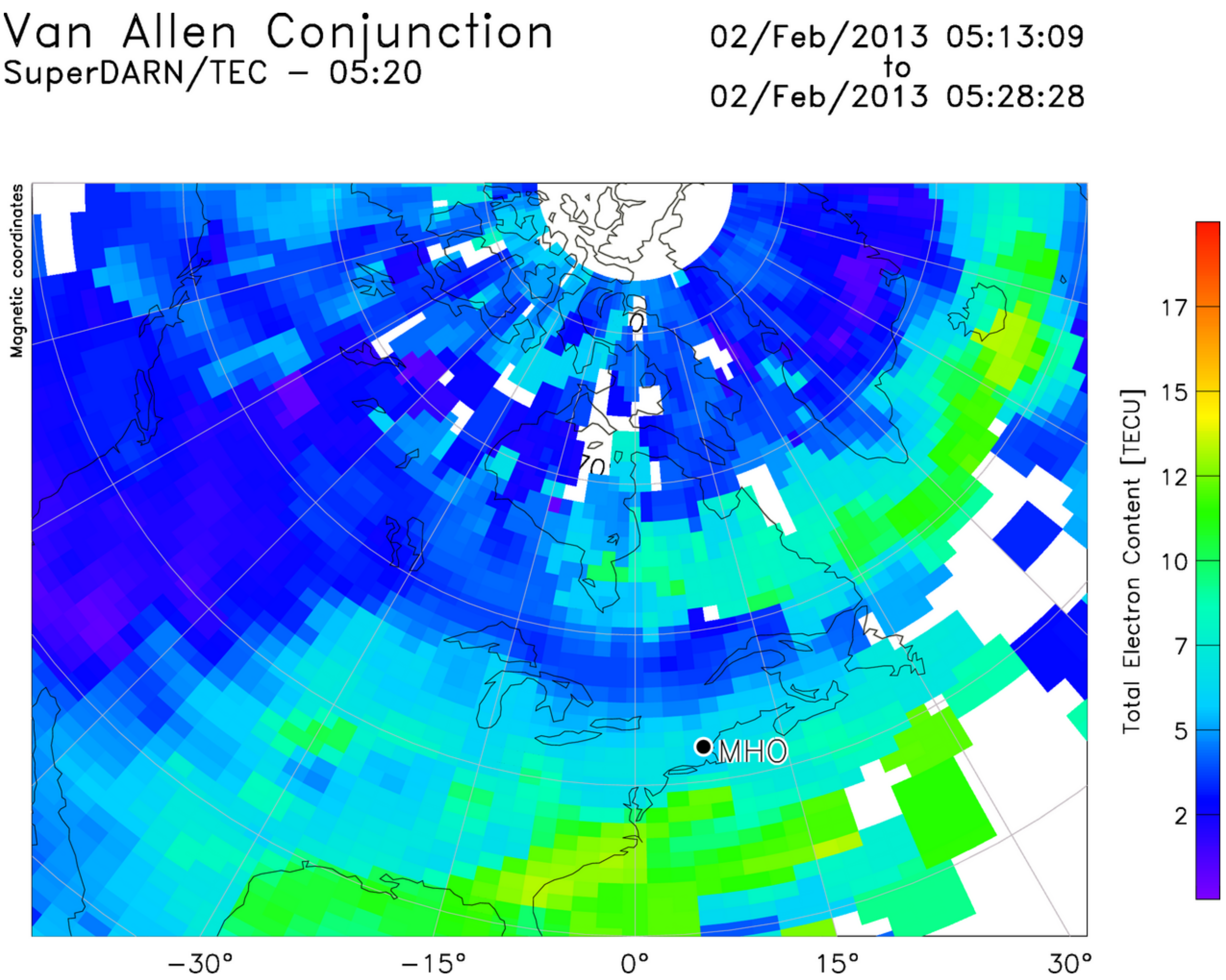


Plot of SuperDARN backscatter velocity measurements overlaid on median filtered TEC values for March 11th, 2011.

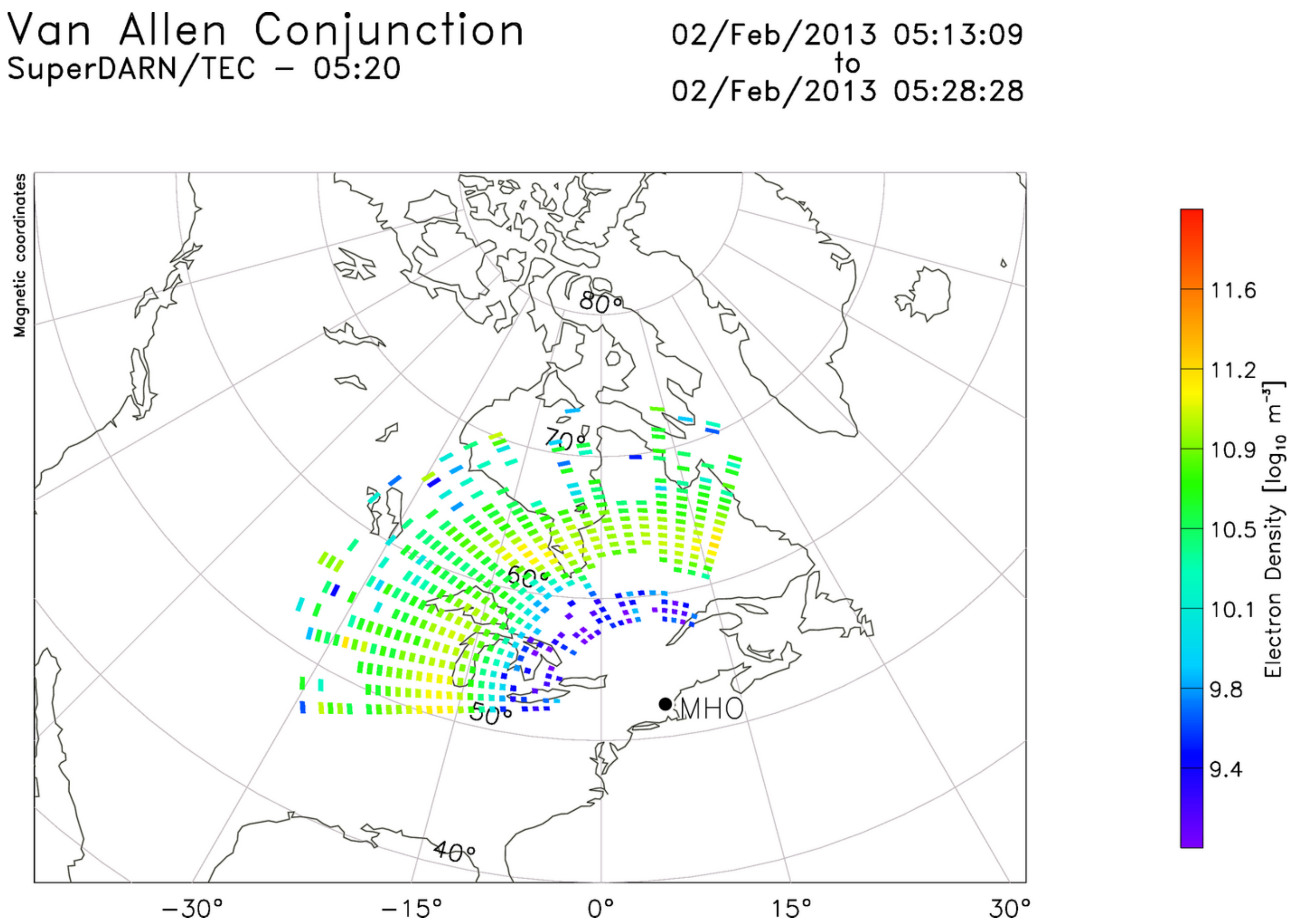
February 2, 2013: ISR-SD Conjunction over a SAPS channel



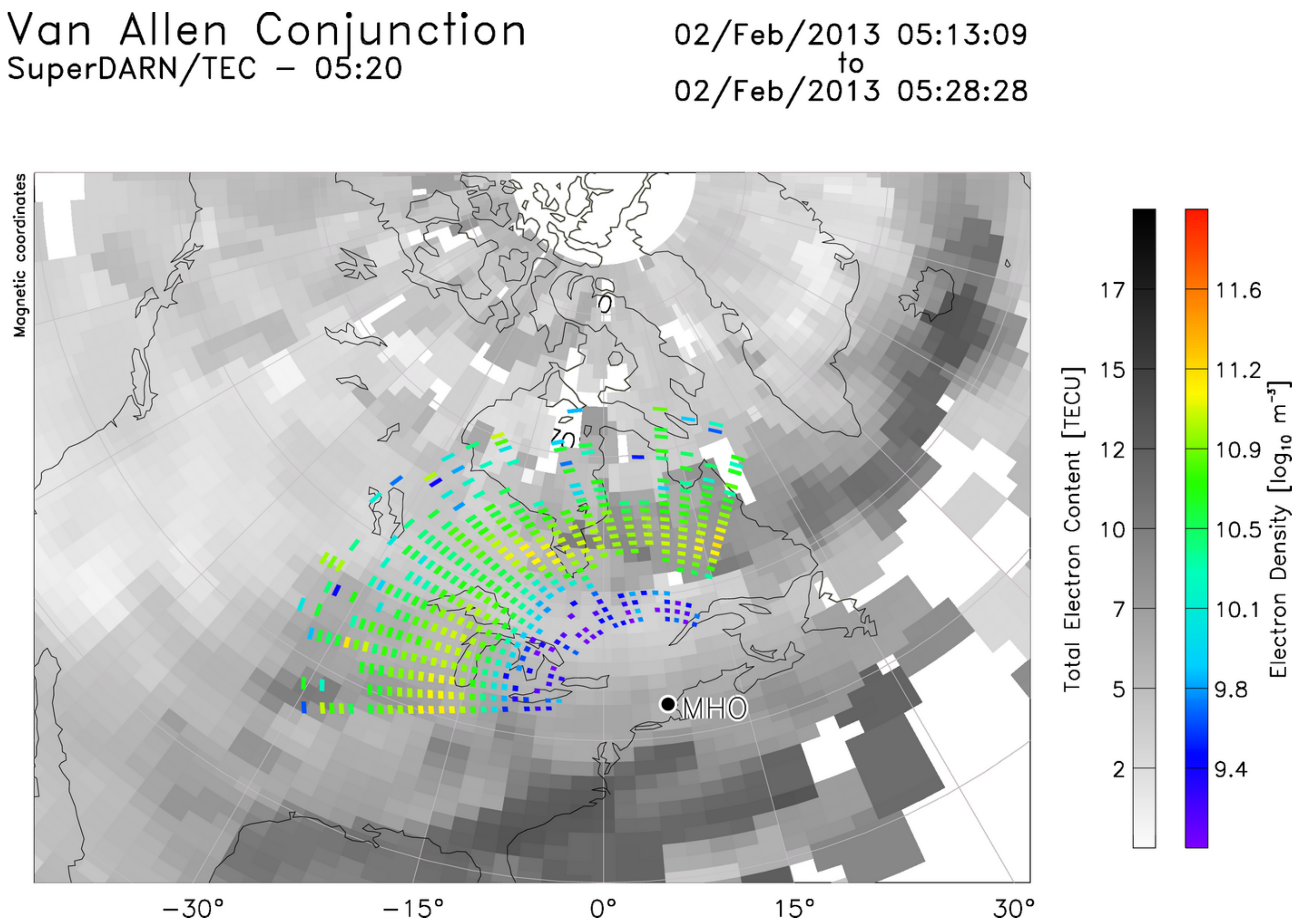
February 2, 2013: 05:20 UT – Map of GPS/TEC



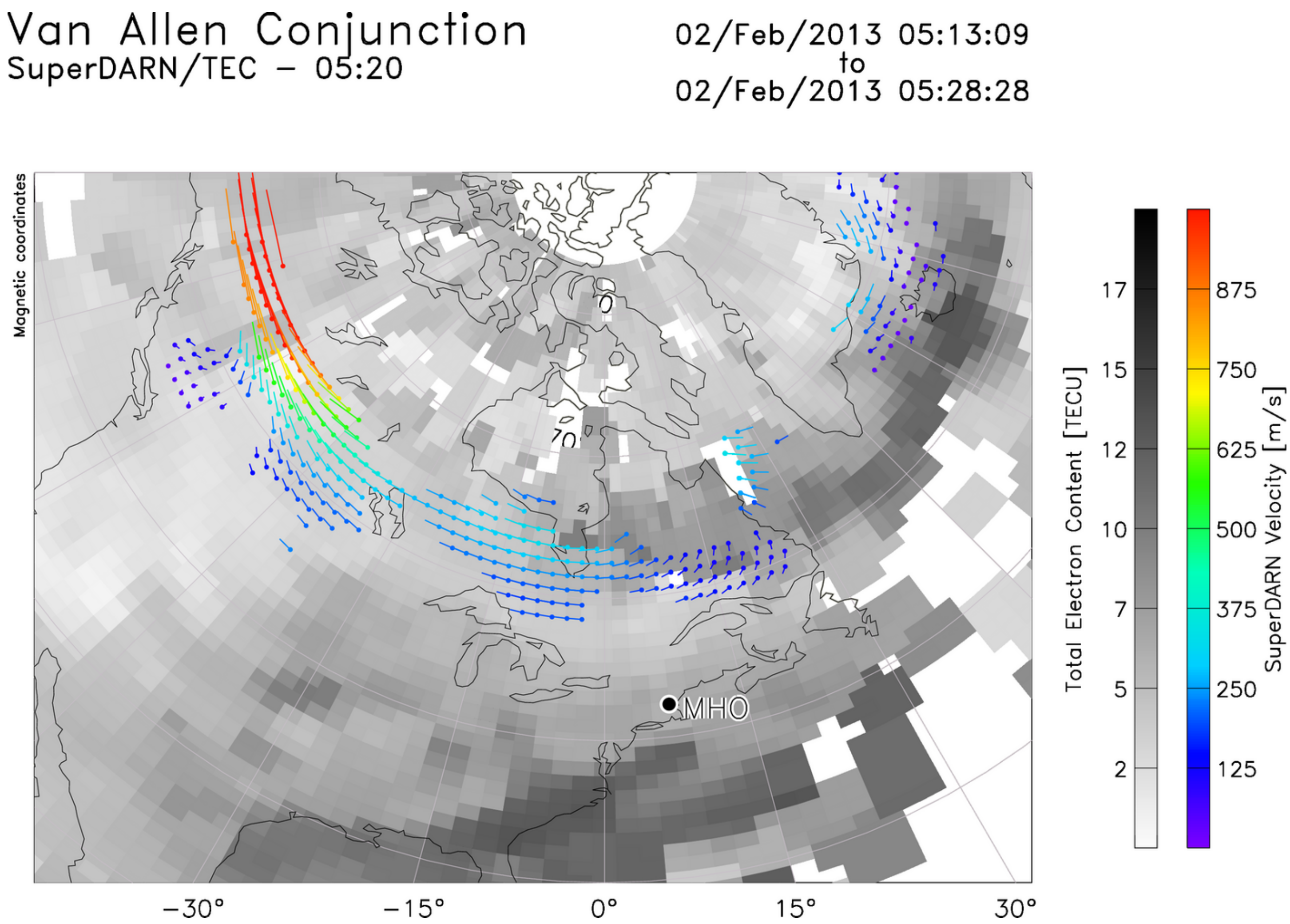
February 2, 2013: 05:13 – 05:28 UT MHO electron density



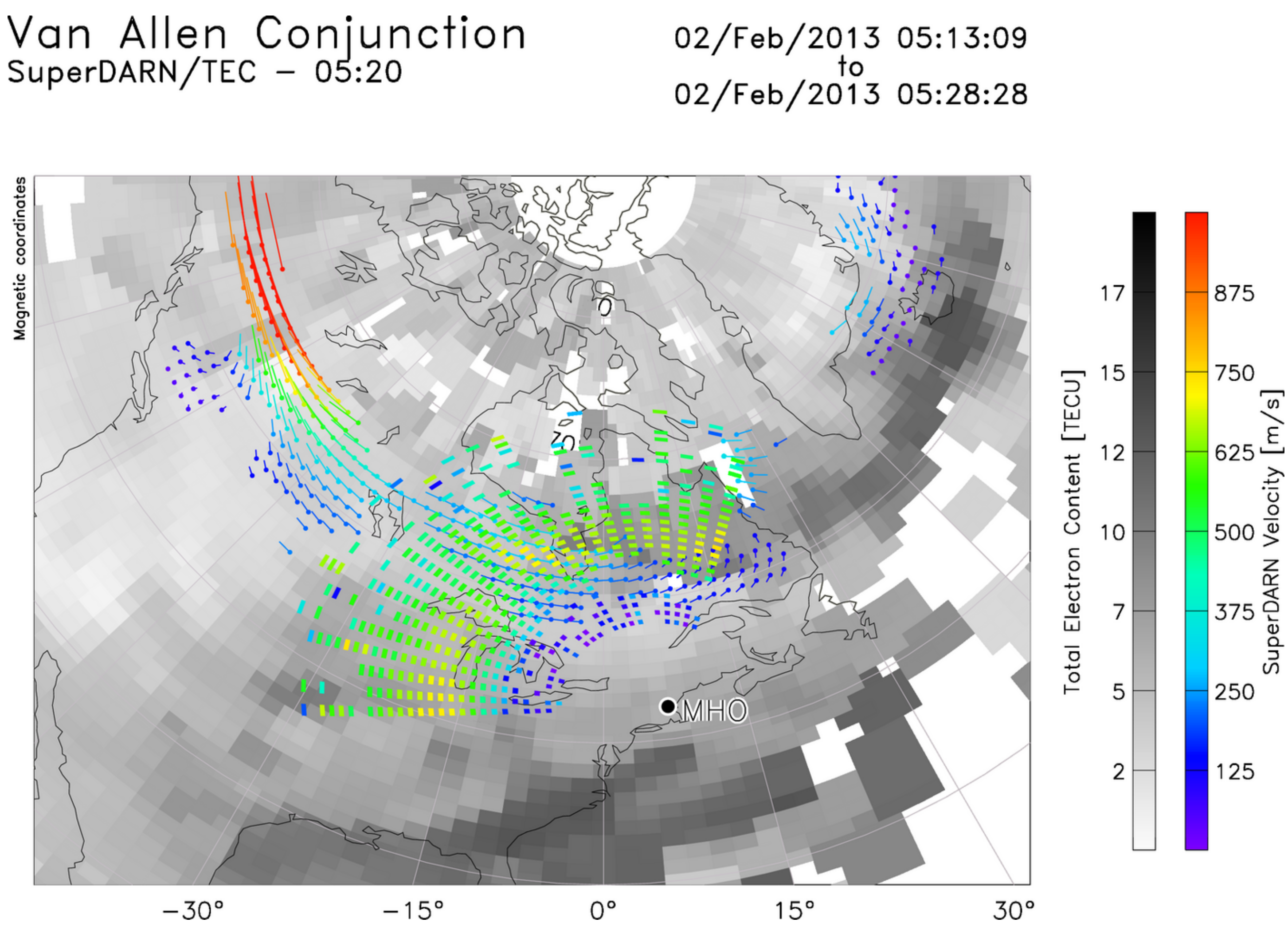
Combined map of MHO electron density and GPS/TEC



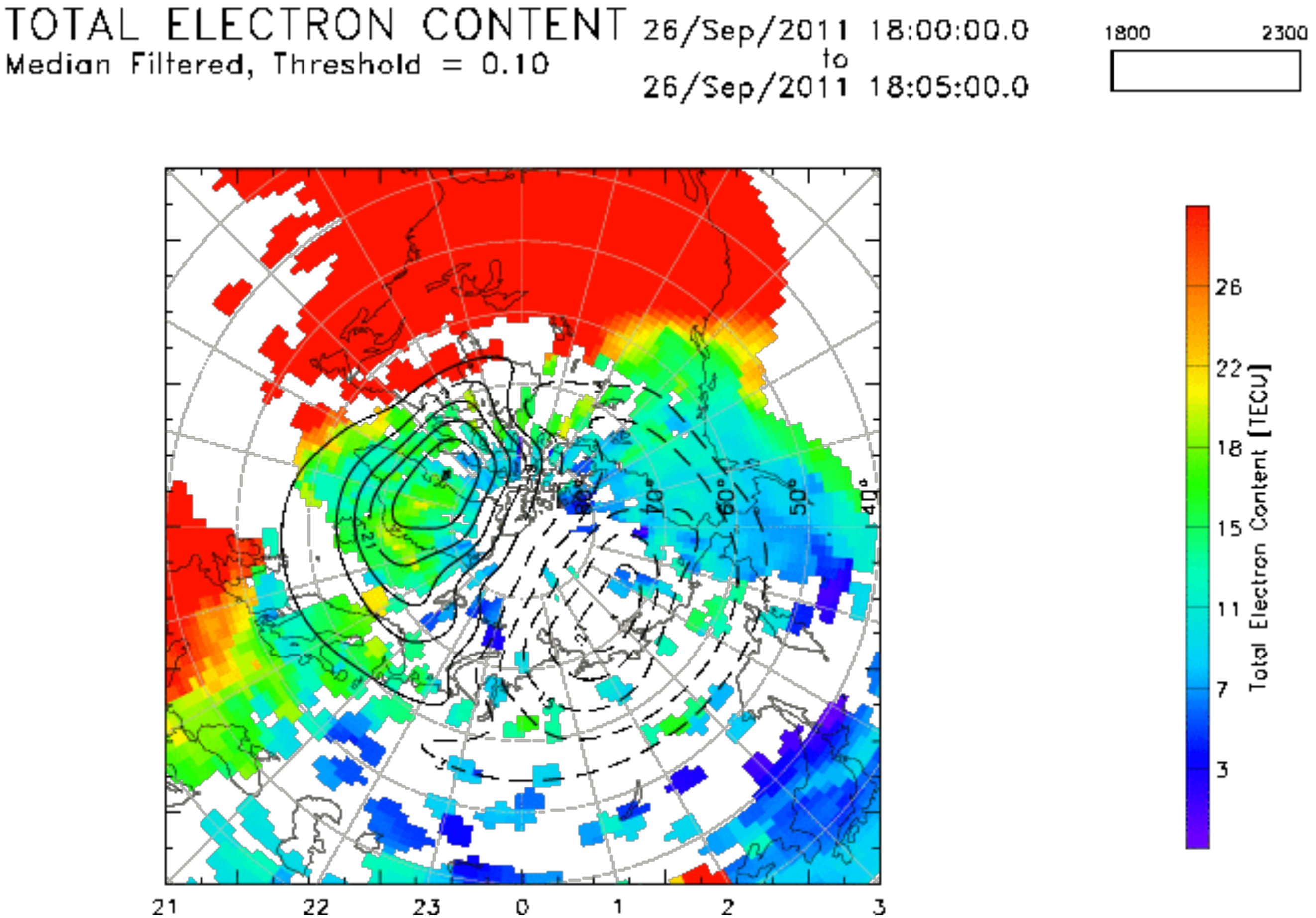
Combined map of SD fitted velocities and GPS/TEC



Combined map of SD, MHO, and GPS/TEC data



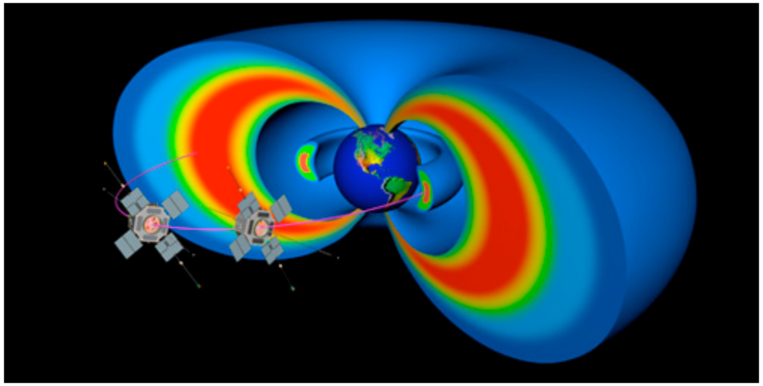
GPS/TEC & SuperDARN

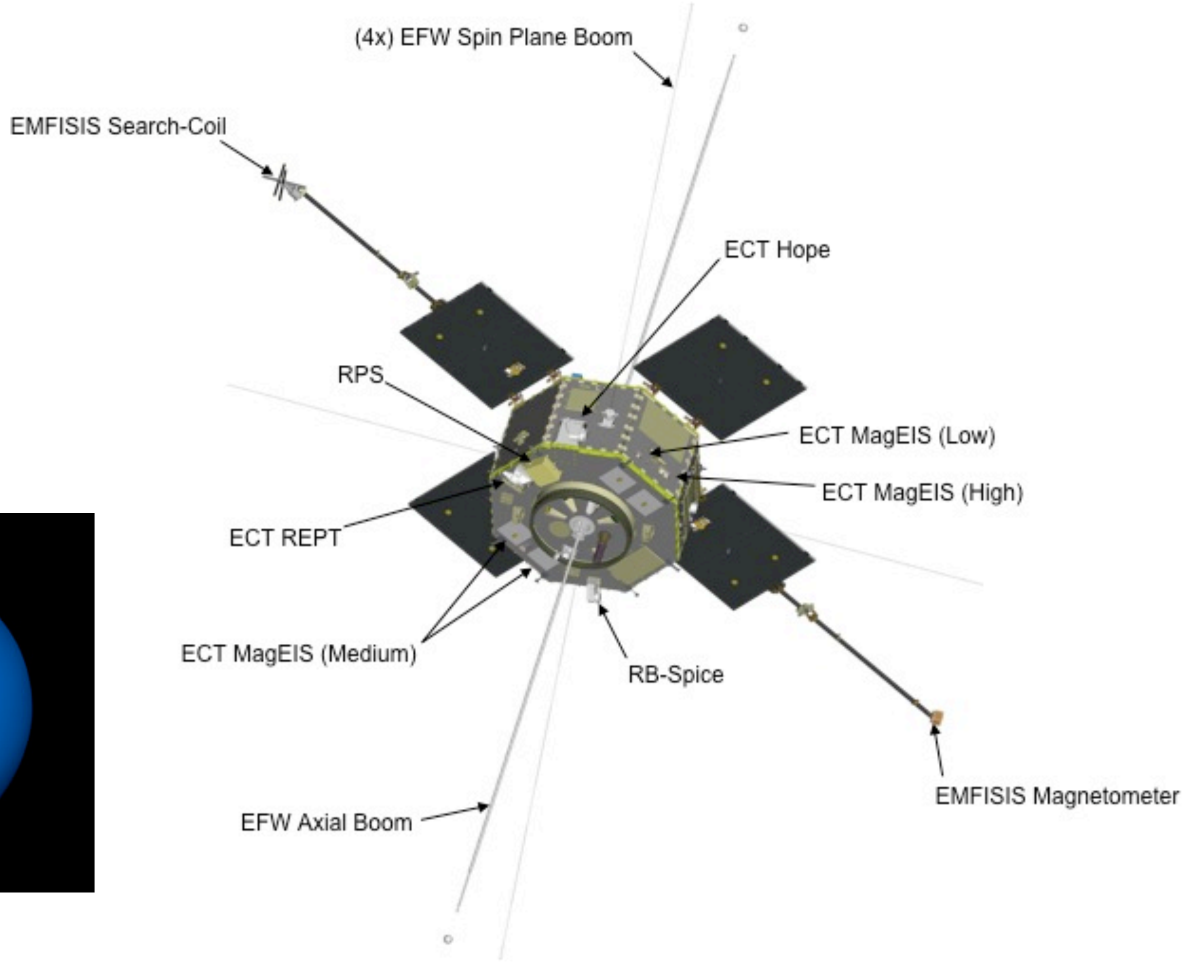


Evolution of tongue of ionization and fossil plume of storm enhanced density for geomagnetic storm on September 26th, 2011 (after *Thomas et al*. [2012], *Zhang et al.* [2013]).

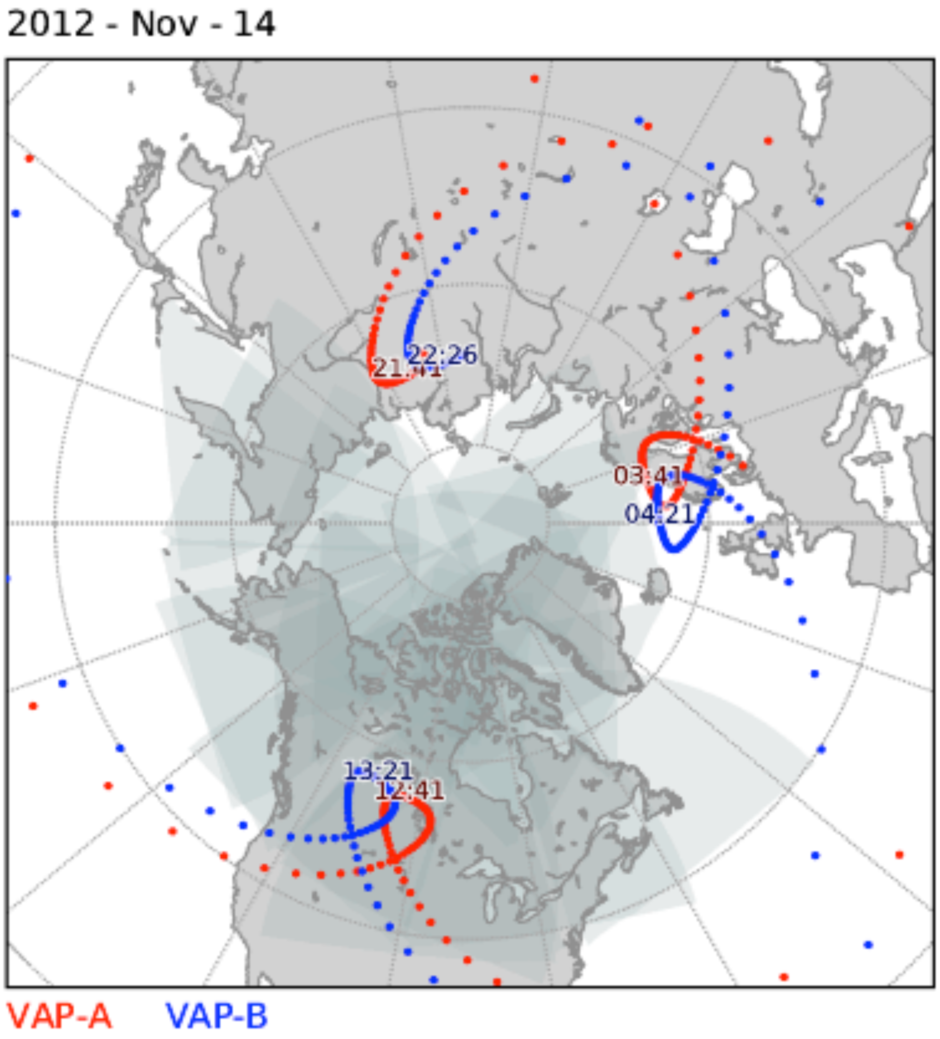
Radiation Belt Storm Probes (RBSP) Satellites Launched on August 30, 2012

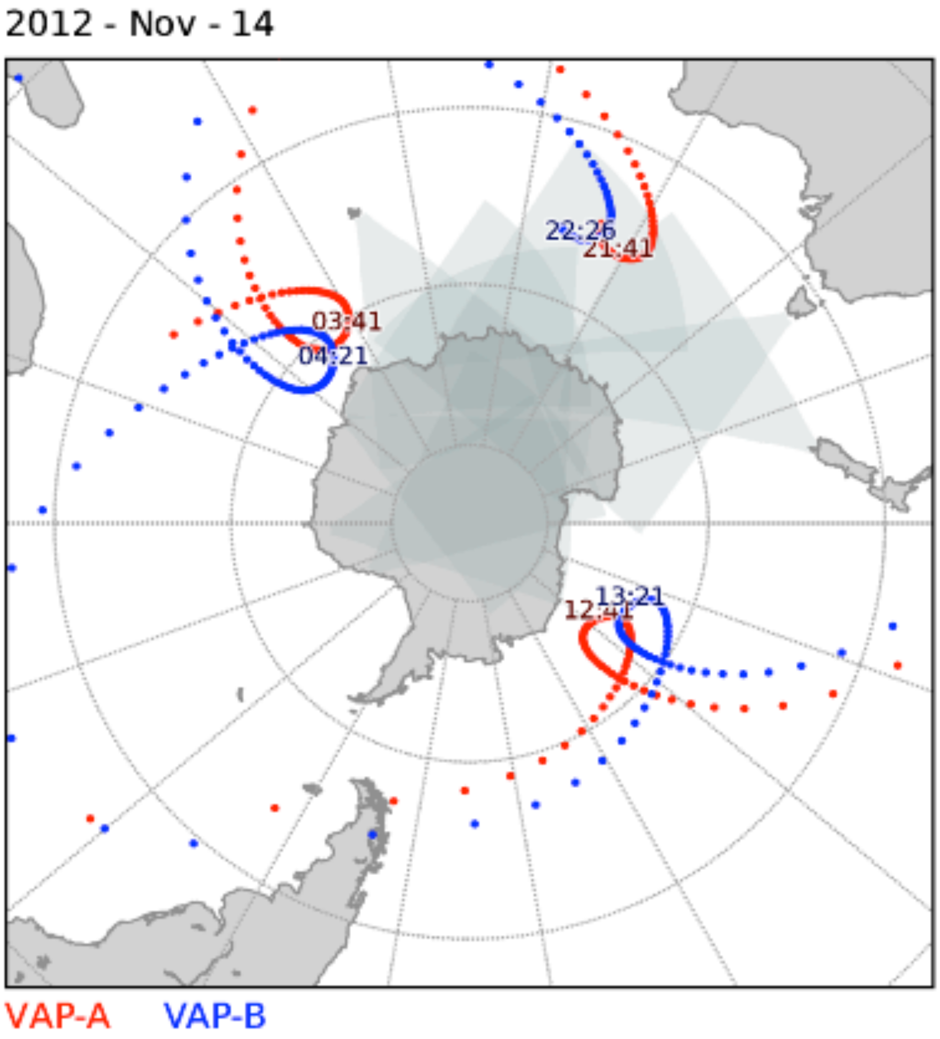
Twin-satellite mission to study Earth's radiation belts during geomagnetic storms



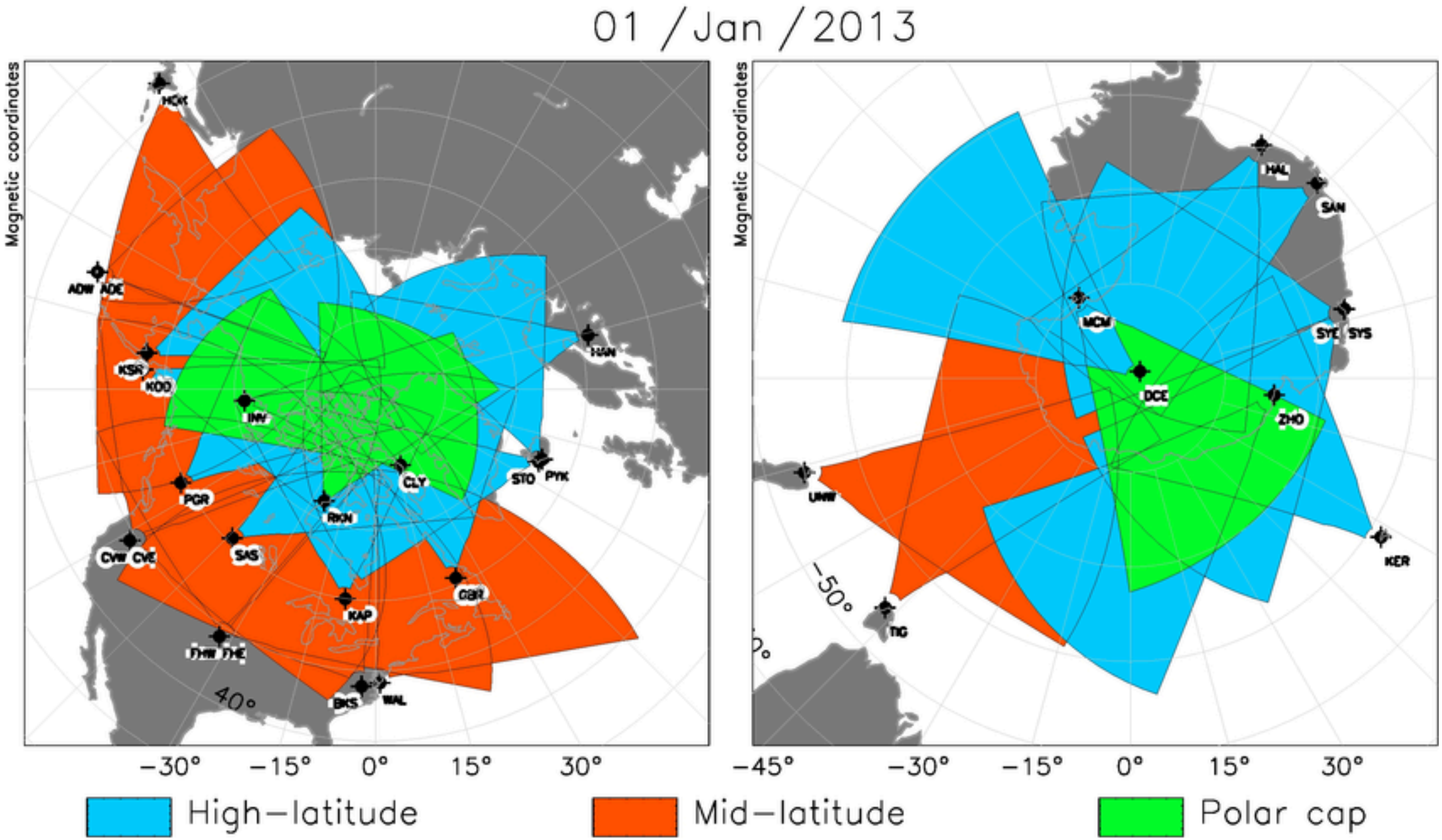


Apogee conjunctions – November 14, 2012





SuperDARN Radar Coverage in the RBSP Era



2nd Event: February 14, 2013: SAPS Channel

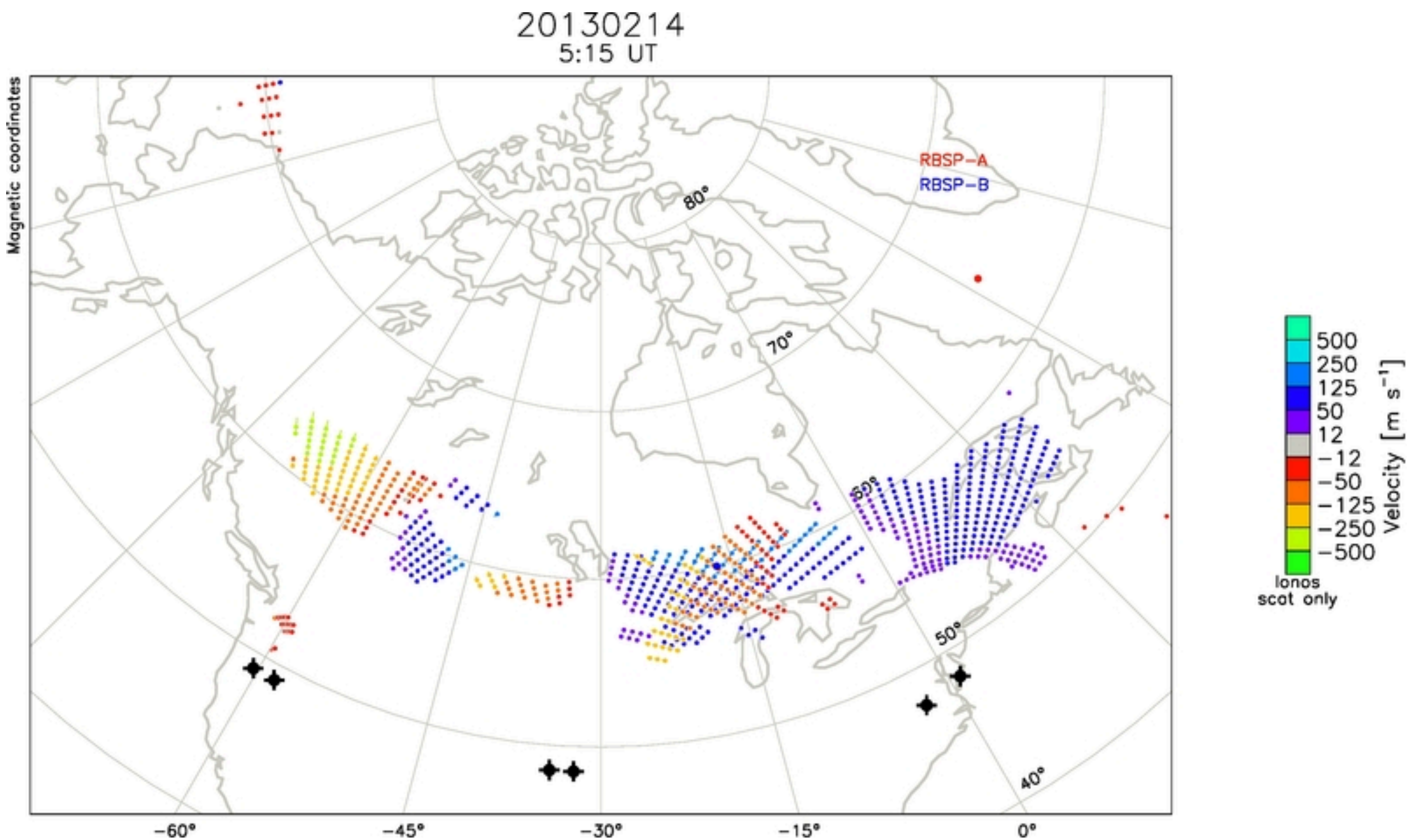
- Subauroral polarization streams (SAPS) are commonly seen with mid-latitude SuperDARN (~140 events counted so far)

- Conjunctions with the RBSP s/c can occur within a SAPS channel

- One example: February 14, 2013, 4 – 12 UT

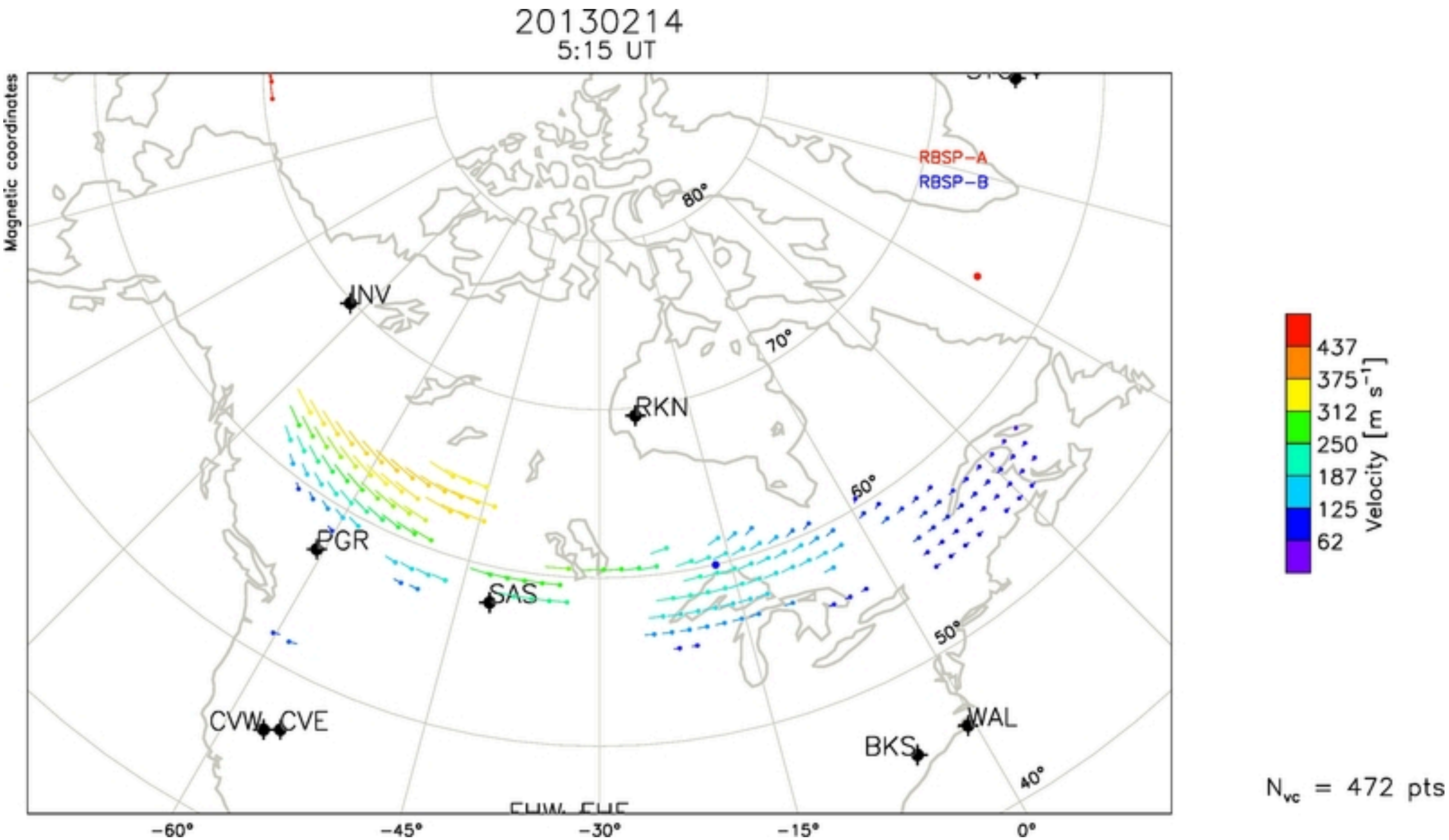
- Comparison with satellite particle precipitation boundaries (not shown) indicates that the mid-latitude flows were subauroral

February 14, 2013: SAPS observed with mid-latitude SuperDARN



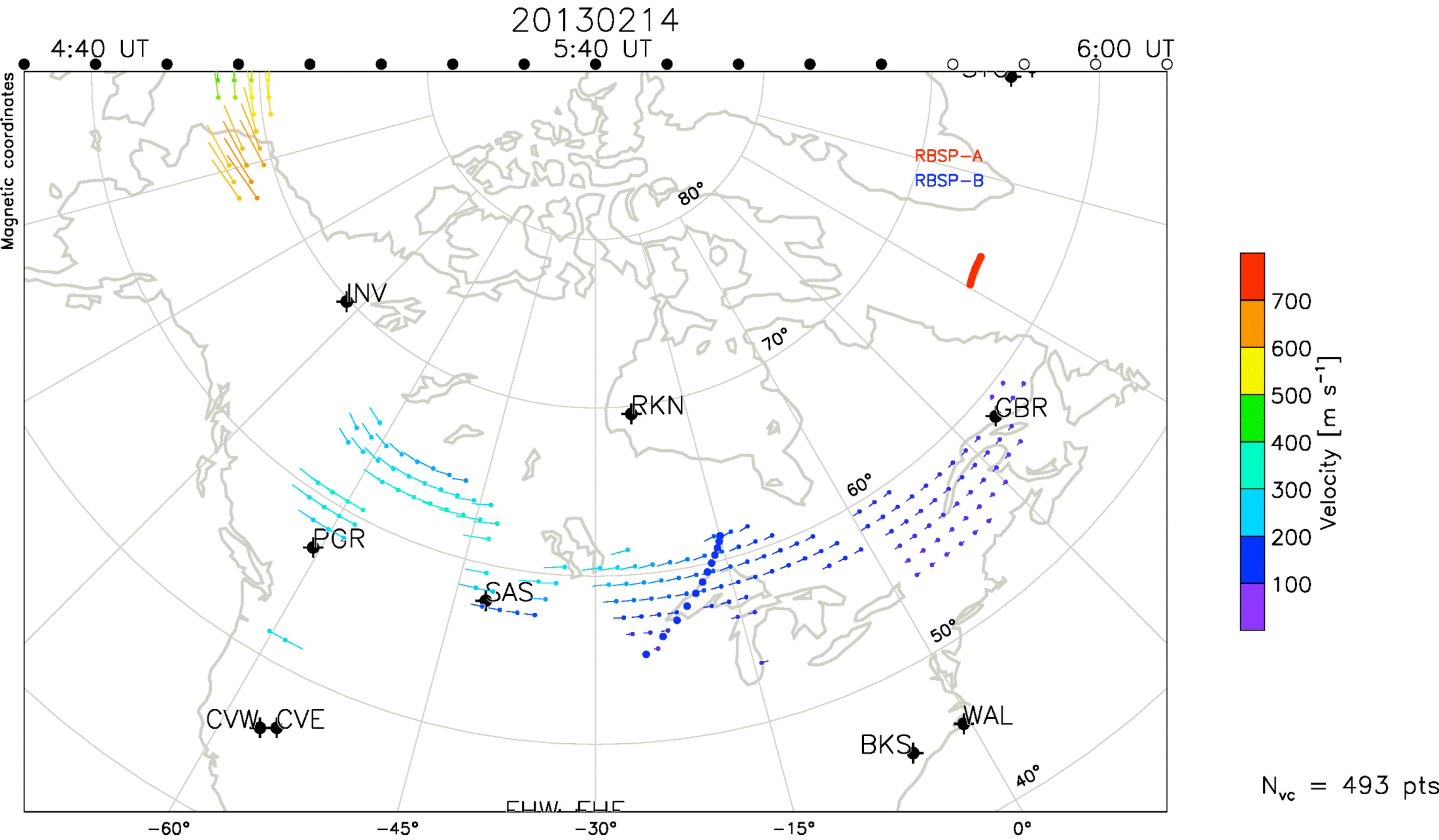
Map of line-of-sight velocities measured at 0515 UT

Expansion of SuperDARN to Mid-Latitudes



Map of fitted velocities measured at 0515 UT

Conjunction over a SAPS channel: Feb 14 04:40 - 06:00 UT



Movie of line-of-sight velocity maps with overlay of RBSP s/c footpoints

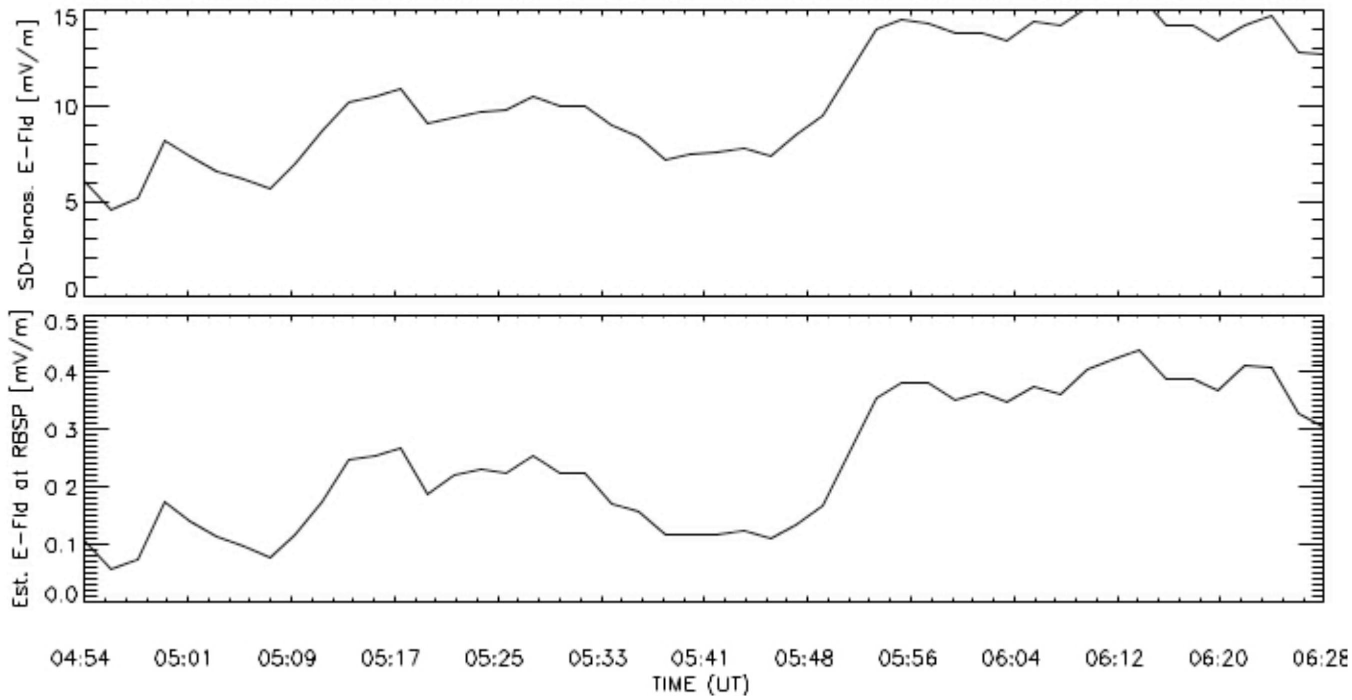
Electric fields at footpoint and s/c positions

February 14, 2013: 04:54 – 06:28 UT

RBSP-B

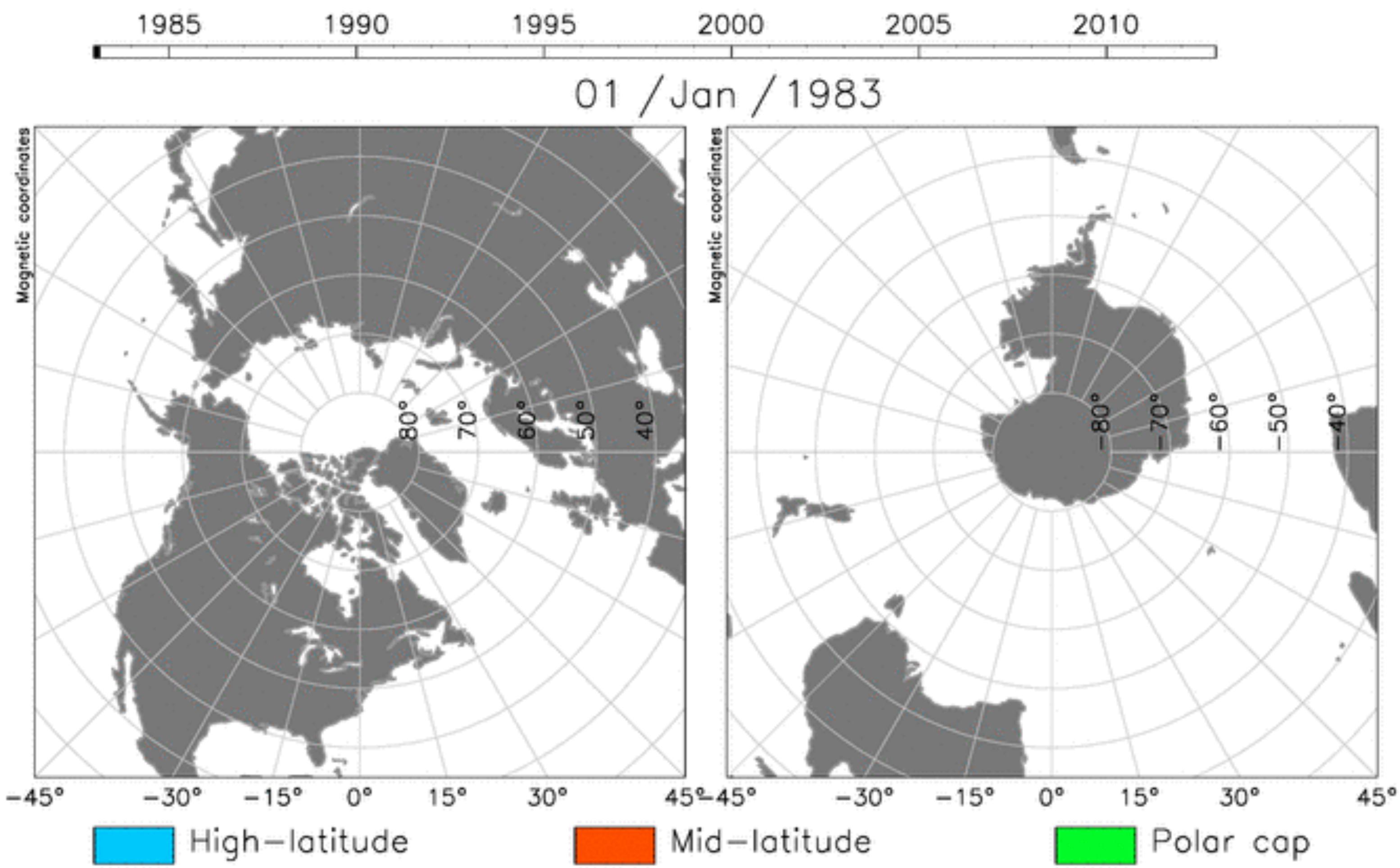
E-field at footpoint

E-field at s/c position (inferred)



Research Areas Advanced by SuperDARN

- Plasma motion in the ionosphere and coupling to the magnetosphere and solar wind
- Plasma instabilities and turbulence
- Propagation of large-scale waves in the atmosphere
- Pulsations in the magnetosphere-ionosphere system
- Ionospheric structure and variability
- Geomagnetic storm and substorm effects (Space Weather)
- Planetary waves and tides (meteor scatter)


1985
1990
1995
2000
2005
2010
01 /Jan /1983
Magnetic coordinates
Magnetic coordinates
80°
70°
60°
50°
40°
−80°
−70°
−60°
−50°
−40°
−45°
−30°
−15°
0°
15°
30°
45°
−45°
−30°
−15°
0°
15°
30°
45°
High−latitude
Mid−latitude
Polar cap