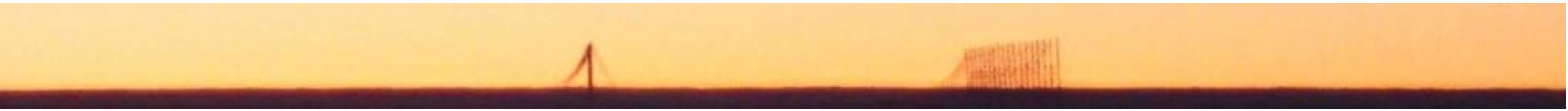


Super **D**ual **A**uroral **R**adar **N**etwork

SuperDARN

Instruments and data

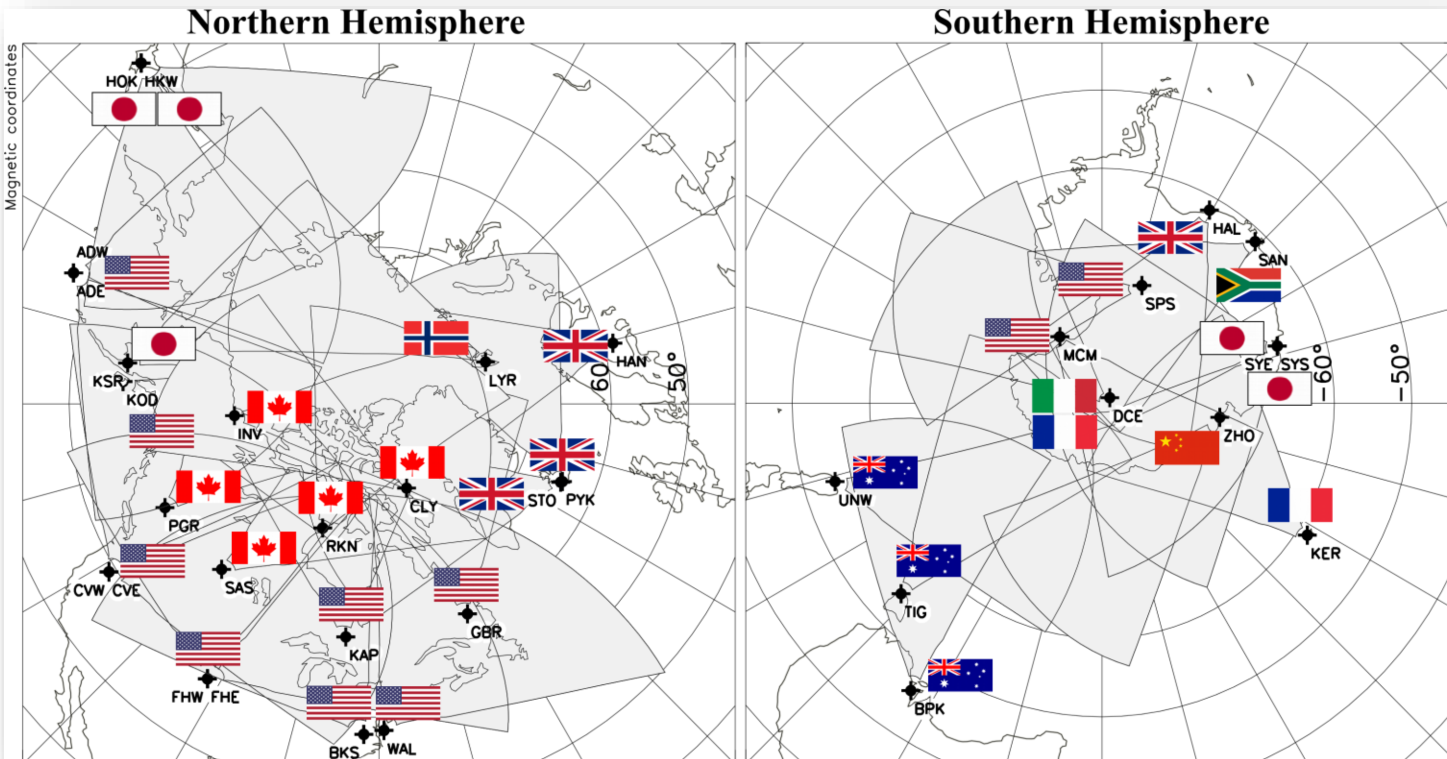
Maria Federica Marcucci

Istituto Nazionale di Astrofisica

ISSS – L'Aquila, 18 September 2018

The Super Dual Auroral Radar Network is comprises more than 30 HF radar manned by ten countries.

The SuperDARN continuously measures ionospheric convection in the southern and northern mid and high latitudes and polar caps and can observe a series of phenomena due to the plasma processes in the near Earth space.



Chisham et al. 2007 published a comprehensive review on “SuperDARN scientific achievements, new techniques and future directions”

Outline

- Introduction about the circumterrestrial phenomena
- A Superdarn radar: how does it work
- Scientific targets
- References

Motivation: Study of the circumterrestrial space phenomena due to the solar wind interaction with the magnetosphere and ionosphere

…we start from our sun and its variable solar wind

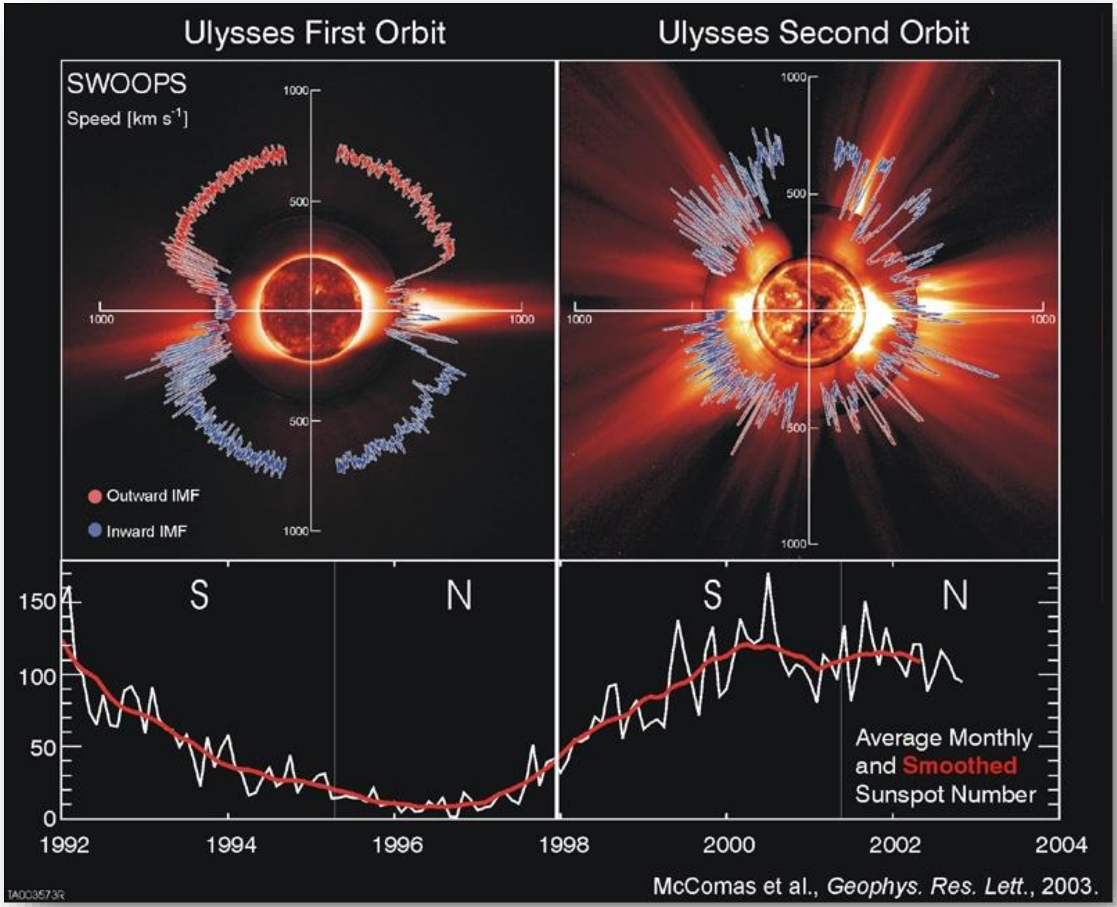
The solar wind is a supersonic flow of ionized plasma (electrons; Ions: 95% protons; 4% He^{++} and few heavier elements) that permeates the interplanetary medium (expansion of the solar atmosphere).

The solar magnetic field lines are *frozen* into the solar wind (highly conductive plasma) and move consistently with the solar wind flow: Interplanetary Magnetic Field (IMF)

At the Earth's orbit:

Proton Number density ~ 5 cm-3;
Velocity ~ 500 km/s
Interplanetary Magnetic Field ~ 5 nT

Actually two types of solar wind are observed: fast (400km/s-800km/s originating from coronal holes) and slow (250km/s-400km/s, from close to the heliomagnetic equator or above the coronal Helmet streamers in active regions where magnetic fields are closed)



Study of circumterrestrial space phenomena

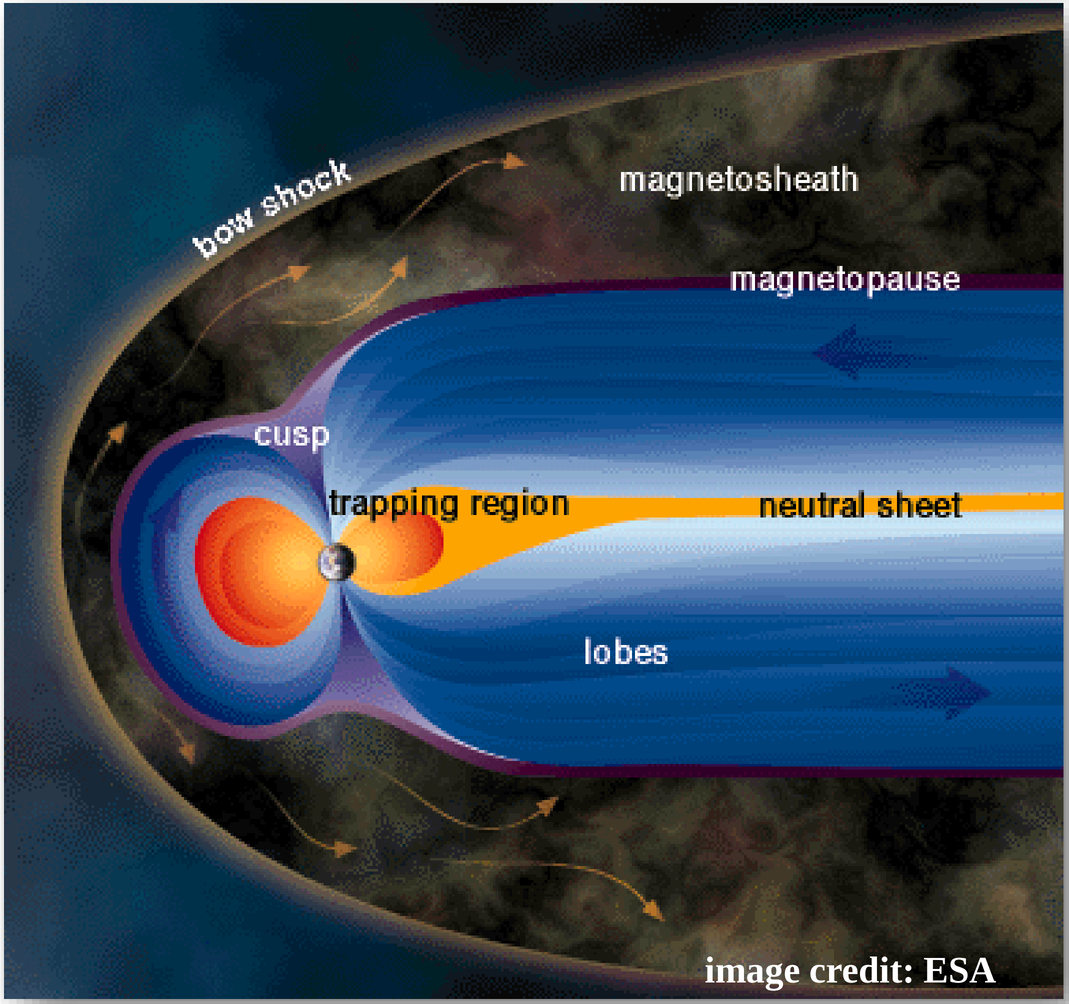
.. and its interaction with the magnetosphere

The solar wind flow is deflected by the Earth's dipolar magnetic field and has no direct access to region around the Earth where the geomagnetic field dominates: the *magnetosphere*. The tear shape of the magnetosphere is conversely due to the solar wind kinetic pressure.

A bow shock is formed in front of the magnetosphere where the supersonic solar wind is slowed down and heated.

The *magnetopause* is the boundary between the *magnetosheath* (shocked solar wind) and the magnetosphere.

This is an example of how collissionless space plasmas, for which the frozen-in-flux condition holds, do not mix, to a first approximation, and naturally organize in plasma "bubbles" of different magnetic topology separated by thin current sheets.



Study of circumterrestrial space phenomena

.. giving rise to the complex environment around the Earth

The *lobes* are rarefied plasma regions (< 0.1 cm^{-3}).

The *plasma sheet* contains hot particles (kilovolt) with a number density of 0.1-1 cm^{-3} .

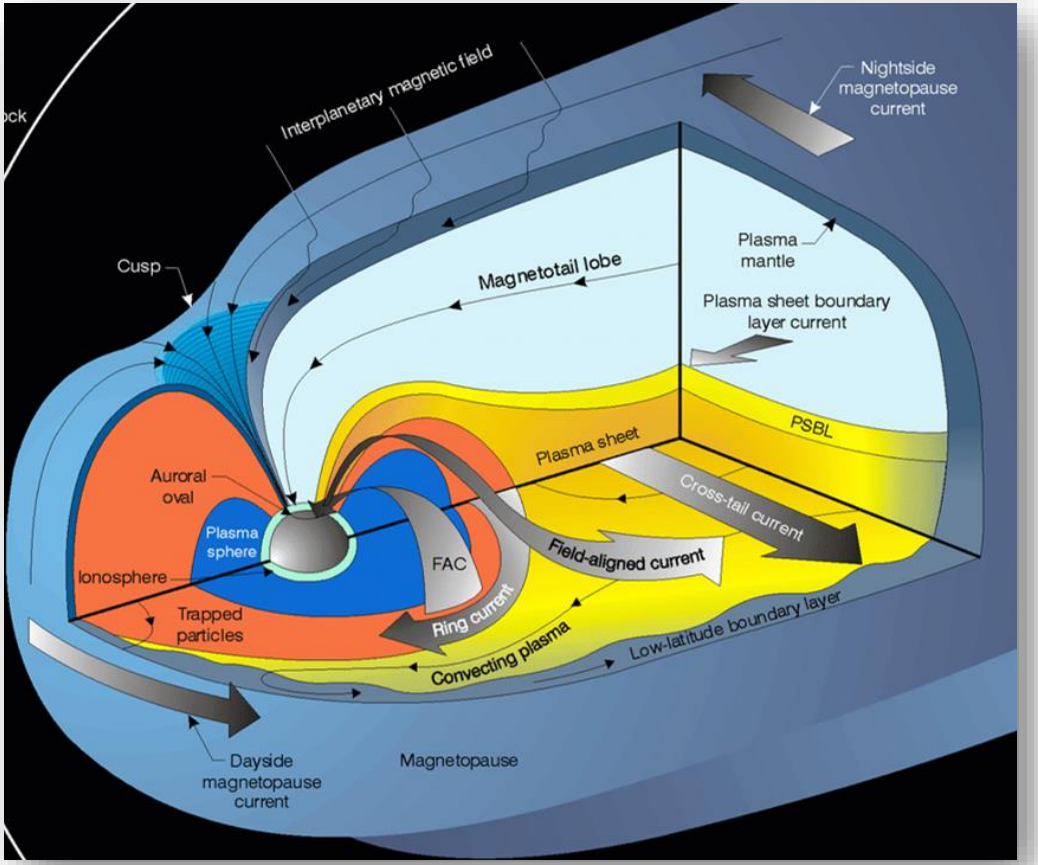
The *plasmasphere* is composed by a cold (1 eV) and dense (~ 10 cm^{-3}) plasma corotating with the Earth.

On the same geomagnetic field lines is found the energetic plasma of the Van Allen *radiation belts*.

Sources of plasma in the magnetosphere are solar wind and ionosphere (to a different degree according to the different regions).

Currents sheets are present where the field is distorted into a non-dipolar configuration: *magnetopause and cross-tail currents, ring current*.

Moreover, the solar wind provides momentum inducing plasma flows inside the magnetosphere and ionosphere: the momentum transfer is achieved by *field-aligned currents (FAC)*

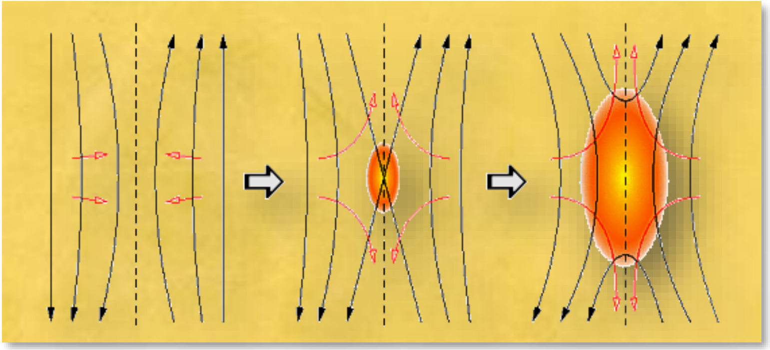


..near Earth space is not only complex but highly dynamic, since the magnetosphere is not 'closed'

Plasma transport processes across the magnetopause:

- Magnetic reconnection
- Kelvin-Helmholtz instability
- Finite Larmor radius effect
- Diffusion
- Impulsive penetration
- Direct cusp entry

The main process for the transfer of energy and mass to the magnetosphere is magnetic reconnection

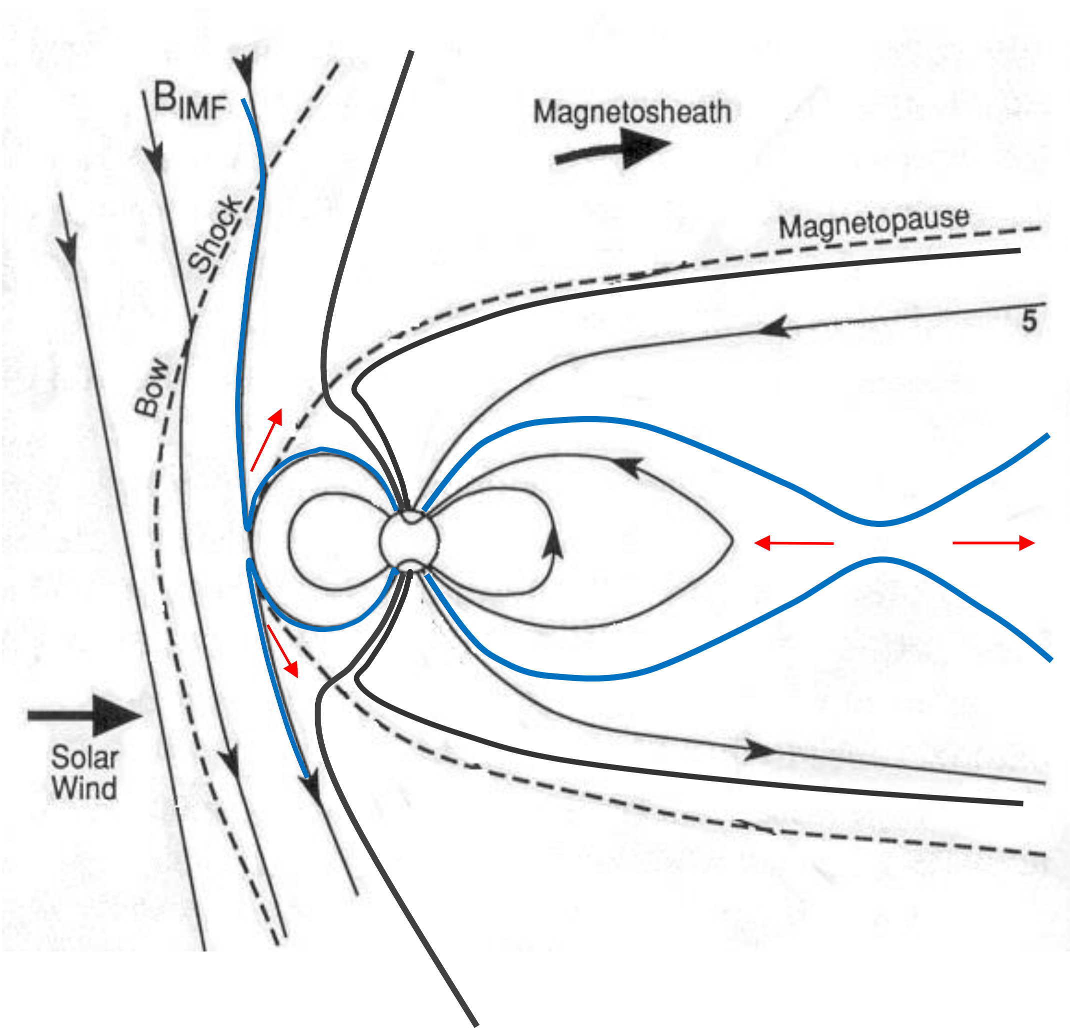


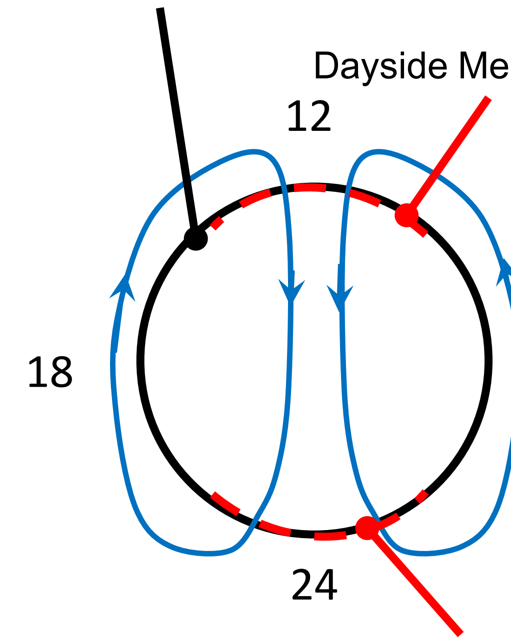
Magnetic reconnection is a dissipative process that occurs when a breaking of frozen-in-field condition occurs.

Magnetic reconnection implies the conversion of magnetic field free energy (stored in complex magnetic field topology) to kinetic and thermal energy – plasma mixing occurs.

Study of circumterrestrial space phenomena - **ionospheric convection**

The open magnetosphere model of Dungey (1961) - Dungey cycle (for Southern IMF and balance between dayside and tail reconnection)

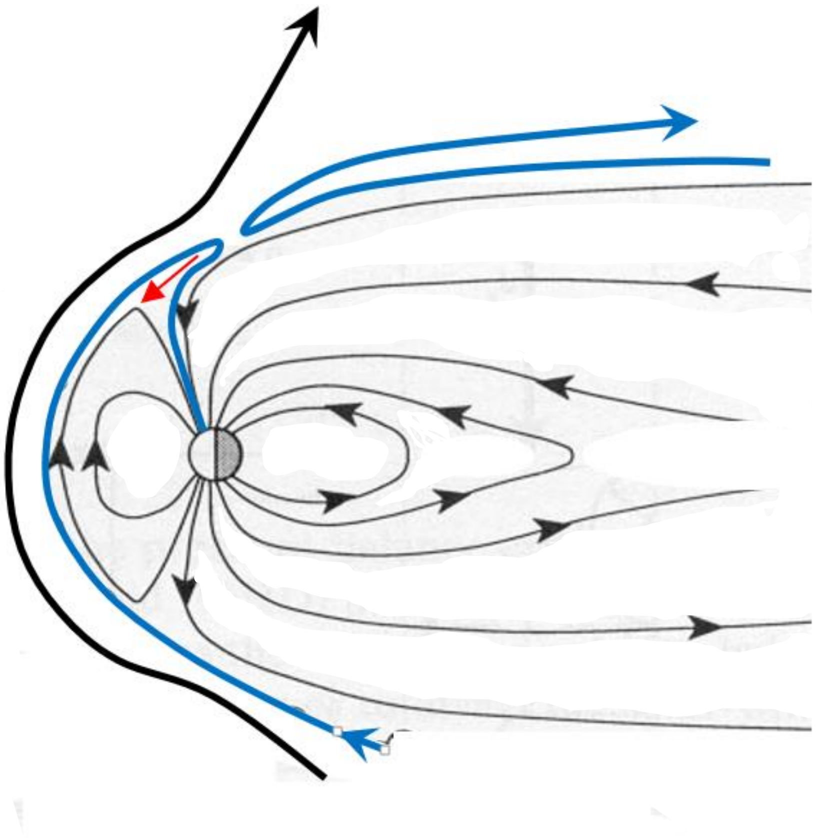


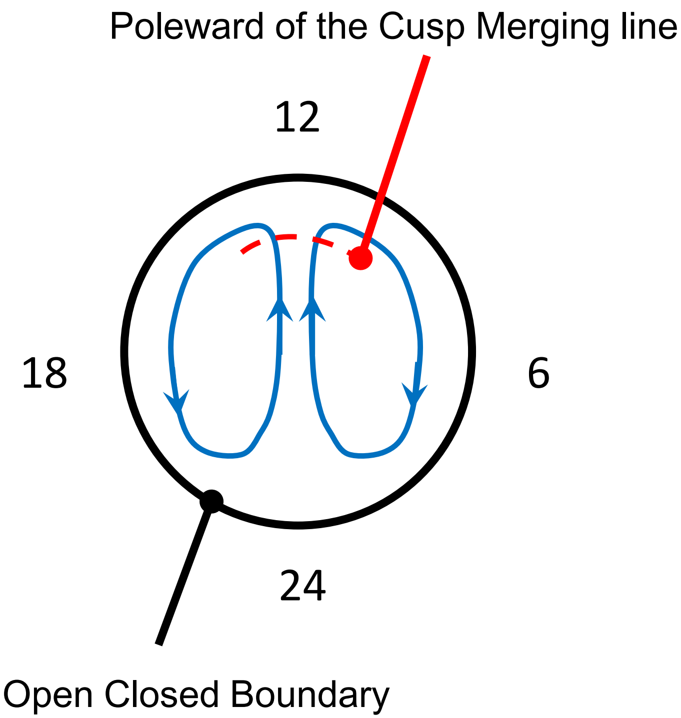


Adapted from Fig 9.11 of W.J.Hughes in *Introduction to Space Physics,* M.G Kivekson and C.T. Russell Editors

Study of circumterrestrial space phenomena - **ionospheric convection**

During Northward IMF - Reconnection poleward of the Northern or Southern cusp
- No tail reconnection





By the way: through simultaneous dual lobe reconnection magnetosheath plasma is captured in the magnetosphere.

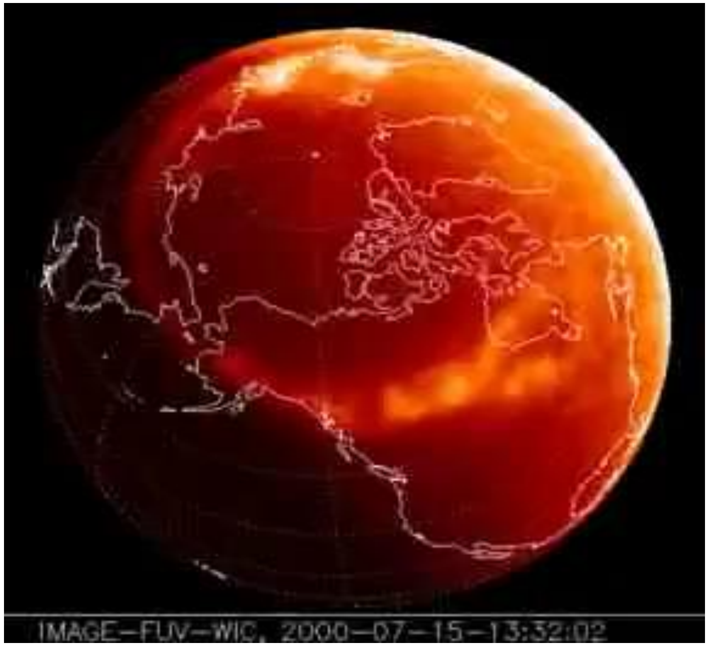
Study of circumterrestrial space phenomena - **substorms and geomagnetic storms**

Polar substorms (can be related with the imbalance between dayside and tail reconnection):
enhancement of nightside auroral activity with typical timescale ~ 1 hour
A pair of upward/downward FACs on either side of the midnight meridian, closing in the *substorm electrojet* across the nightside auroral ionosphere is observed and is associated to a disruption of the near-Earth portion of the cross-tail current.

Storms: global perturbations of geospace characterised by a an enhacement of the ring current and occurring after prolonged and strong forcing by the solar wind (a geomagnetic storm will occur if the IMF B south component stays >10 nT for over 3 hours - Gonzalez and Tsurutani, 1987)

The storm – substorm relationship still not clear

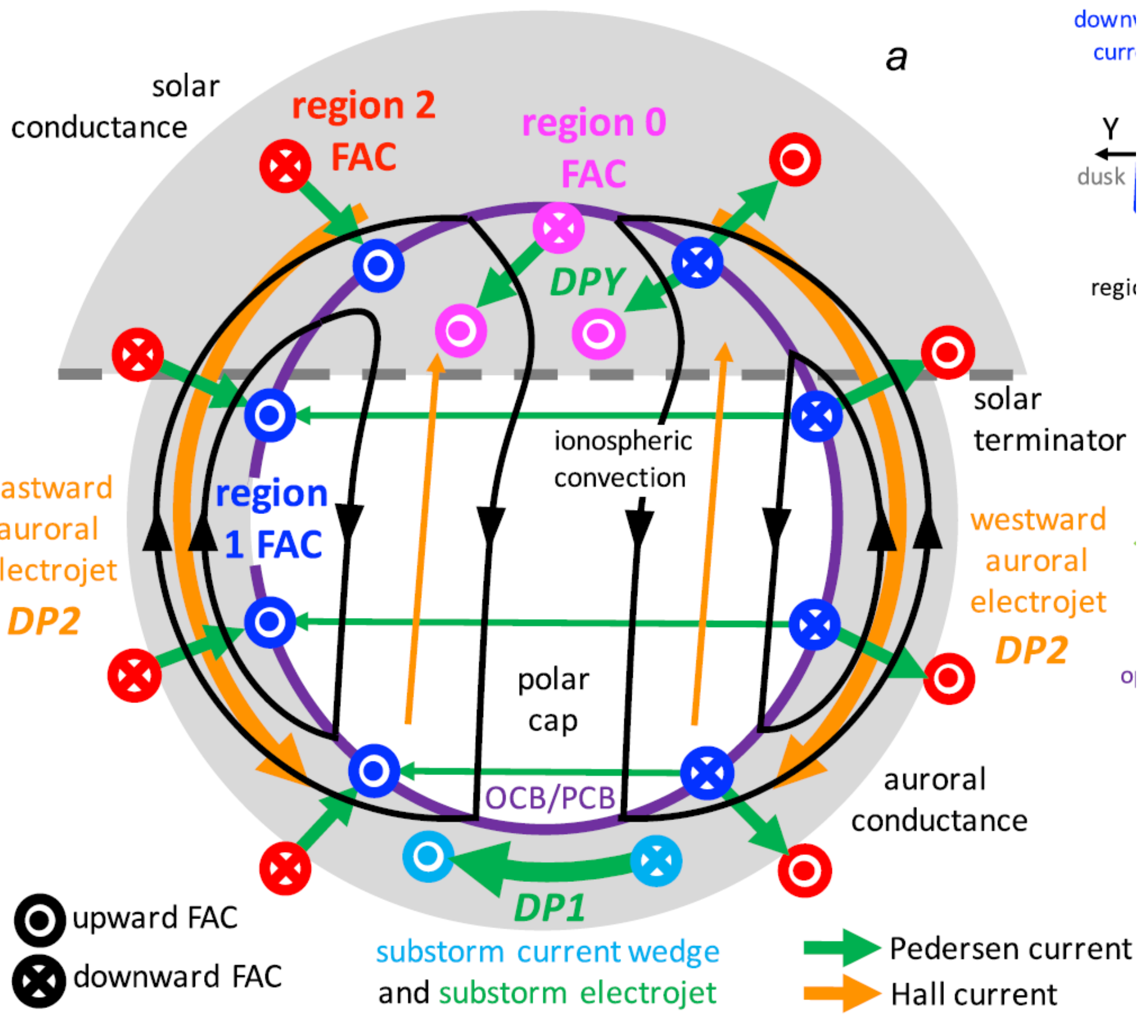
These perturbations can be monitored by the geomagnetic indices as *Dst, Sym-H, Kp, aa, ap, AL. AU, AE* and *PC* derived by the magnetic field measurements on ground.



The Wide Band Camera observations of the Far Ultraviolet Instrument on-board the IMAGE mission (Courtesy of NASA)- http://sprg.ssl.berkeley.edu/image/

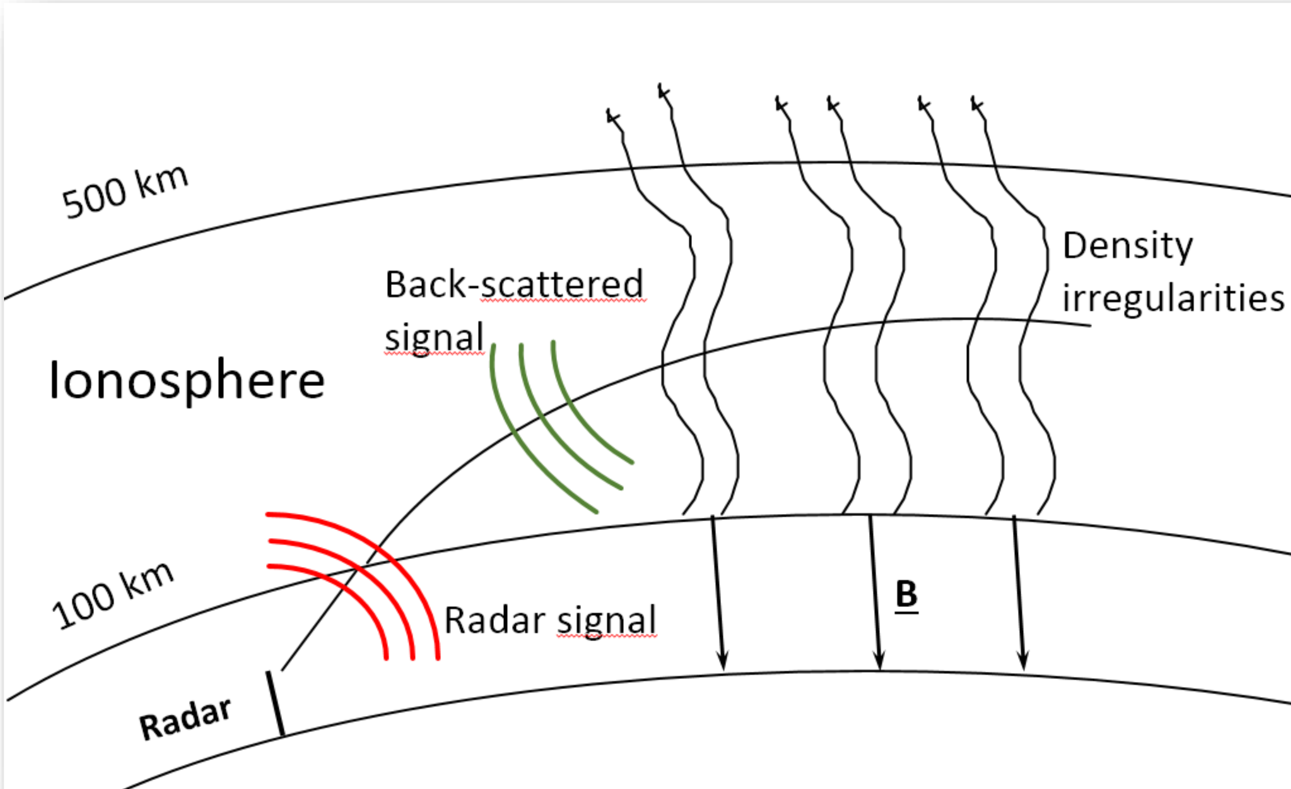
Study of circumterrestrial space phenomena

Cunductance, currents and convection in the polar ionosphere



from Milan et al. SSR, 2017

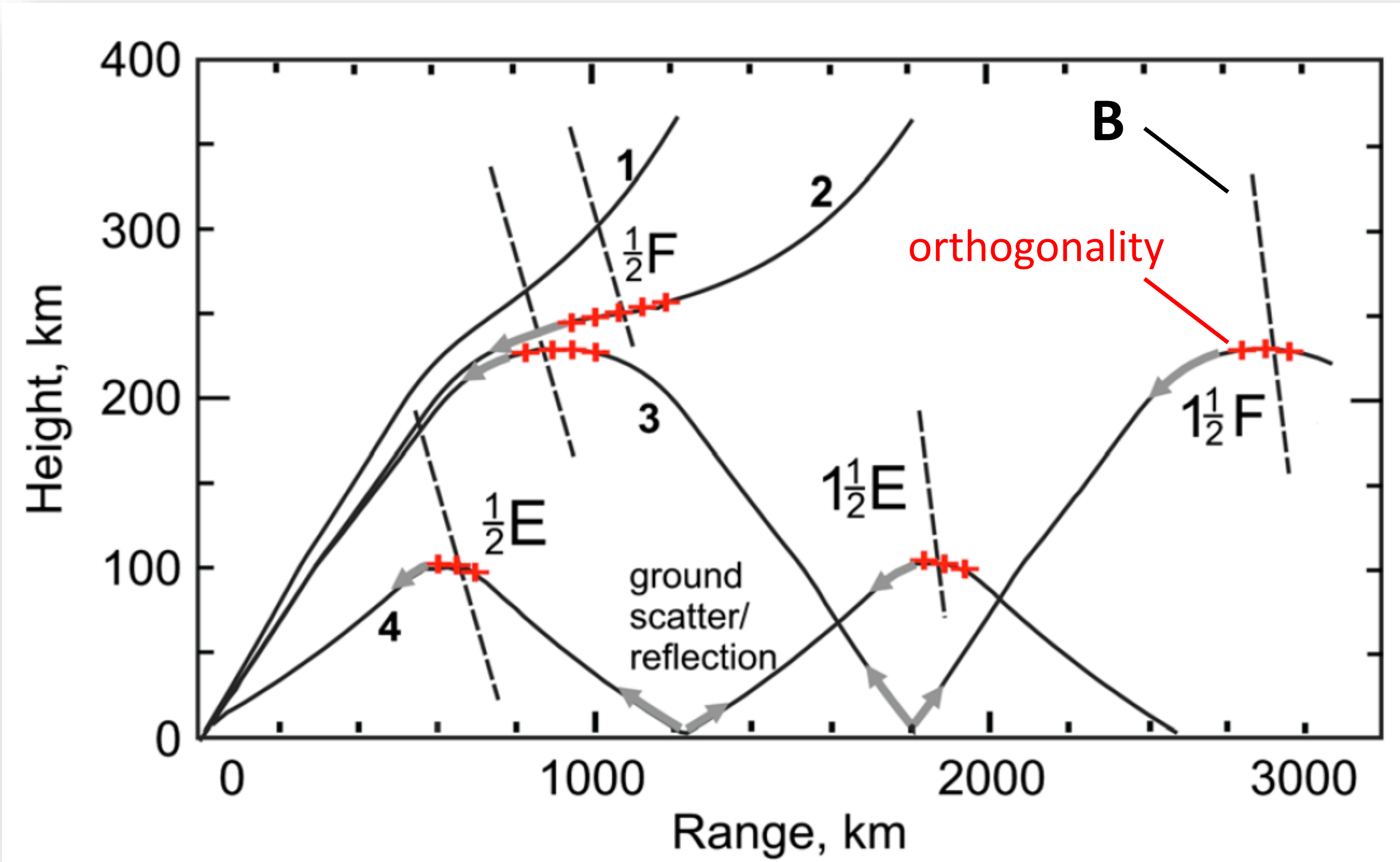
SuperDARN – How the radar works



HF radars signals (3-30 MHz) are refracted in the ionosphere, become roughly perpendicular to the local magnetic field lines and are coherently back-scattered by *field aligned decameter scale* (1/2 the radar wavelength ~20 m) *irregularities of the electron density*

SuperDARN – How the radar works

schematic propagation modes and backscatter regions



ray 1 penetrates the ionosphere with no returned echo,
ray 2 gives backscattered signal through ½ hop mode (F region),
ray 3 gives an additional echo through1½ hop propagation mode (F region)
ray 4 is gives backscattered signal through 1/2 hop mode from E region

from Ghezelbash et al, JGR, 2014, see also Milan et al, AG, 1997

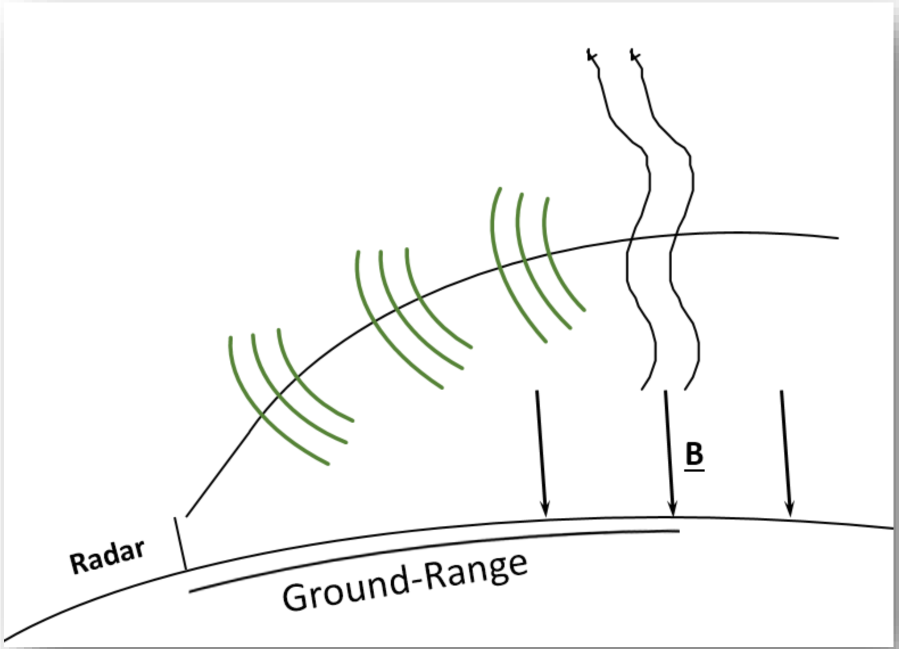
SuperDARN – How the radar works

In order to *measures ionospheric convection in the southern and northern mid and high latitudes and polar caps and observe the phenomena due to the plasma processes in the near Earth space* from the radar data are derived:

The velocity of the electron density irregularities (F region convection) from the Doppler shift in frequency between the transmitted signal and the received signal.

The back scatter signal power from the power of the received signal at the time of an echo.

The distance of the back-scattering irregularities from the time delay between transmission of an electromagnetic signal and reception of the echo.



SuperDARN – How the radar works

The radar is designed to detect targets out to a range of 4500 km with Doppler velocities of up to 2 km/s.

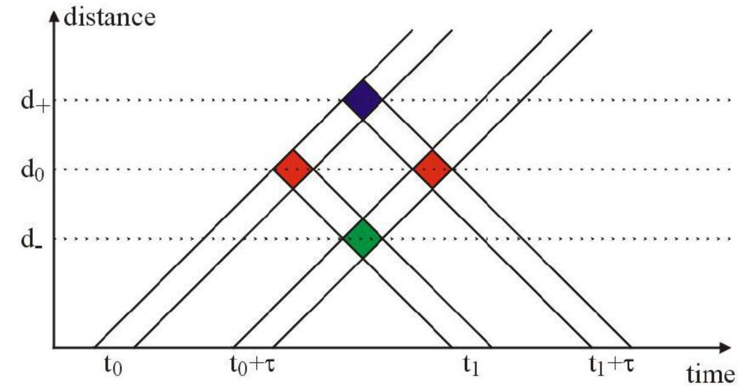
For a good estimate of the *range* a *long* interpulse period is required whereas to determine the *Doppler shift* a *short* interpulse period is necessary.

-> to simultaneously determine the range and Doppler velocity the radar uses sequences of unevenly pulses separated in time by integer multipliers of an "elementary lag time" τ

By sampling the *in-phase* and *quadrature voltages* returned by a coherent receiver, the complex autocorrelation function (ACF) can be computed for a fixed range and for each pulse of the sequence.

Averaging the returns over multiple sequence transmissions (~ 60 ACFs) partially suppresses the contributions from pulses that encounter other scattering regions at the same sampling times.

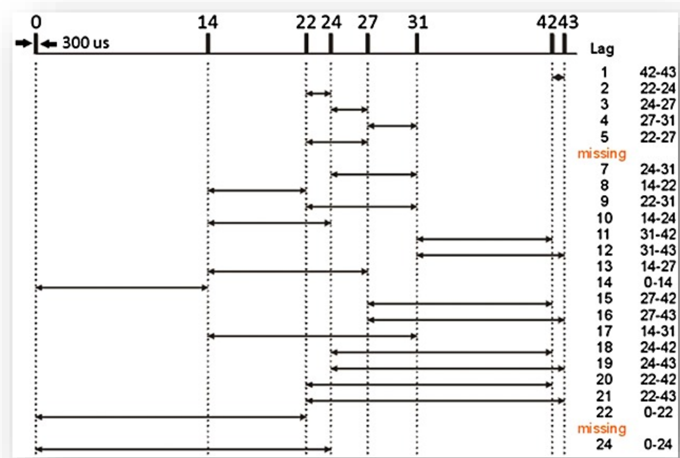
Averaged ACF for gate d0 at lag τ



$$\langle A(t_1)\cdot A(t_1+\tau)\rangle = \langle A_1(d_0)\cdot A_2(d_0)\rangle + \langle A_1(d_0)\cdot A_1(d_+)\rangle + \langle A_2(d_-)\cdot A_1(d_+)\rangle + \langle A_2(d_-)\cdot A_2(d_0)\rangle$$

- Average several return signals to minimize uncorrelated signal (phases) from different ranges (⟨ ⟩).
- This works if ionosphere correlated at d_0 over averaging time

$$\langle A(t_1)\cdot A(t_1+\tau)\rangle \sim \langle A_1(d_0)\cdot A_2(d_0)\rangle$$



See Ribeiro et al. 2013 and reference there in (e.g. Farley et al. 1972) and the tutorial by K. McWilliams et al., 2003

SuperDARN – How the radar works

The integrated ACFs are fit to model functions to get the velocity of the plasma, the spectral width, and the back scatter signal power (signal-to-noise ratio) as functions of range.

- The Doppler shift imposed on the frequency of the returned signal is manifested as a systematic variation of phase with lag:

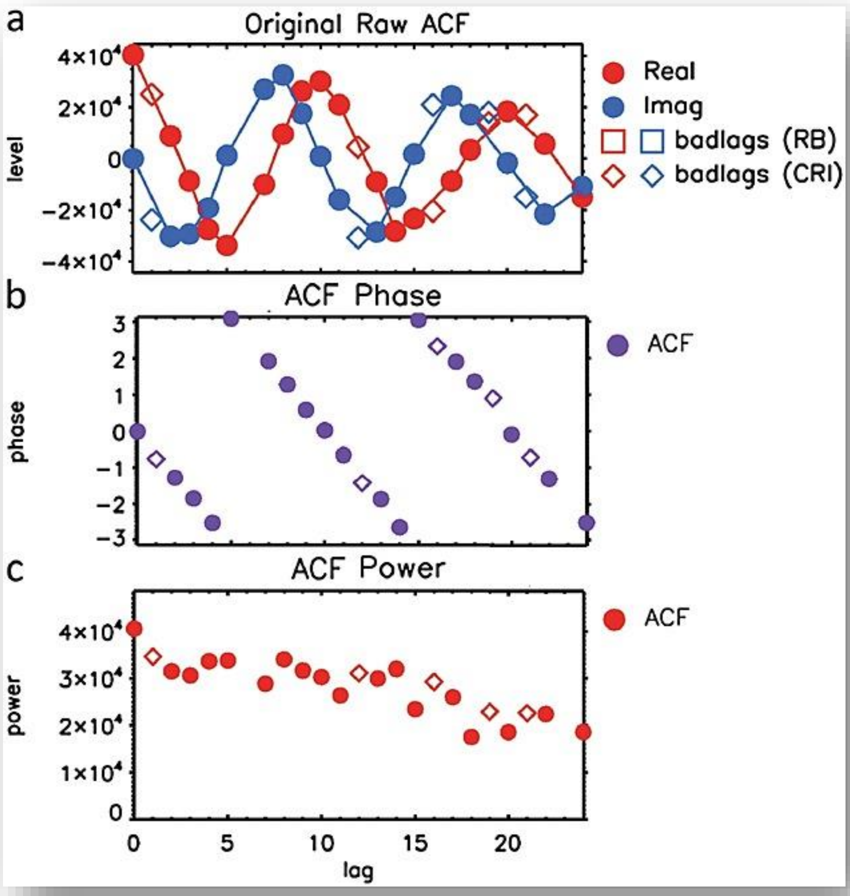
  $\phi = \arctan(Imag(\tau)/Real(\tau))$

  The line of sight (los) velocity of the plasma is given by the slope of the ACF phase.
- The spectral width is given by the ACF power decay time.
- The power is found using the fitted signal level at lag zero (maximum ACF power).

Computation of ACF parameters is achieved by fitting the lag phases and powers of the ACFs.

- Raw ACF data are contained in *.dat* files

- los velocity, power and spectral width are contained in *.fit* files obtained after the raw ACFs are processed with the traditional FITACF routine



From Ribeiro et al. 2013

SuperDARN – How the radar works

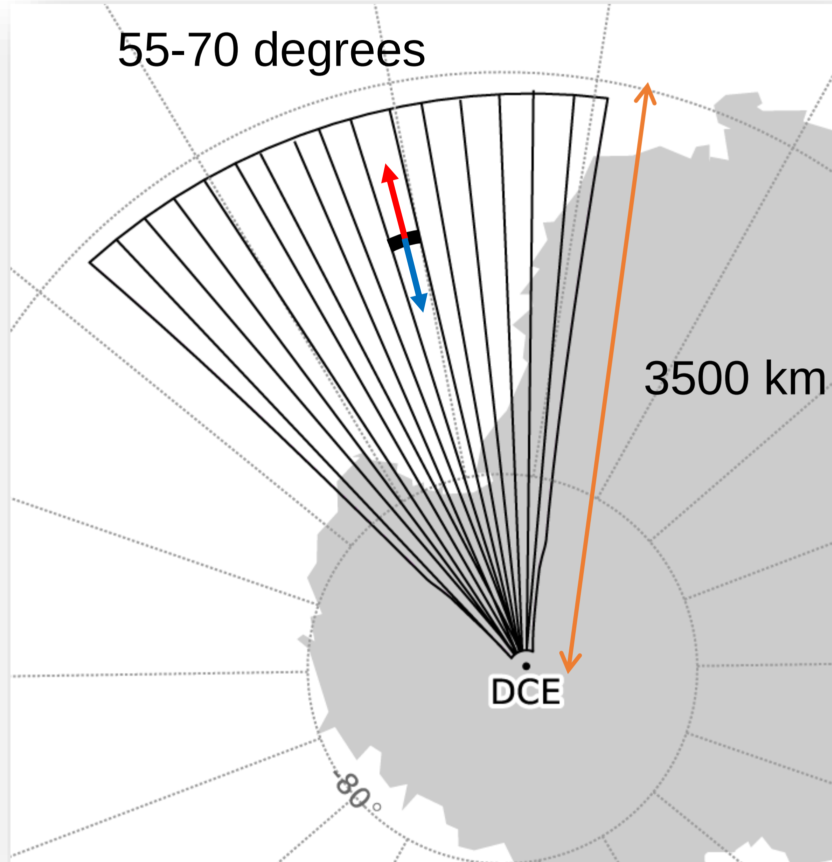
A phased array of antennae is used to steer the signal in **16 beam directions**

Multi-pulse sequences are used to produce the autocorrelation function (ACF) of the backscattered signal at each **range gate** and compute:

- The power of the backscattered signal (Signal to Noise Ratio)
- The width of the Doppler power spectrum
- The mean Doppler velocity: the line-of-sight component of the F-region plasma drift velocity.

75 range gates with **45 km** resolution
Total Field of View: **1200** range – beam cells

Time resolution for a complete scan:
1-2 minutes.



SuperDARN – How the radar works – Elevation angles

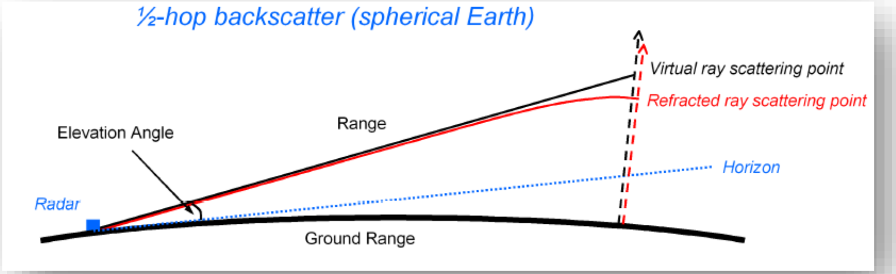
Knowing the scattering locations is very important for the mapping accuracy (the ground range determination) and requires estimation of the propagation paths of the high-frequency radio signal to and from the scattering volume.

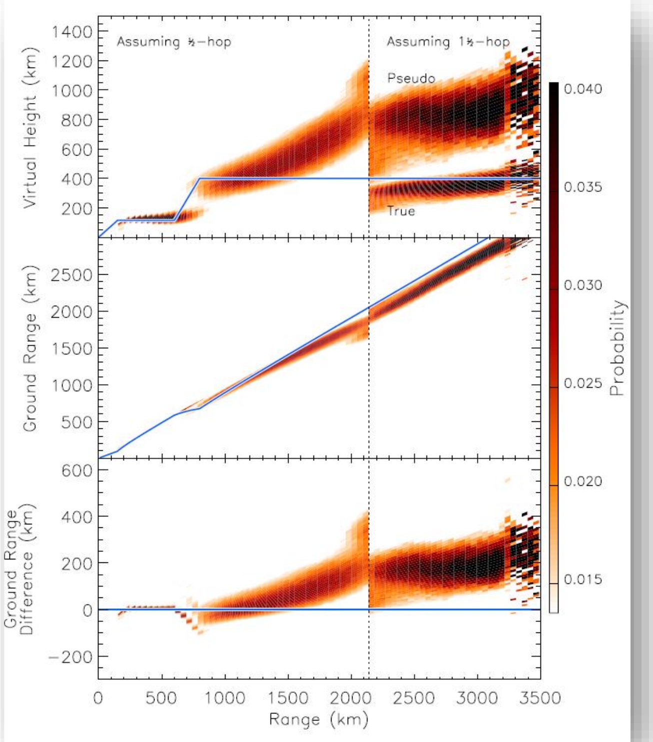
The SuperDARN radars comprise both a main (16 transmitting/receiving) and interferometer (4) antenna array to allow the estimation of the *elevation angle of arrival* of the returning signal.

However, elevation angle data have not been routinely used because they are based on the phase difference measurements whose calibration is critical.

The co-ordinates of scattering locations are usually estimated using a combination of the measured range and a model virtual height, assuming a straight line virtual propagation path.

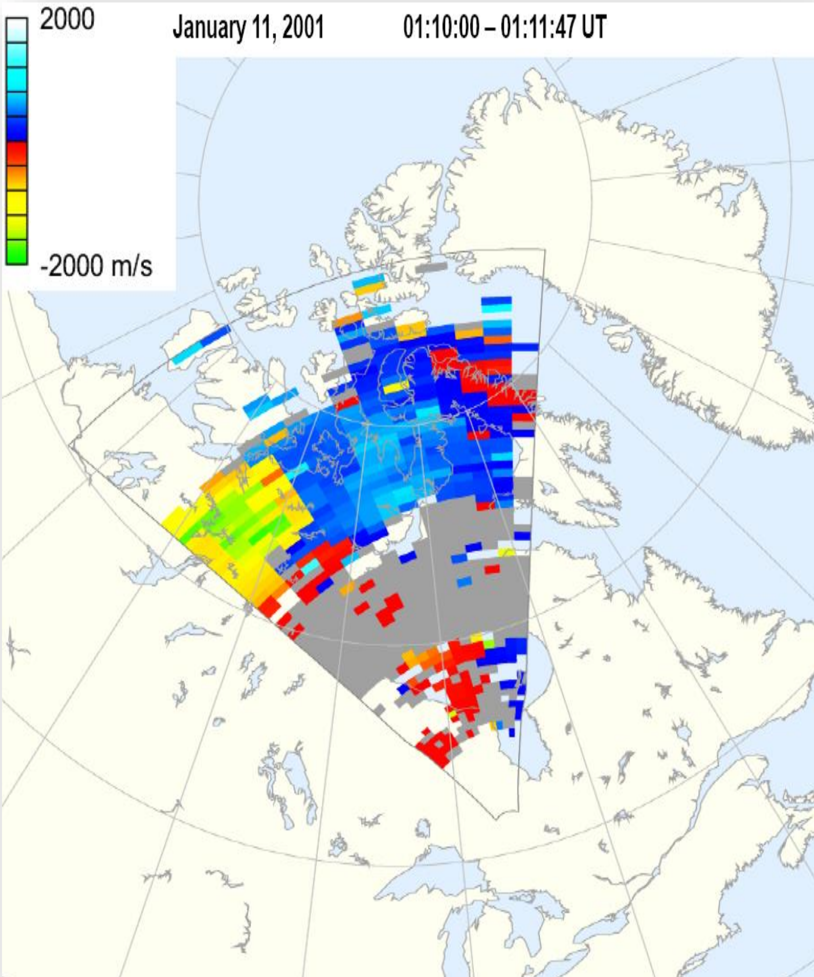
By studying the elevation angles of echoes from 5 years of data from the Saskatoon radar the actual distribution of the scattering locations in range-virtual height space has been determined and a new empirical virtual height model has been derived (giving more accurate mapping of geolocation).

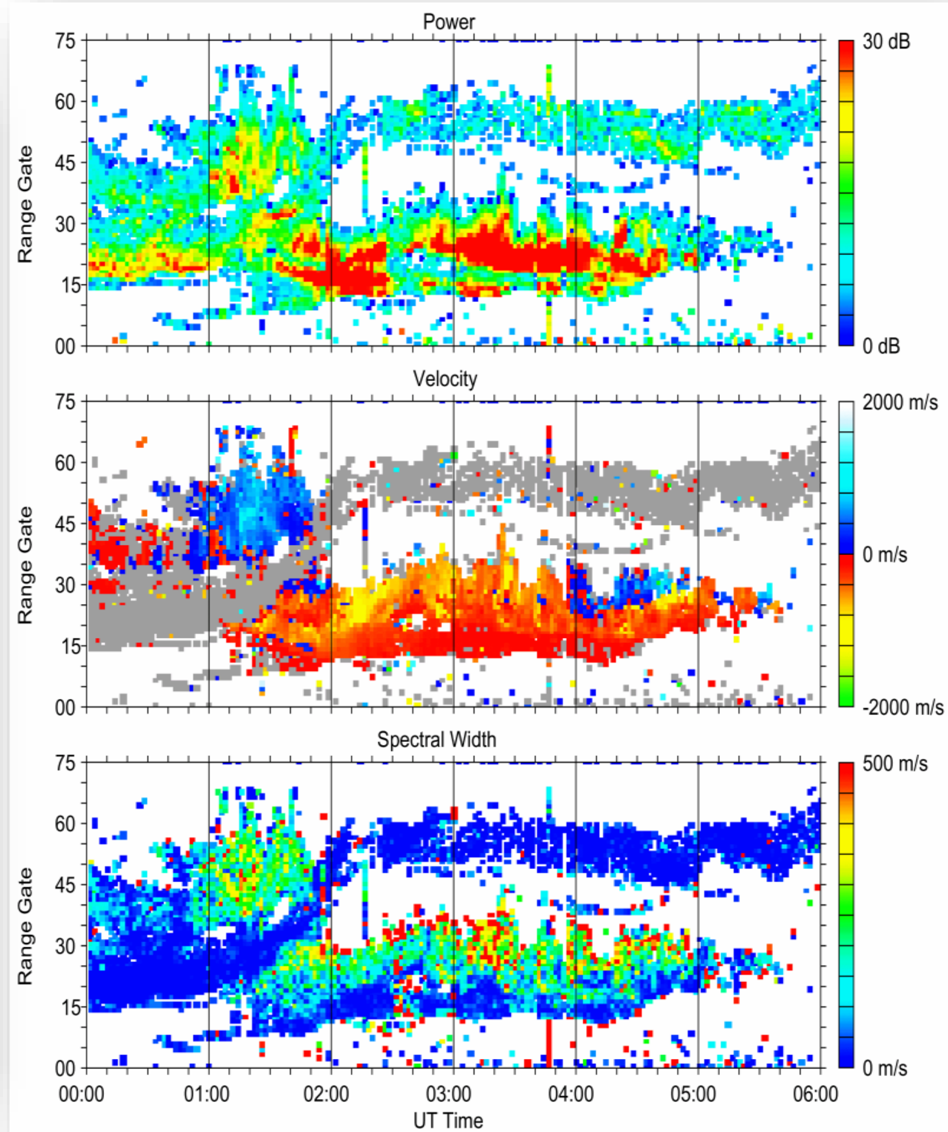




From Chisham et al. 2008

SuperDARN – Field of View and Range Time Plot





SuperDARN – ionospheric irregularities

Sources: Magnetospheric plasma circulation, electron-density gradients, FAC, shear flows, temperature gradients.

Instability processes:
Gradient Drift instability (E and F region) – most relevant - strong electric field not aligned with a background plasma density gradient.
(Two-stream instability - E-region, Electrostatic Ion Cyclotron instability - E and F region, Temperature Gradient instability - F region, Kelvin-Helmholtz instability - F region, … ?)

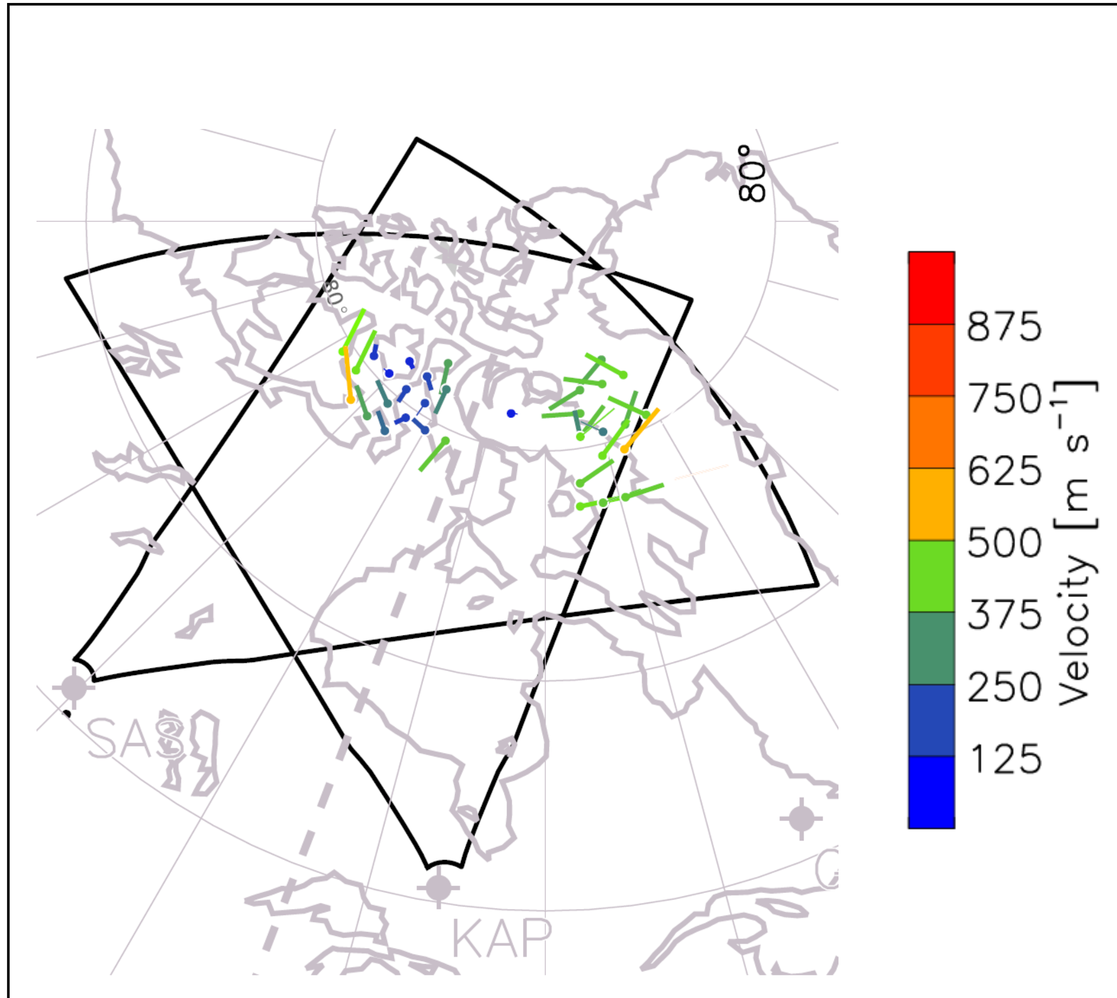
Echos occurrence: varies with radar location, time of day, season and solar cycle, interplanetary magnetic field (IMF) magnitude and orientation, occurrence of magnetic storms and substorms.

Absence of Echos: degradation of propagation conditions, precipitation-induced D-region radio absorption (substorms), sunlight smoothing

SuperDARN – that's why *Dual*

Usually the radars form pairs:

- their beams intersect roughly at right angles
- the full two dimensional horizontal velocity vector of the ionospheric plasma convection can be calculated from the Doppler speed measured along each beam.



SuperDARN – coverage

In the 1980s - first coherent-scatter radars to study ionospheric convection at polar latitudes with the Scandinavian Twin Auroral Radar Experiment (STARE)

Radio Science, Volume 13, Number 6, pages 1021–1039, November–December 1978

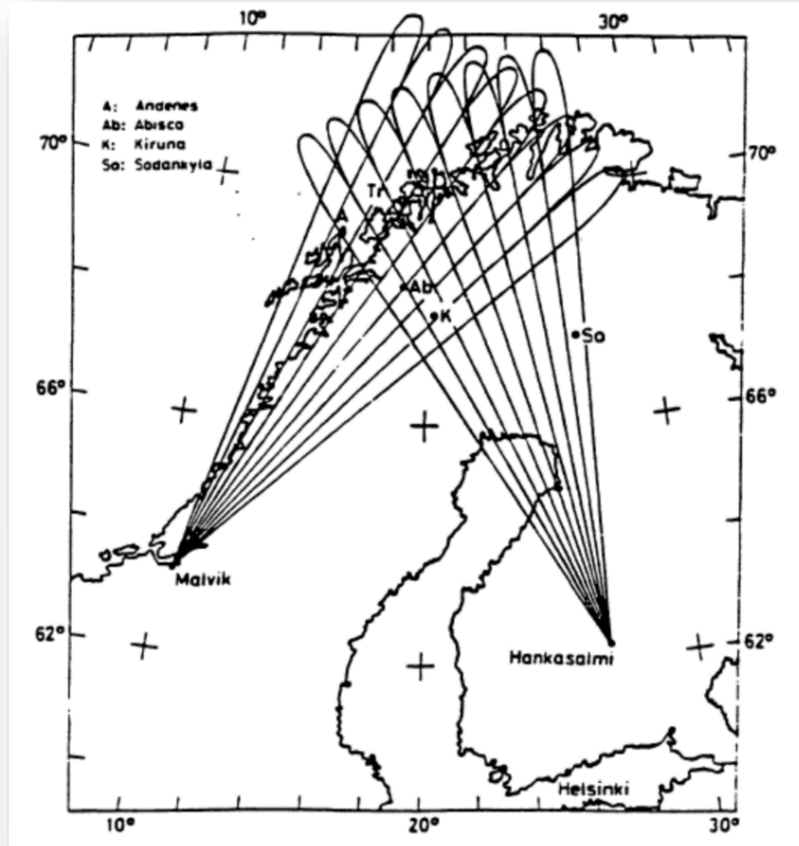
STARE: A new radar auroral backscatter experiment in northern Scandinavia

R. A. Greenwald, W. Weiss, and E. Nielsen

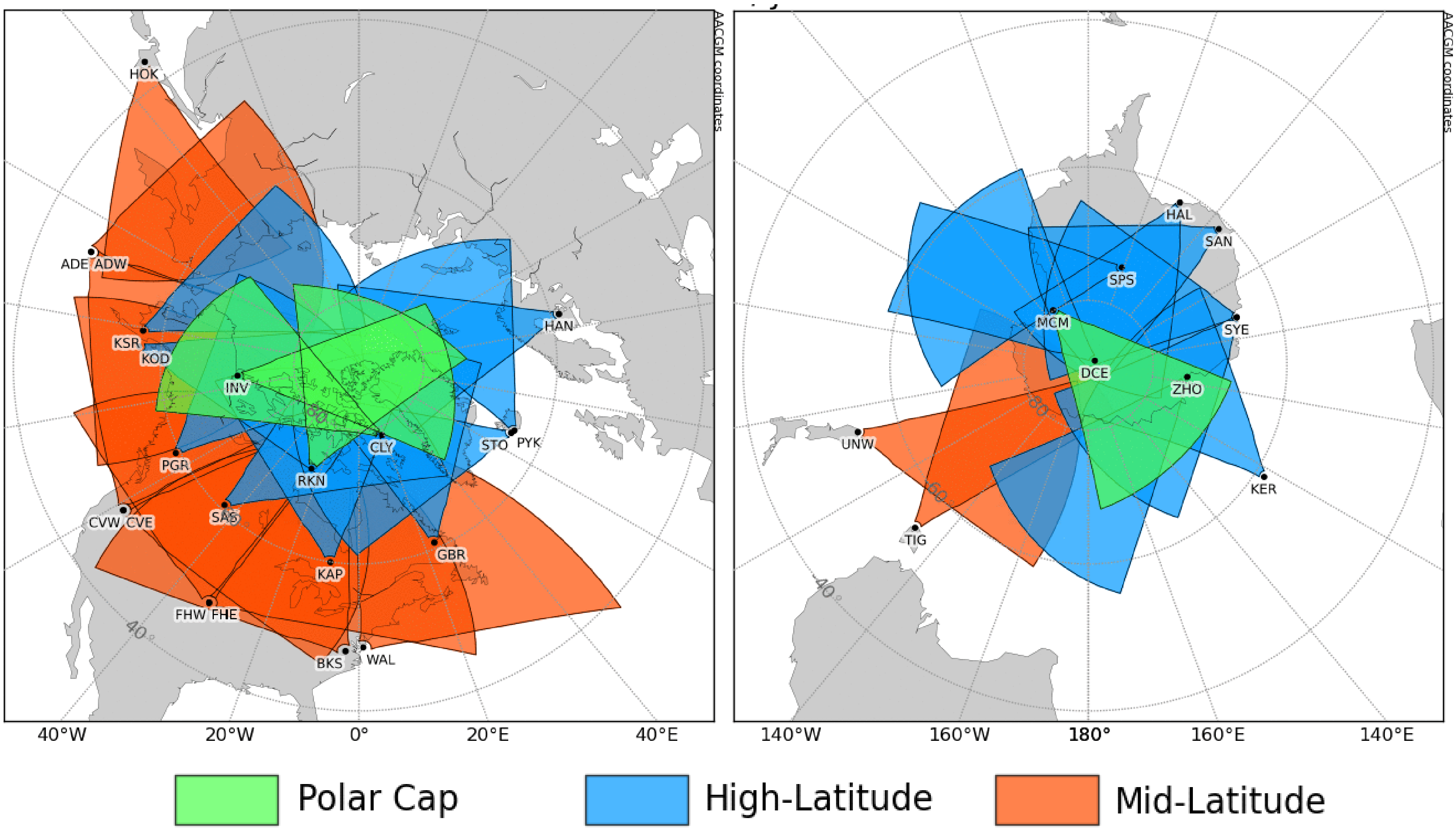
Max-Planck-Institute für Aeronomie, 3411 Katlenburg-Lindau 3, Federal Republic of Germany

N. R. Thomson

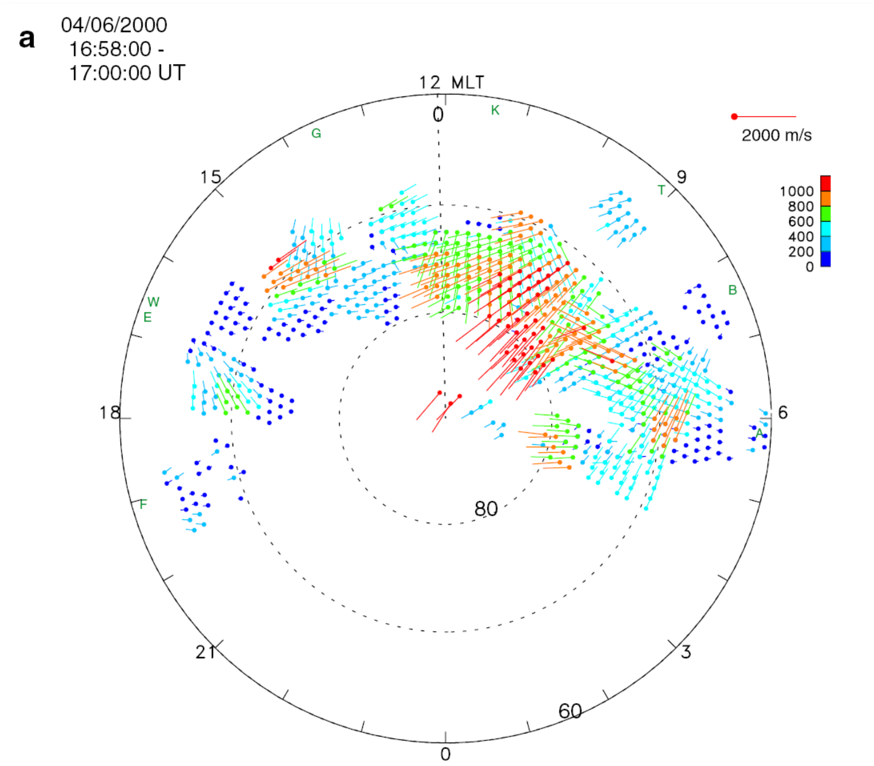
Physics and Engineering Laboratory, DSIR, Lower Hutt, New Zealand

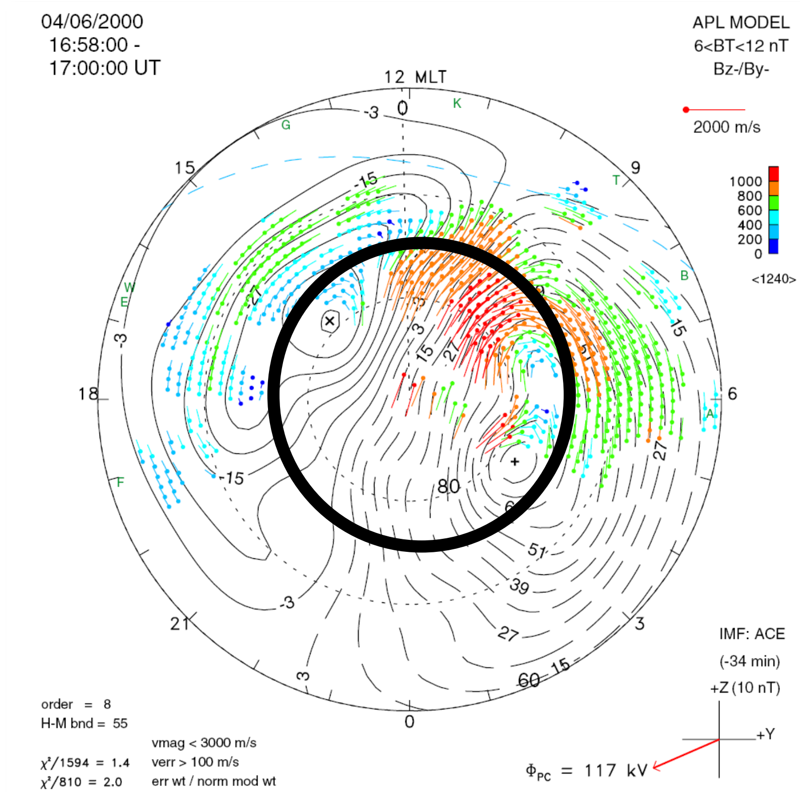


SuperDARN – coverage



SuperDARN – **global ionospheric convection**





SuperDARN filtered line of sight velocity vectors that have been fitted to an equi-area global grid.
(.grd files)

Convection map based on SuperDARN velocity measurements. The measurements are used to determine a solution for the electrostatic potential exspressed as a series expansion in spherical harmonics. A statistical model is used to constraint the solution in region with no data.
(.map files)

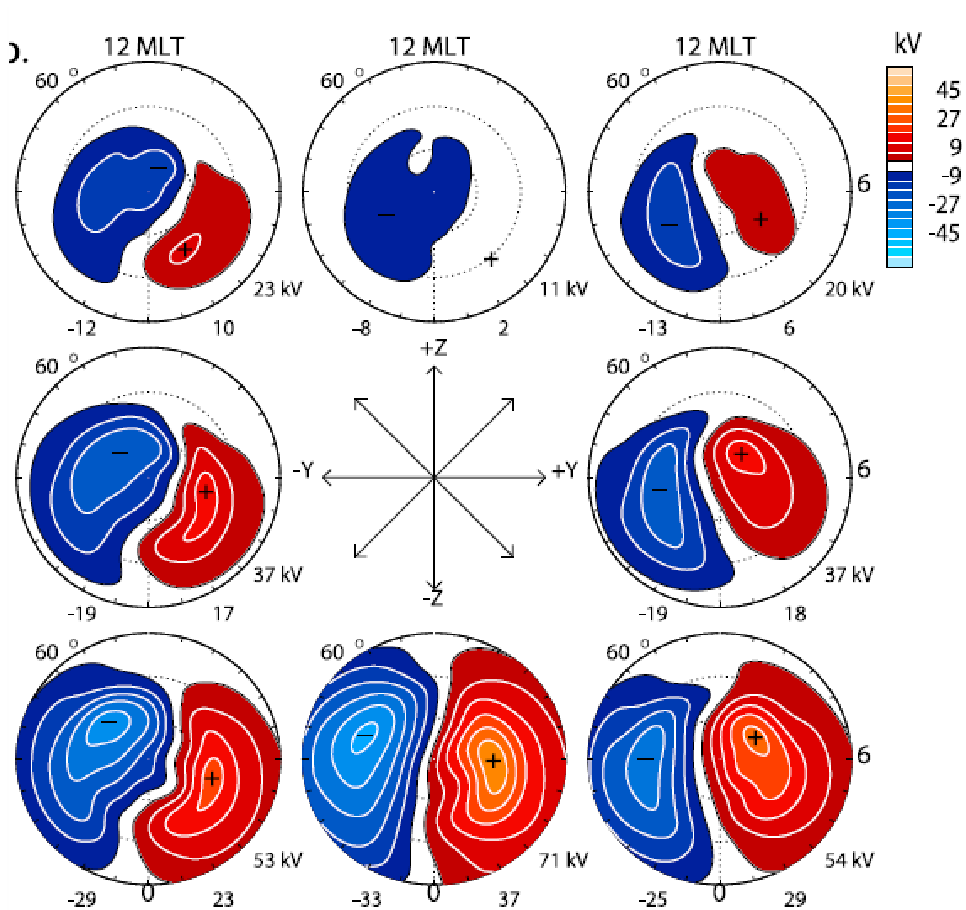
Ruohoniemi and Greenwald, 1996

SuperDARN – **global ionospheric convection**

A discrete set of climatological patterns of high-latitude ionospheric convection derived independently for the Northern Hemisphere and Southern Hemisphere and for different

- solar wind
- IMF
- and dipole tilt angle

based on velocity data from nine high-latitude radars in the Northern Hemisphere and the seven radars in the Southern Hemisphere **from January 1998 through December 2005**.

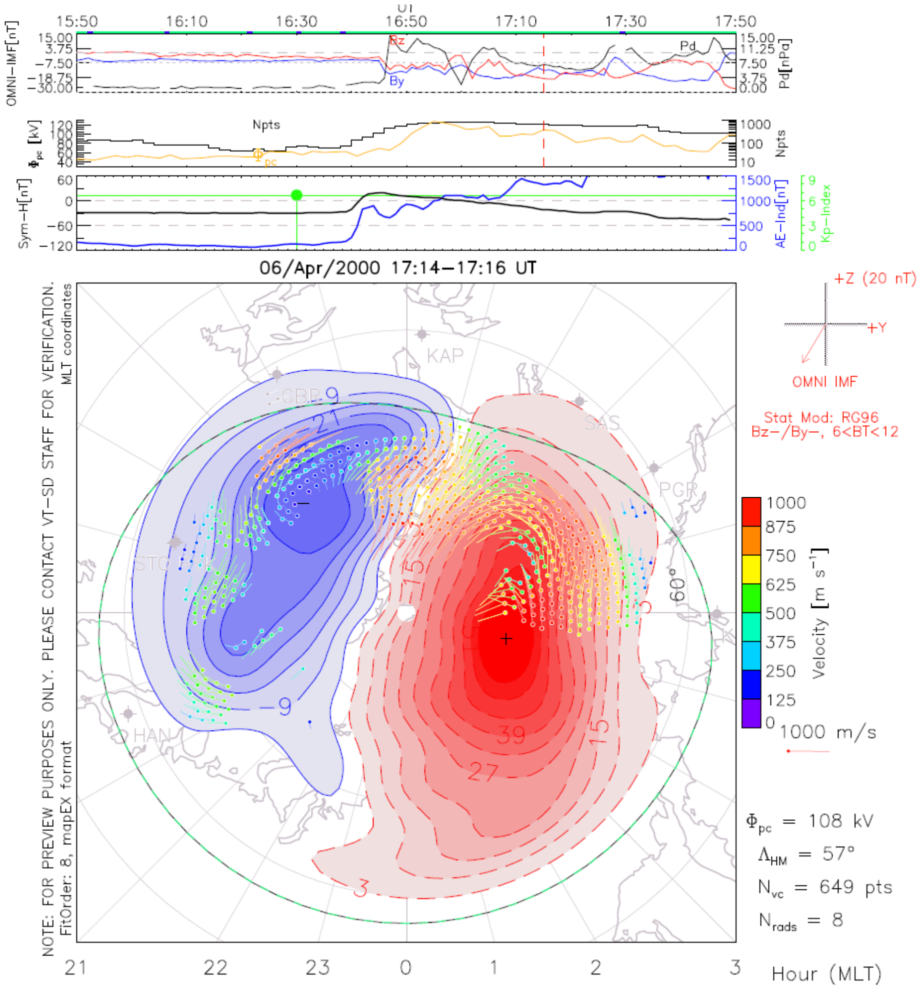


Cousins and Shephard, 2010

SuperDARN – **global ionospheric dynamics**

Following a southward turning the convection intensify rapidly (2 m) and the cross polar cap potential rises to its maximum value in 10 m.

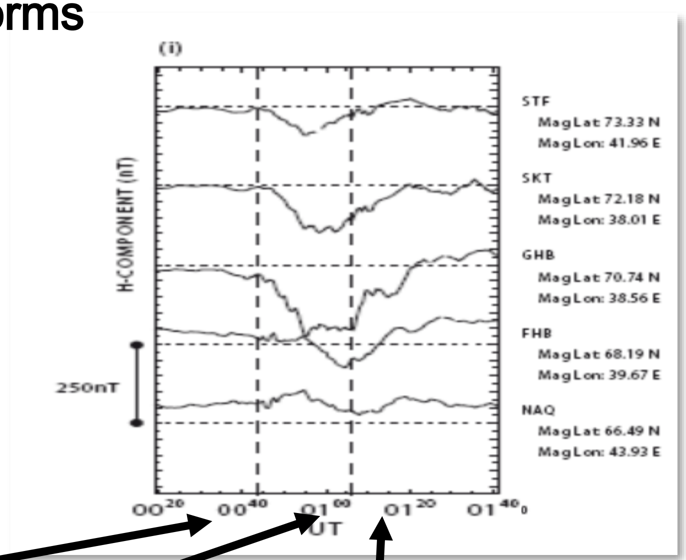
Capability of observing the temporal evolution of the convection reconfiguration in response to variations in the IMF and within the magnetosphere.

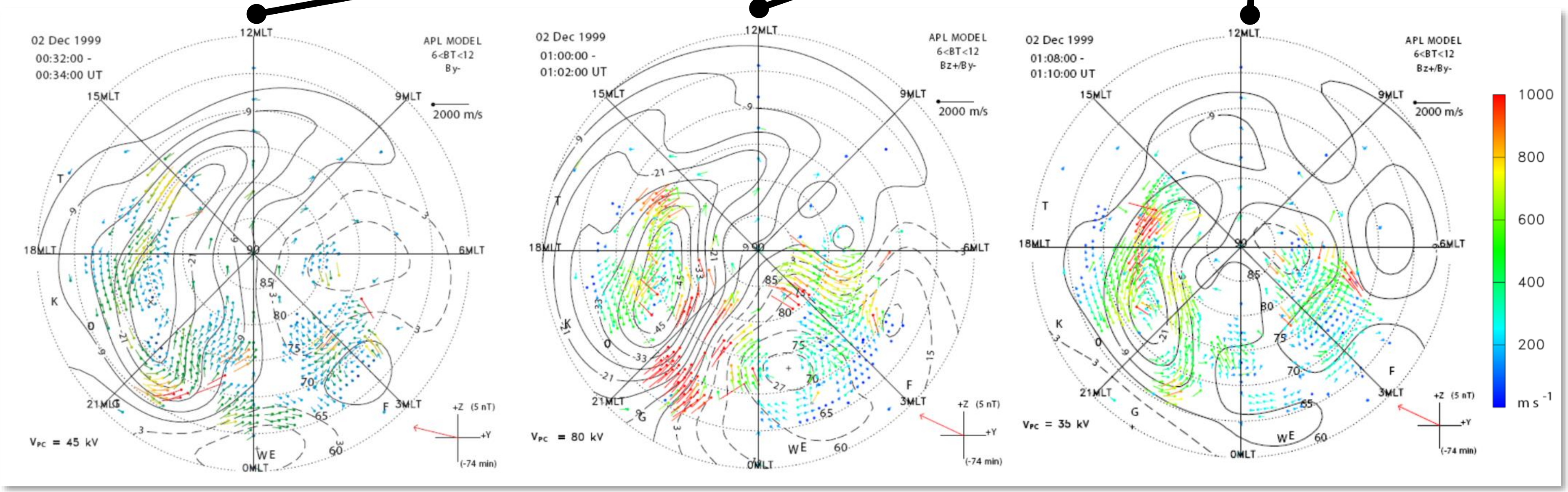


SuperDARN – **enhanced flows associated with substorms**

Substorm occurred during steady northward IMF:

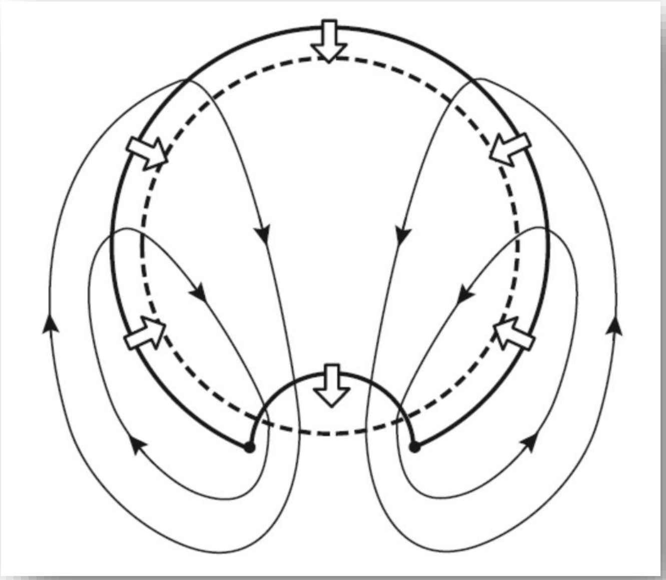
large-scale flow associated with the substorm expansion phase.





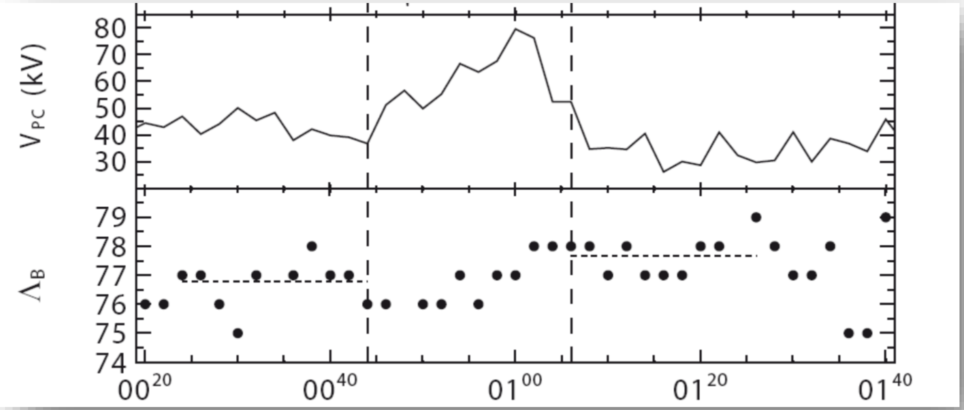
Grocott, 2002

SuperDARN – **enhanced flows associated with substorms**



The flow pattern was of twin-vortex form.

The net closure of open flux represents 15–20% of the open flux present at onset corresponding to an overall contraction of the open-closed field line boundary by 1 degree in latitude.



Total transpolar voltage and the estimate of the latitude of the flow reversal boundary on the dusk meridian, related to the OCB obtained from the minimum in the electrostatic potential

Grocott, 2002

SuperDARN – imaging magnetospheric regions with the spectral width

The Doppler spectral width is a measure of the spatial and temporal structure in the ionospheric electric field on scales comparable to, or less than, the radar measurements.

– A region of very high spectral width (350 m/s) is collocated with the ionospheric cusp/cleft region.

– An oval shaped region of high spectral width (250 m/s) near the poleward limit of the Holzworth and Meng auroral oval. This region could be linked to magnetic field lines originating in the outermost regions of the magnetosphere.

– A region of lower spectral width at lower latitude that could be related to closed field lines, associated with regions located deeper in the magnetosphere.

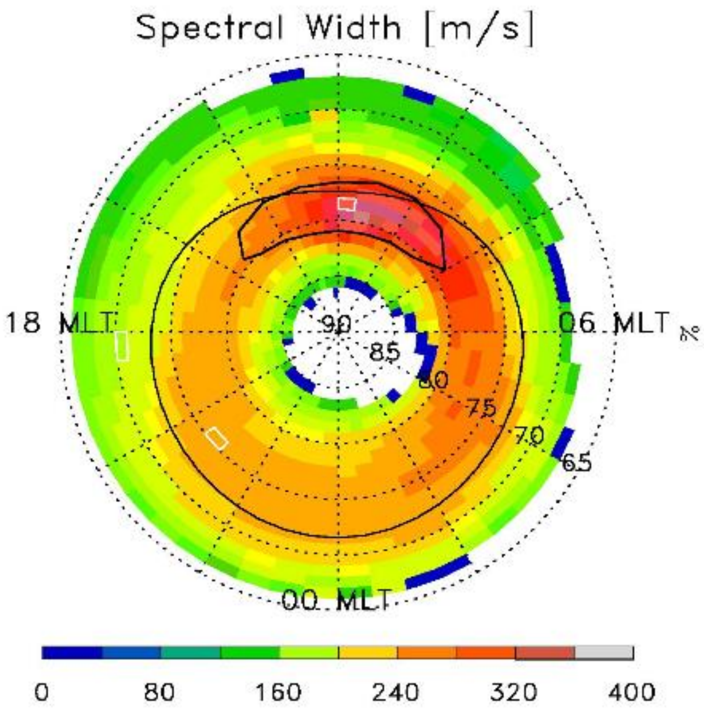
– A region of lower spectral width at very high-latitudes that could be related to magnetic field lines connected with the Interplanetary Magnetic Field (IMF).

Annales Geophysicae (2002) 20: 1769–1781 © European Geosciences Union 2002

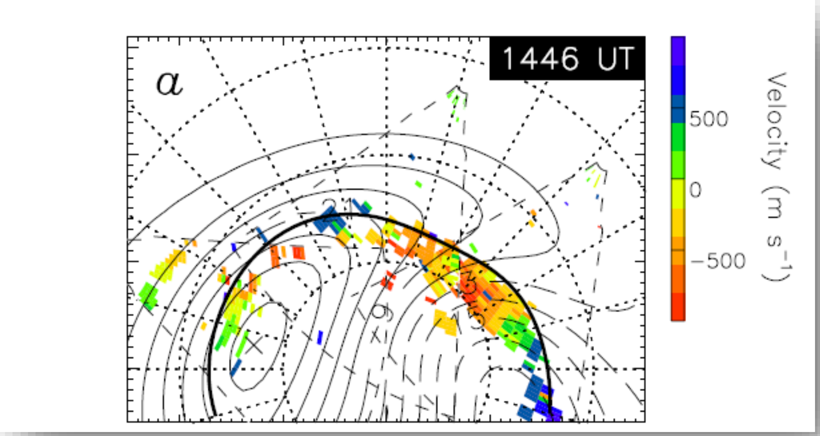
Annales Geophysicae

A Statistical study of the Doppler spectral width of high-latitude ionospheric F-region echoes recorded with SuperDARN coherent HF radars

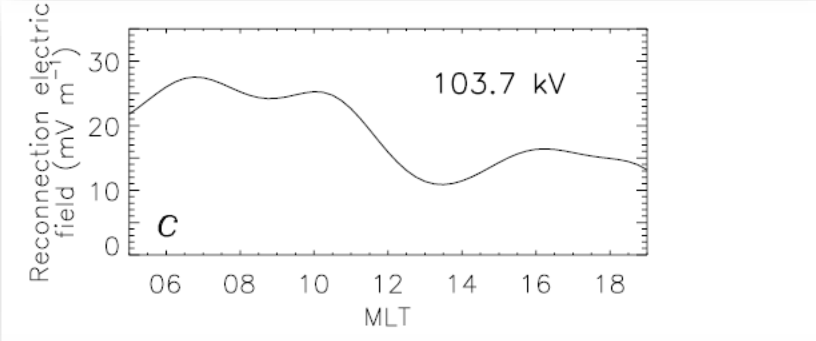
J.-P. Villain[1], R. André[1], M. Pinnock[2], R. A. Greenwald[3], and C. Hanuise[4,*]



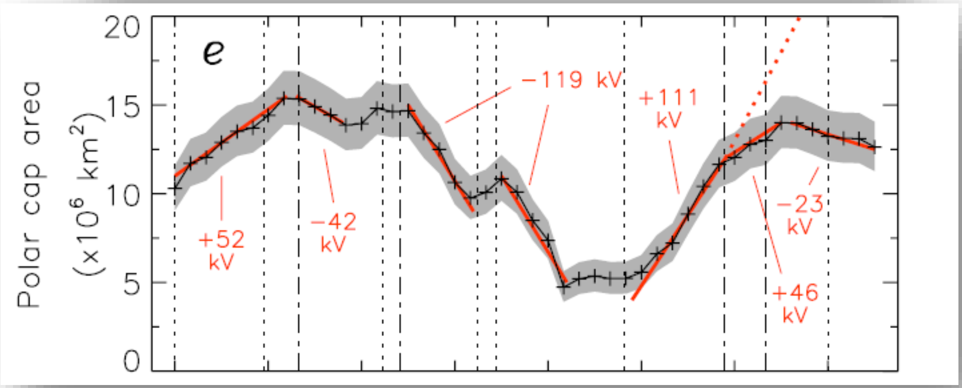
SuperDARN – **OCB identification and reconnection rate estimation**



The OCB (solid line) determined from the equatorward edge of high spectral width backscatter.



The reconnection electric field determined from the plasma drift perpendicular to the OCB. The integral of this along the boundary between 05 and 19 MLT

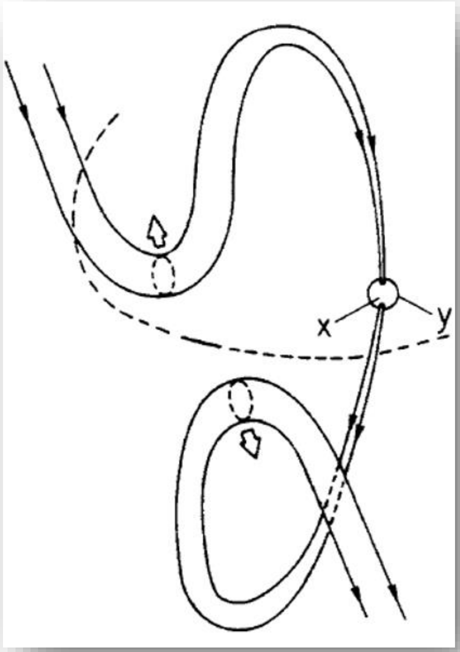


Polar cap area variation deduced from the OCB estimates during substorm

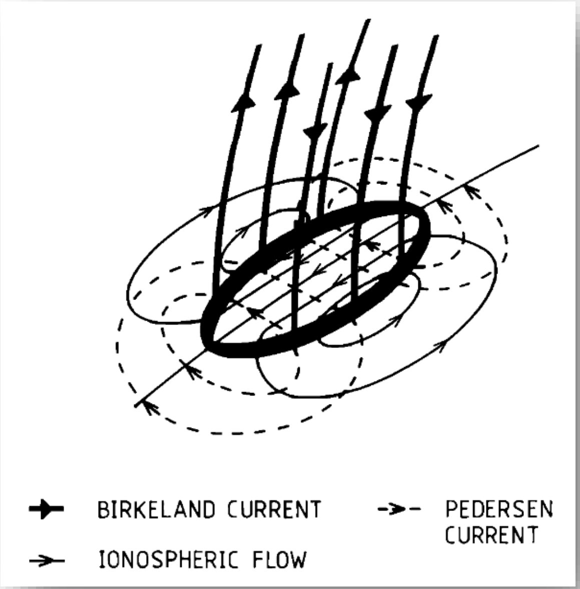
Milan et al. 2003

SuperDARN – **Flux Transient Events**

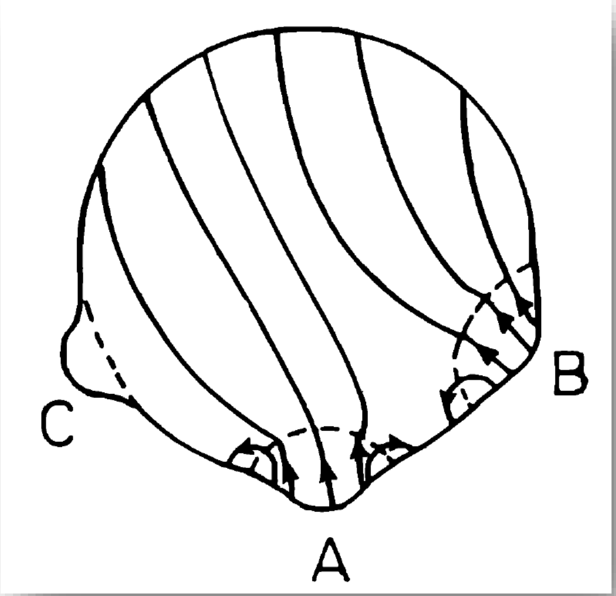
Patchy and transient reconnection



Size 1-2 RE

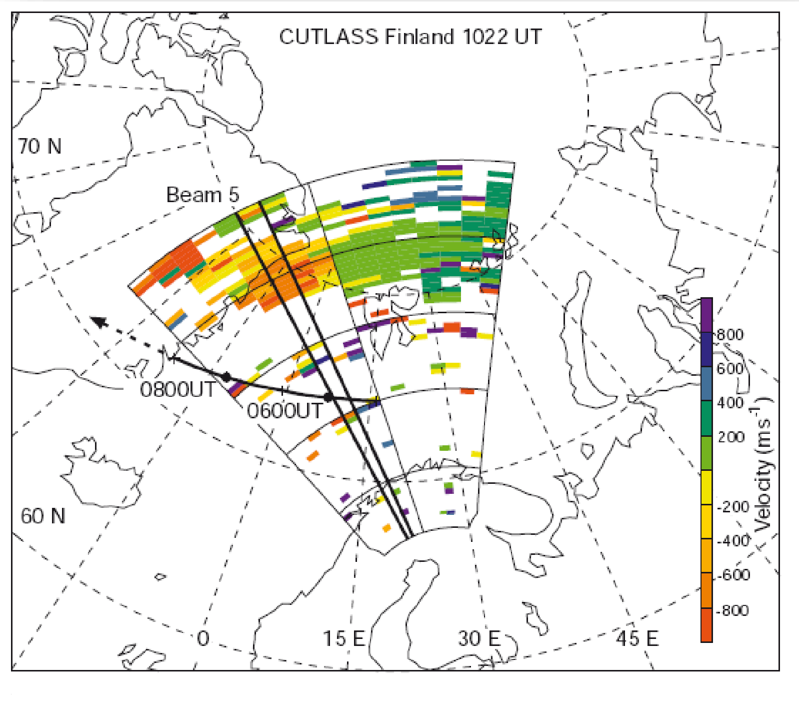


Southwood (1987) model

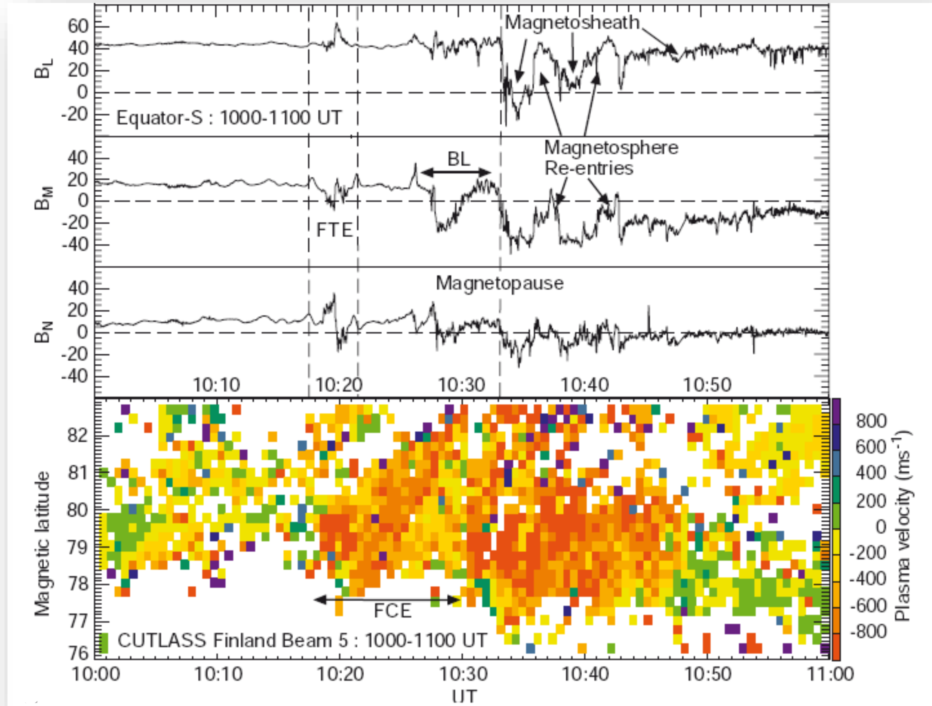


Mesoscale signature on ionospheric convection

SuperDARN – **Flux Transient Events**



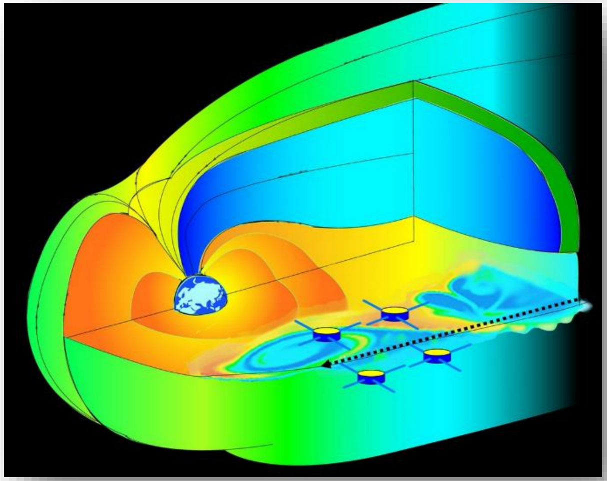
“Flow channels" on newly-opened cusp field lines



The equatorward border of the region of backscatter moves equatorward consistent with an overall expansion of the polar cap.

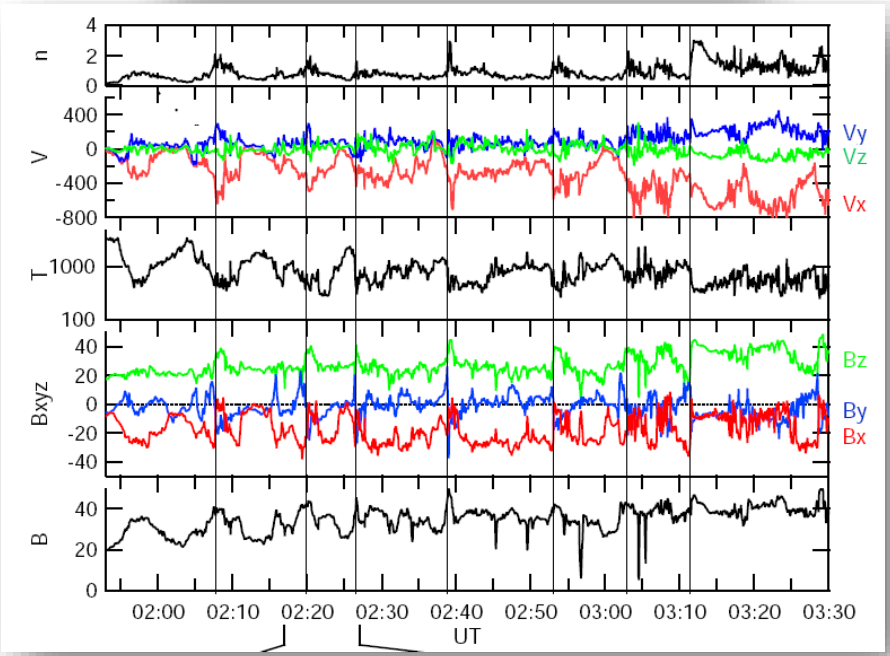
Neudegg et al., 1999

SuperDARN – **K-H at the magnetopause**



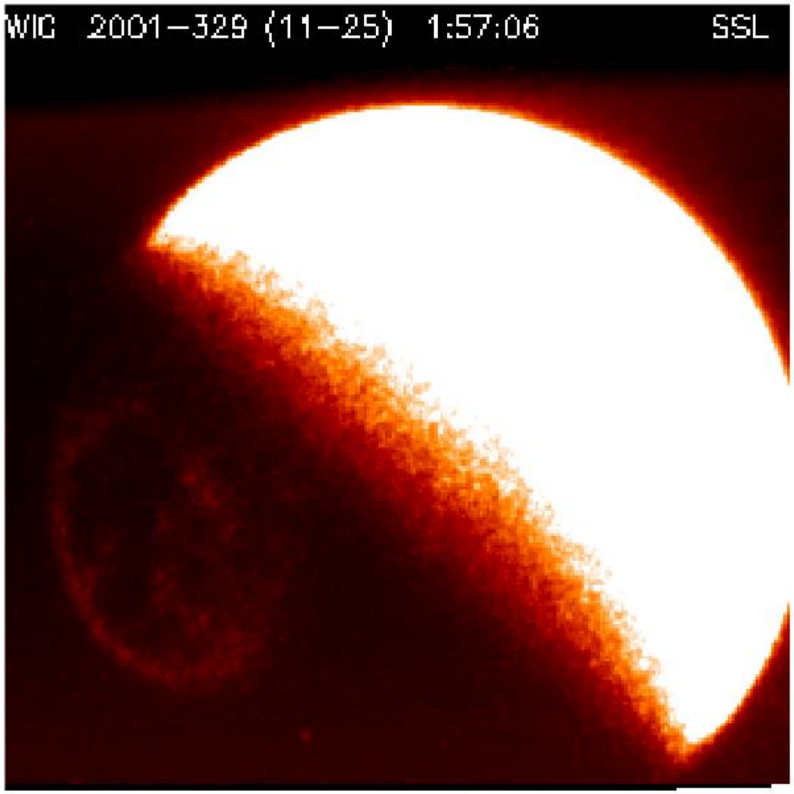
When a large a large velocity shear exists across the MP, the condition for onset of KHI are favorable and large scale vortices develop at the flank of the magnetopause

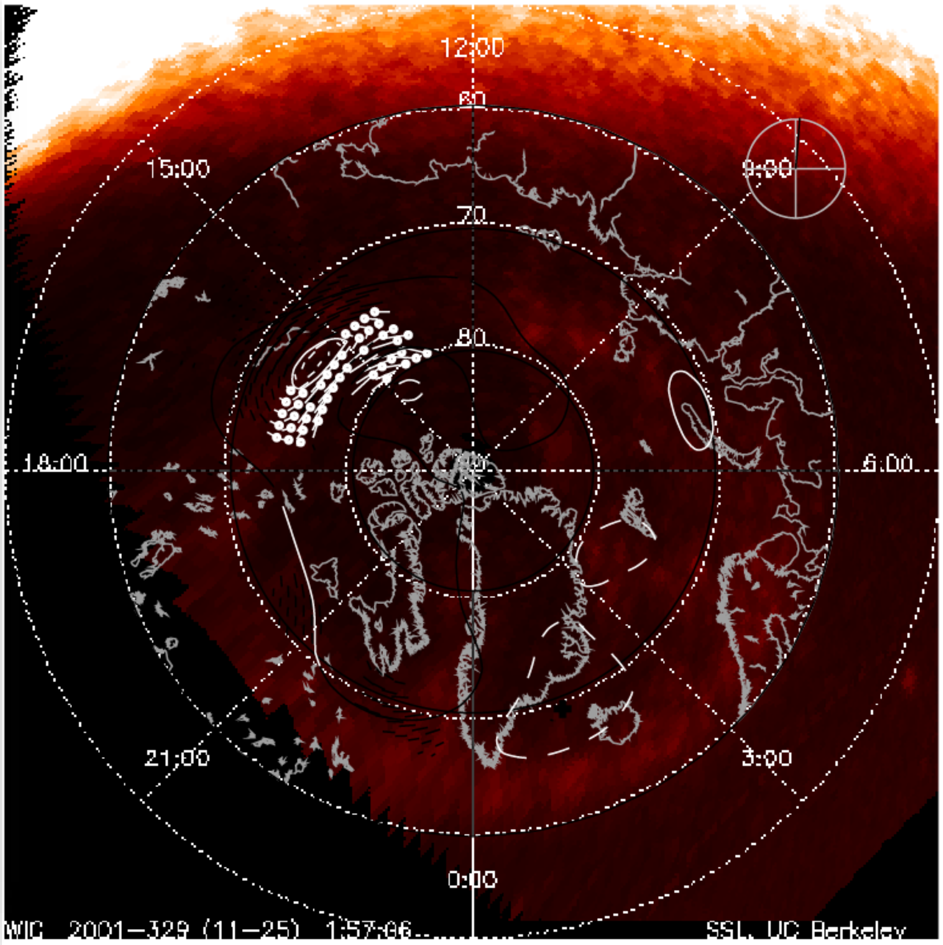
During a long lasting period of northward interplanetary magnetic field and high solar wind speed (above 700 km/s), Cluster spacecraft constellation traversed the dusk magnetopause and went across a number of very large rolled-up Kelvin-Helmholtz (KH) vortices.



Bavassano Cattaneo, 2010

SuperDARN – **K-H at the magnetopause**

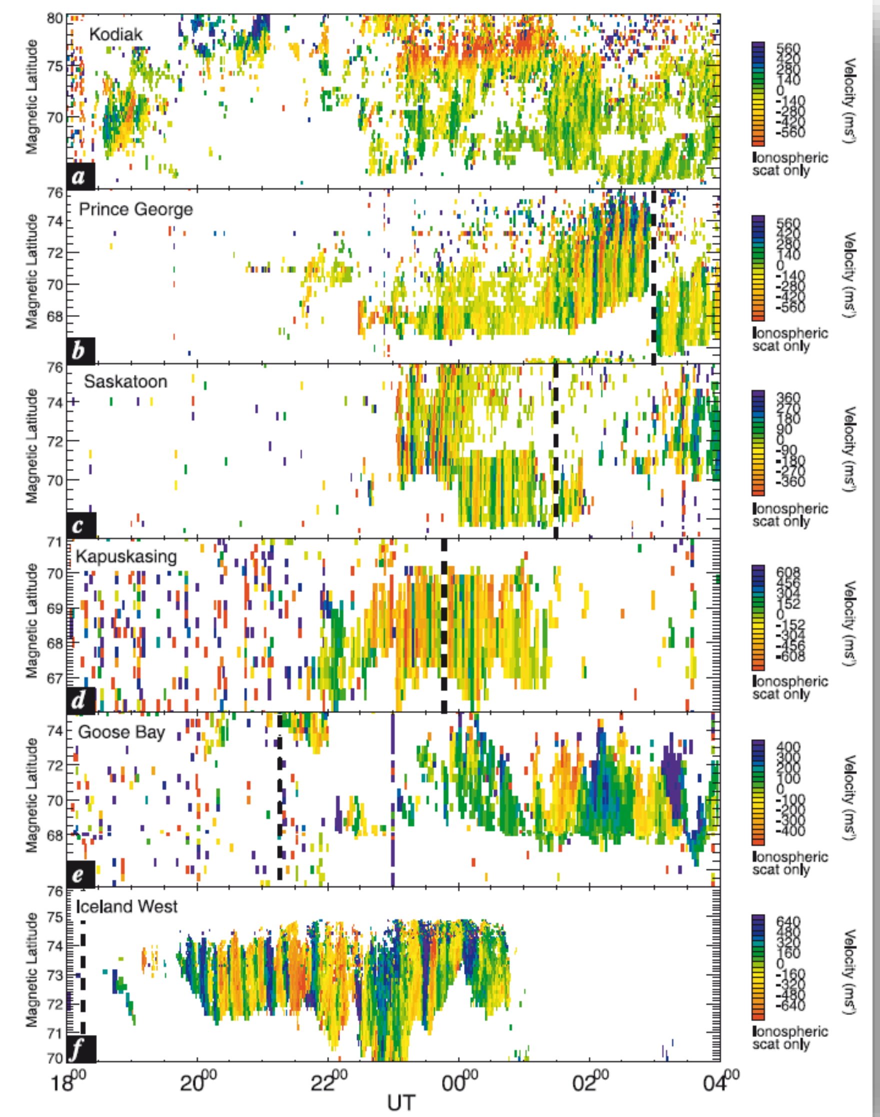




SuperDARN – **K-H at the magnetopause**

Large-amplitude nearly monochromatic pulsations were observed ubiquitously in the magnetosphere and ionosphere.

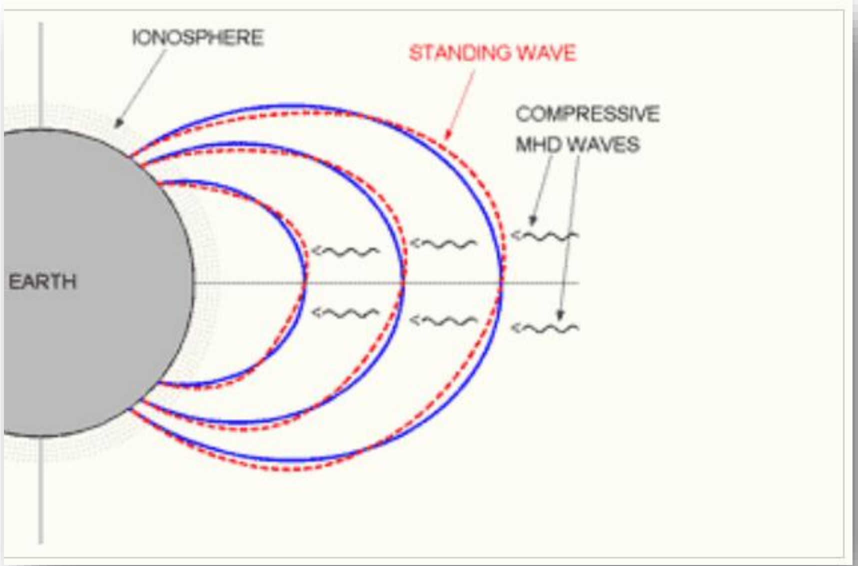
Since the SuperDARN HF radars appear to be poleward of the region of the excited FLR and map to L shells close to the magnetopause, the ionospheric flows must be related to the K-H mechanism rather than the excited field line resonance observed in the magnetometer stations.



Rae et al., 2005

SuperDARN – **ULF waves**

Different processes taking place in the magnetosphere results in two types of MHD waves:
The magnetosonic wave - propagating in any direction and generating compression and rarefaction both of the magnetic field and plasma;
Alfvén waves - propagating along the direction of the ambient magnetic field and producing magnetic perturbations transversal to the field lines.

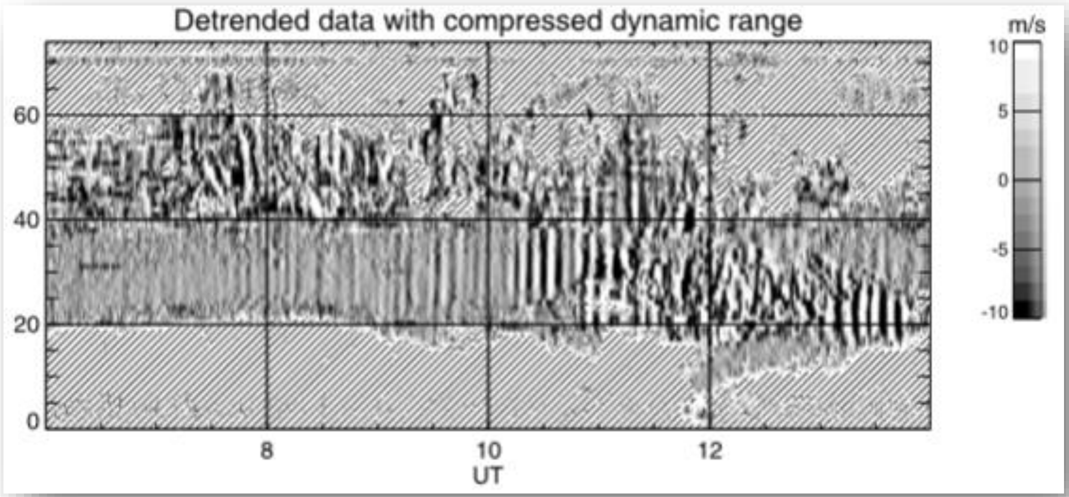


Origin of ULF can be in the solar wind or internal

SuperDARN – **ULF waves**

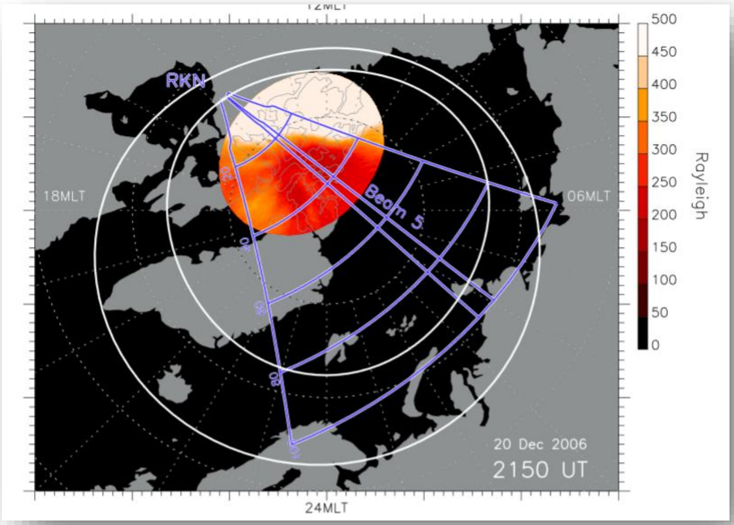
Periodic oscillations in the Doppler velocity arise due to the drift velocity generated in the ionosphere by the ULF wave electric field and background geomagnetic field.

In ionospheric backscatter, these oscillations arise mostly from the horizontal component of V and have amplitudes up to about 100 m/s.



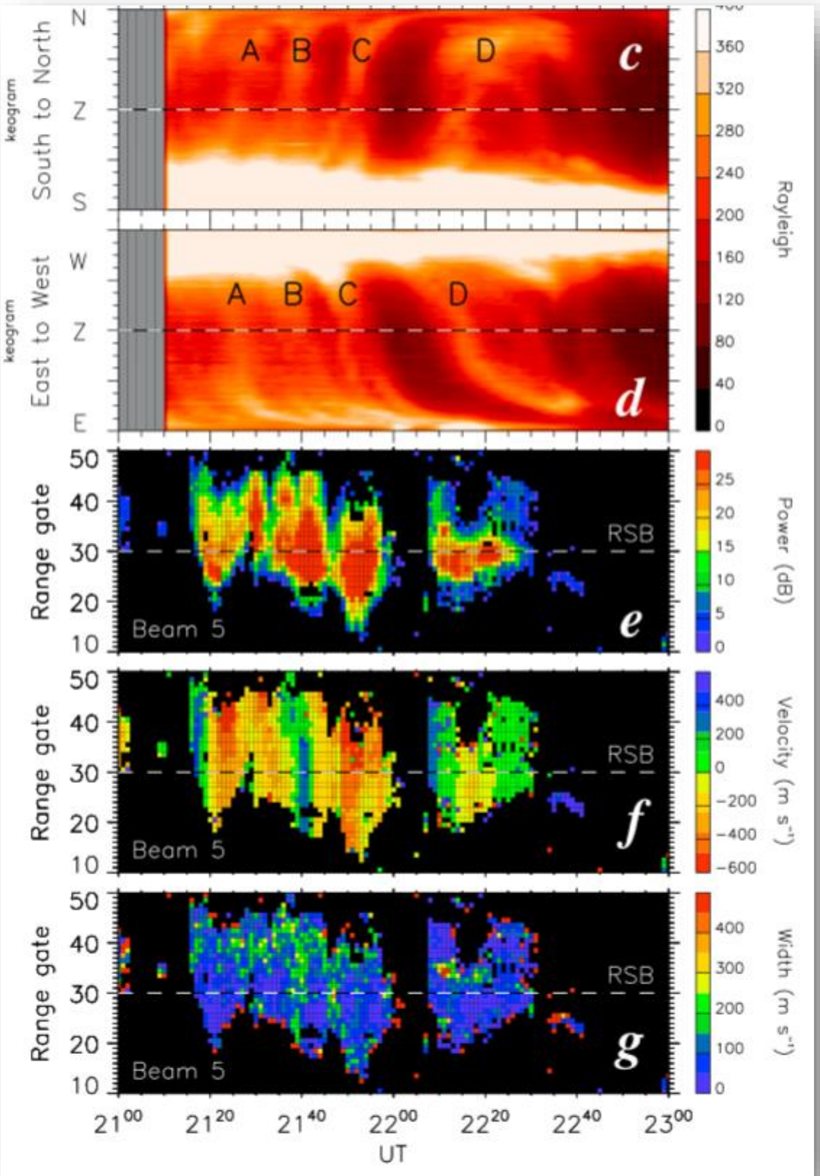
Ponomarenko et al. , 2005

SuperDARN– **polar cap patches**



Radar echoes are caused scatter from field-aligned irregularities associated with polar patches.

Investigation of the instabilities producing the irregolarities and dynamics of patches

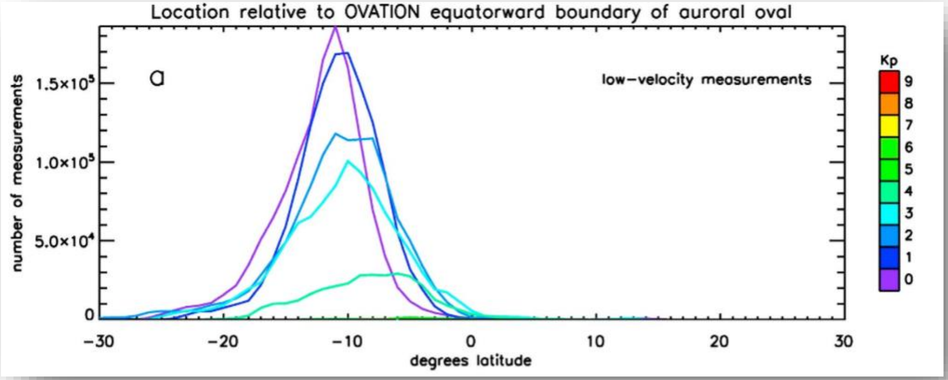


Hosakawa et al. 2009

SuperDARN– mid latitude radars

Mid latitude radars - new areas of research. SuperDARN in this latitude region commonly make measurements within the region of the ionosphere that is conjugate to the inner magnetosphere

- Subauroral Polarization Streams during geomagnetic storms
- Penetration electric fields during storms and non-storm periods
- Structuring and transport of sub auroral plasma (plasmaspheric plumes)
- Subauroral plasma irregularities (plasmasphere instabilities)
- ULF waves and pulsations



The mid latitude ionosphere is quite active as far as irregularities presence, the associated scatter has low Doppler velocities and spectral widths and is distinctly sub-auroral - on field lines that map into the plasmasphere.

Ribeiro et al. 2013

SuperDARN– summary of scientific topics

Structure and dynamics of global ionospheric convection.

Mesoscale signatures of magnetosphere-ionosphere coupling.

Ionospheric flow bursts associated with magnetopause reconnection (FTEs).

Convection associated with auroral substorms.

Electromagnetic waves: MHD, ULF, Magnetic Field Line Resonances.

Ionospheric irregularities and highlatitude plasma structures (patches).

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