Using the Radio Spectrum to Understand Space Weather

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Topics to be Covered

- What is Space Weather?
  - Origins and impacts
- Analogies with terrestrial weather
- Monitoring Space Weather
  - Spacecraft, Radars, Optics, Magnetometers
- Goose Bay radar → SuperDARN
- What does SuperDARN contribute to Space Weather research?
- Summary

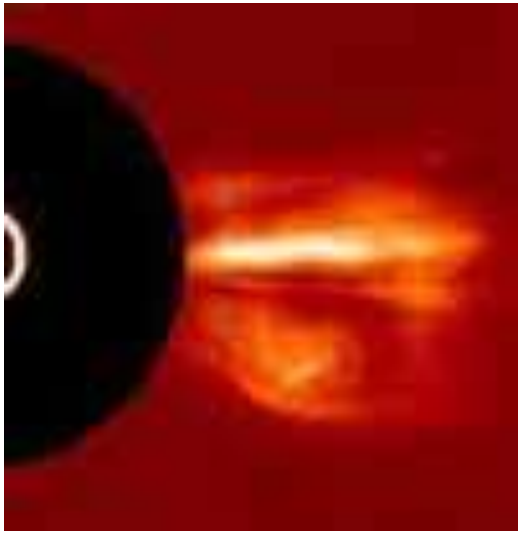
Space Weather: An Evolving Discipline

- Space has been known to be a hazardous environment since the beginning of the “space age”.
  - e.g. Van Allen Radiation Belts, Major Solar Eruptions
- We have mapped the particle and field environment throughout much of the solar system and are beginning to understand how the various regions interact.
  - Importance of Coronal Mass Ejections
  - IMF control of solar-wind/magnetosphere coupling
  - Importance of ionospheric boundary conditions

Space Weather: An Evolving Discipline

- We have developed a wide range of models to describe the solar-terrestrial system, but
  - the models have varying degrees of sophistication
  - they are not been properly coupled,
  - they do not include all of the necessary physics.
- We do not have an space-weather monitoring network that adequately measures important geospace parameters.
  - temporal resolution
  - spatial coverage

Sun-Earth Energy Flow

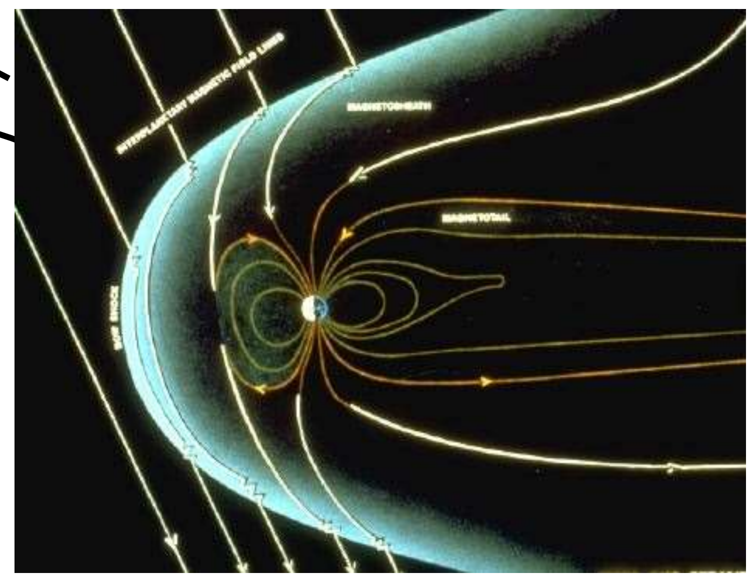


Solar explosion

collides with Earth's magnetosphere

Causing currents to flow

Into high-latitude ionosphere



Magnetosphere-Ionosphere Energy Flow

- Within the context of these global current systems, the ionosphere plays a very important role.
  - Ionosphere provides a closure path for magnetospheric currents.
  - Ionospheric conductance affects magnetospheric processes by controlling where currents close.
  - Ionospheric conductance varies spatially and temporally and is impacted by magnetospheric processes.

Magnetosphere-Ionosphere Energy Flow

- Energy flows into the upper atmosphere through
  - Particle precipitation (*Auroras in northern and southern polar regions.*)
    - Causes electron density structure in the ionosphere
  - Electrical currents
    - Ionosphere is a conductor.
    - High-latitude ionosphere contains significant electric fields.
- ***Electric fields*** and ***electron density gradients*** are building blocks for plasma turbulence.

Analogy with Terrestrial Weather

- Terrestrial weather prediction has improved considerably over the past 40 years. Improvements due to:
  - better large-scale and nested grid models
  - better observing networks
- Space weather prediction has gained much more visibility and is undergoing growth due to multi-agency programs:
  - National Space Weather Program
  - NSF GEM
  - NASA Living With a Star
  - Advances in numerical simulation and improved observing networks?
    - Relative to terrestrial weather we have a long way to go!

Analogy with Terrestrial Weather

Consider Lower Atmosphere Weather Systems

Wind Direction: Controlled by pressure gradients

Analogy with Terrestrial Weather

Fluid Equations in the Lower Atmosphere

- Continuity Equation:

$$\partial\rho/\partial t + \nabla\bullet(\rho\mathbf{U}) = 0$$

- Momentum Equation for Horizontal Motion:

$$d\mathbf{U}/dt = 2\mathbf{U}\mathrm{x}\boldsymbol{\Omega} - \nabla p/\rho$$

  - **U** is the horizontal velocity of neutral atmosphere
  - **Ω** is the angular rotation frequency of the Earth

- In a steady state:

$$\mathbf{U} = \boldsymbol{\Omega} \times \nabla\Phi/2\,\boldsymbol{\Omega}^2$$

where $\Phi = p/\rho$ = geopotential

Analogy with Terrestrial Weather

- Continuity Equation:

$$\partial n_j/\partial t + \nabla \bullet (n_j \mathbf{V}_j) = q_j - l_j$$

  - Ionospheric densities change through source and loss terms.
  - To understand the temporal evolution of a parcel of plasma one needs to track it as it is convected by an evolving high-latitude electric field.

- Momentum Equation for Horizontal Motion:

$$d\,\mathbf{V}_j/dt = (q_j/m_j(\mathbf{E} + \mathbf{V}_i \times \mathbf{B}) - \nabla p)/\rho_j + \nu_{jn}(\mathbf{V}_j - \mathbf{U})$$

  - Note that the Lorentz force replaces the Coriolis Force (Dominant term).
  - Electromagnetic forces much stronger than pressure gradients.
  - Momentum transferred to neutral atmosphere via collisions.
  - Rapid response time of ionized gas to changing electric field.

Analogy with Terrestrial Weather

- Ignoring all terms except the Lorentz force term in the momentum equation, we have:

$$\mathbf{V}_j = q_j/m_j\ \boldsymbol{\omega}_j \times \nabla\phi/\omega_j^2 = \mathbf{E} \times \mathbf{B}/B^2$$

- Comparing $\mathbf{V}_j$ with $\mathbf{U} = \boldsymbol{\Omega} \times \nabla\Phi/2\,\boldsymbol{\Omega}^2$, we see much similarity in form

Neutral Atmosphere: Geopotential → Ionosphere: Electrical Potential

$2\pi/\,\boldsymbol{\Omega}$ = 24 hours → $2\pi/\,\omega_j$ = 30 ms or less

Accel.: $8\text{x}10^{-4}\text{ms}^{-2}$ (1mB@100 km) → $1.2\text{x}10^{5}\ \text{ms}^{-2}$ (20 mV/m, O^+)

- Response time of the high-latitude ionosphere much shorter than that of the lower atmosphere. Also, electromagnetic forces much stronger.

How Do We Monitor Space Weather?

- Many Parameters:
  - Solar Conditions, Energetic Particles, Electric Fields, Magnetic Fields
- Many Regions:
  - Solar Surface, Solar Wind, Magnetosphere, Ionosphere
- Many Techniques:
  - Optical, Radiowave, *In-Situ* Observations with Spacecraft

- Desirable Features:
  - Multipoint or Imaging, Continuous, Direct rather than Inferred

How Do We Monitor Space Weather?

Importance of Measuring High-Latitude Electric Fields

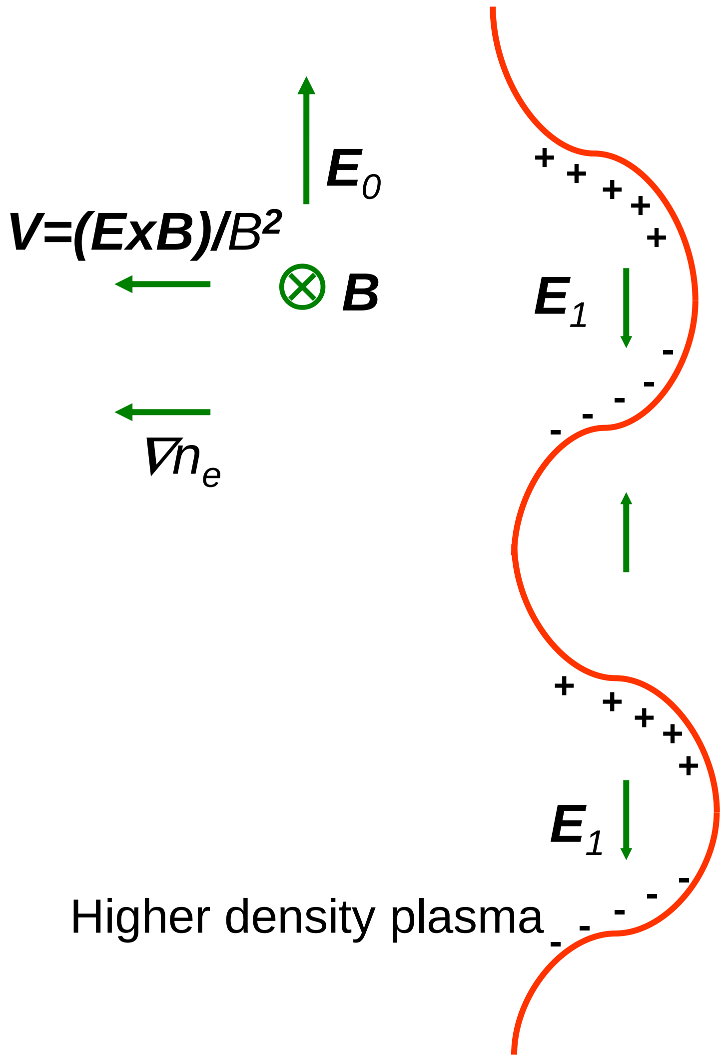
- Electric fields drive the ionospheric currents that close field-aligned currents flowing between the ionosphere and magnetosphere.
    - Ionospheric boundary conditions affect magnetospheric processes.
- Electric fields control the circulation of ionospheric plasma.
    - Affects electron density structure at high latitudes (Communications).
- Electric fields cause Joule heating of the upper atmosphere.
    - $Q_j = \Sigma_p E^2$
    - First step in upwelling of ionospheric plasma into the magnetosphere.

History of the Goose Bay Radar

1983 onwards

- The Goose Bay radar was designed to be sensitive to electron-density irregularities in the E and F-regions of the high-latitude ionosphere. (200-400 km altitude)
    - Irregularities produced by plasma turbulence
        - Streaming instabilities in E-region
        - Gradient and shear instabilities in F-region
    - **Data yields information on high-latitude electric fields**
- Radar is sensitive to Bragg scatter from plasma turbulence.
    - $\lambda = \lambda_{radar}/2$ for backscatter.
- Irregularities are elongated along the magnetic field.
    - Therefore, $k_{radar} \perp B$

F-Region Gradient Drift Instability

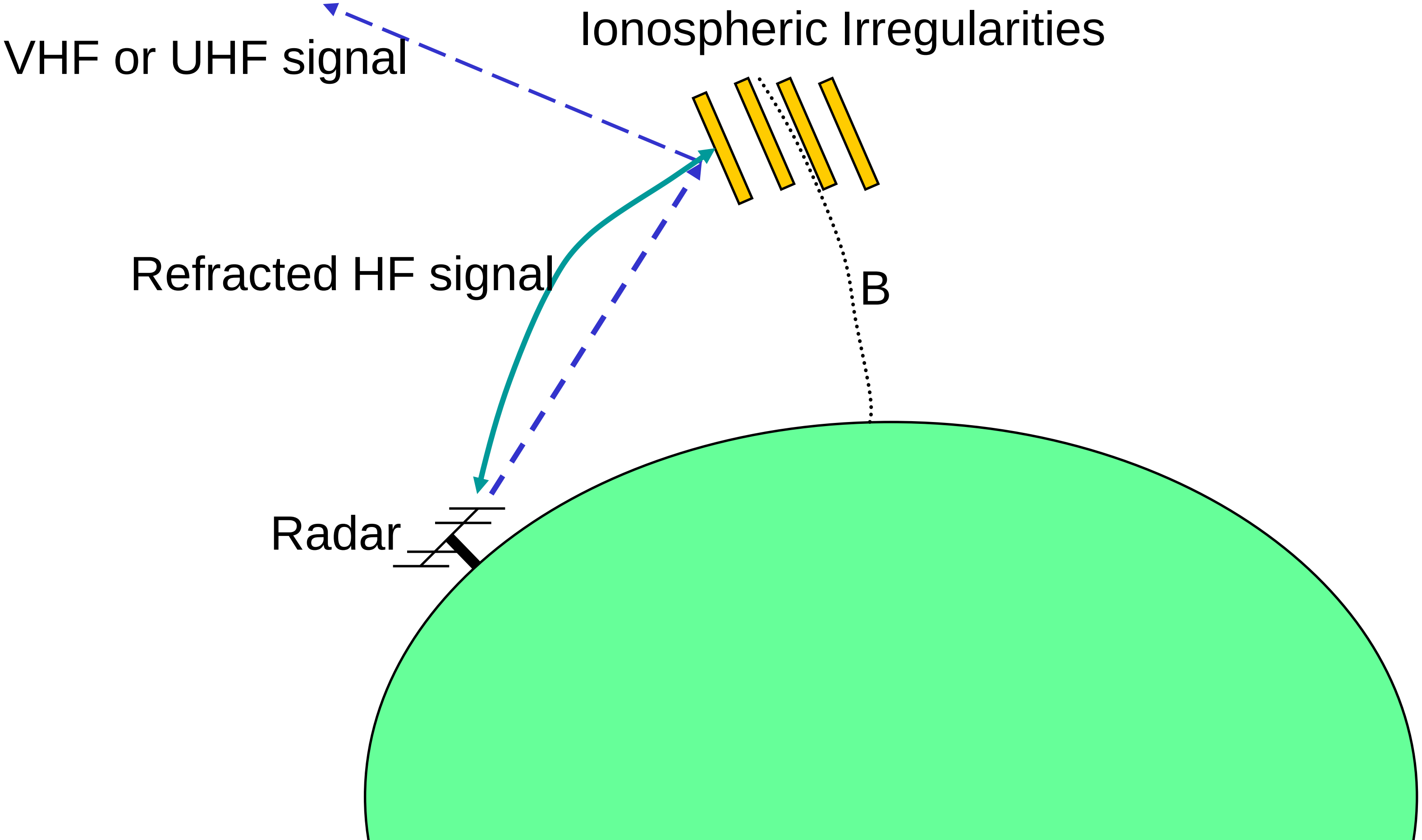


- Electrons collisionless
- Ions almost collisionless
- Residual collisions cause ions to drift in direction of ambient electric field.
- $E = E_0 + E_1$

History of the Goose Bay Radar

1983 onwards

High-Latitude Ionospheric Radars Must Operate at HF Frequencies



History of the Goose Bay Radar

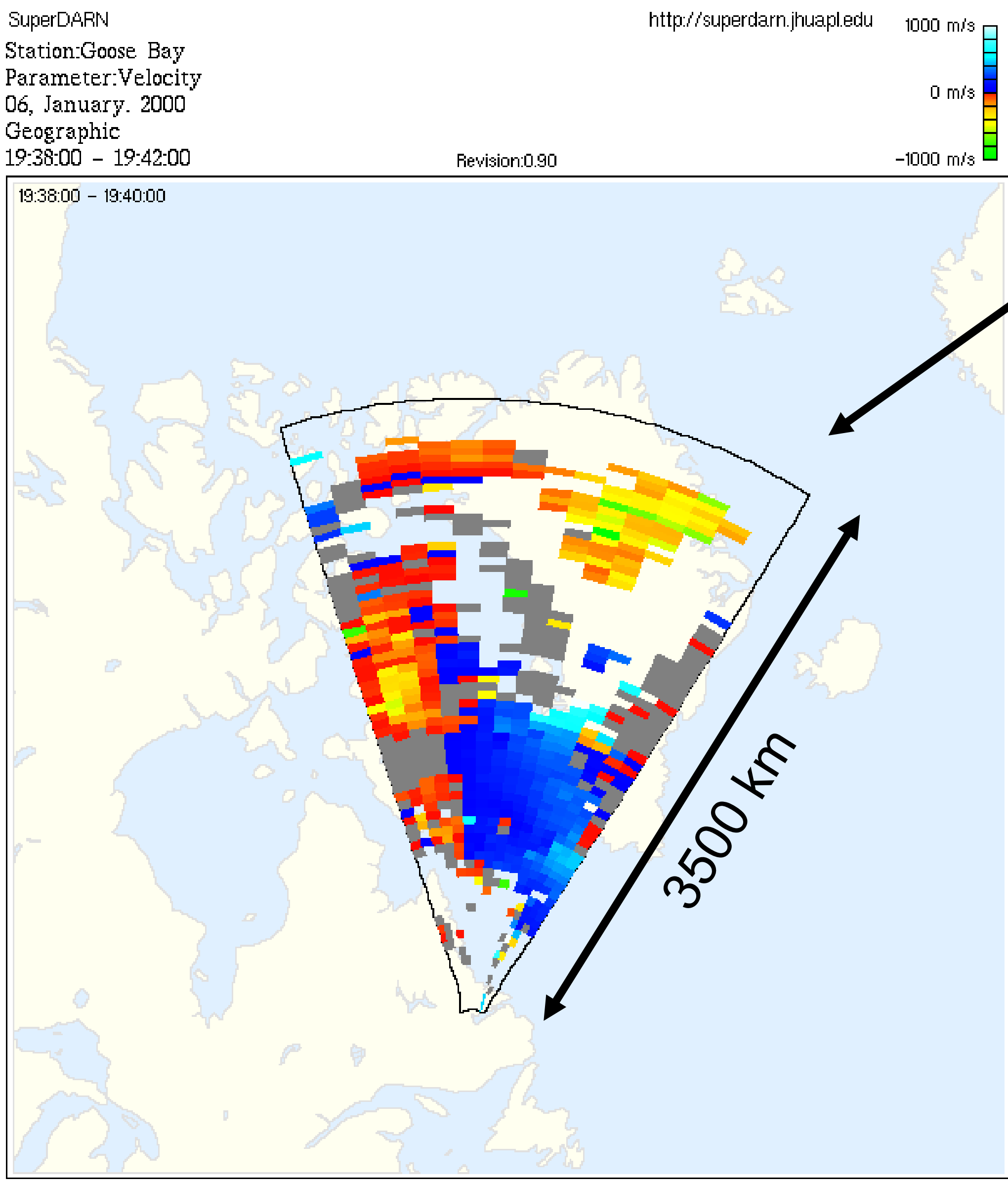
1983 onwards

Artist's Conception ca. 1982

Reality ca. 1988

Front array used for interferometry

Goose Bay Doppler Data



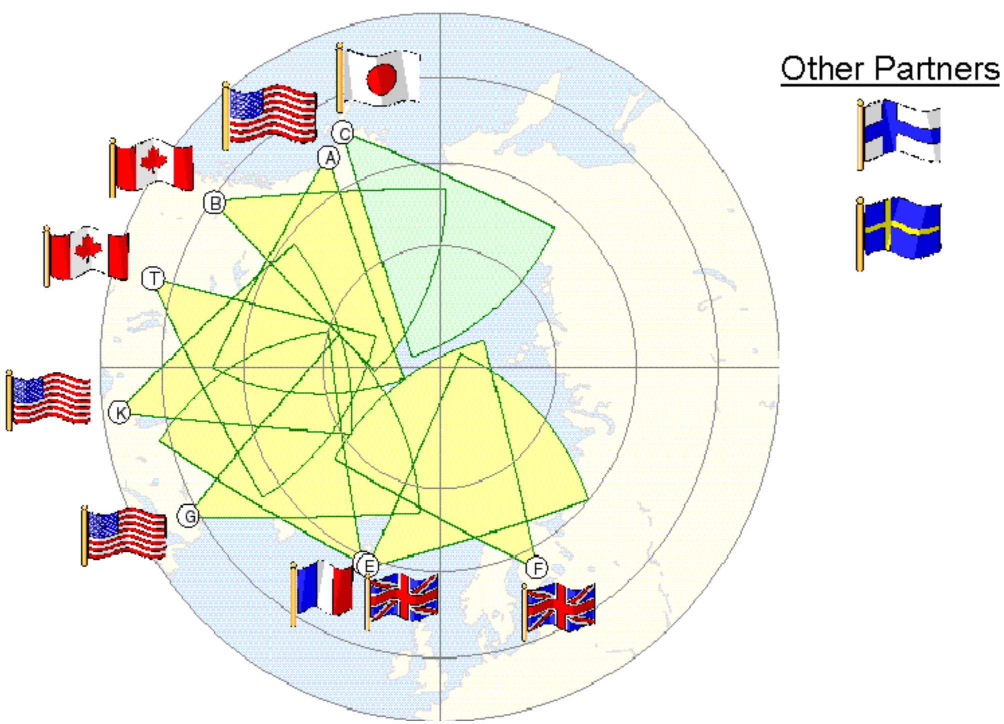
Radar scan showing Doppler velocities of ionospheric irregularities over northeastern Canada and Greenland

Data such as these are archived on our web site at superdarn.jhuapl.edu

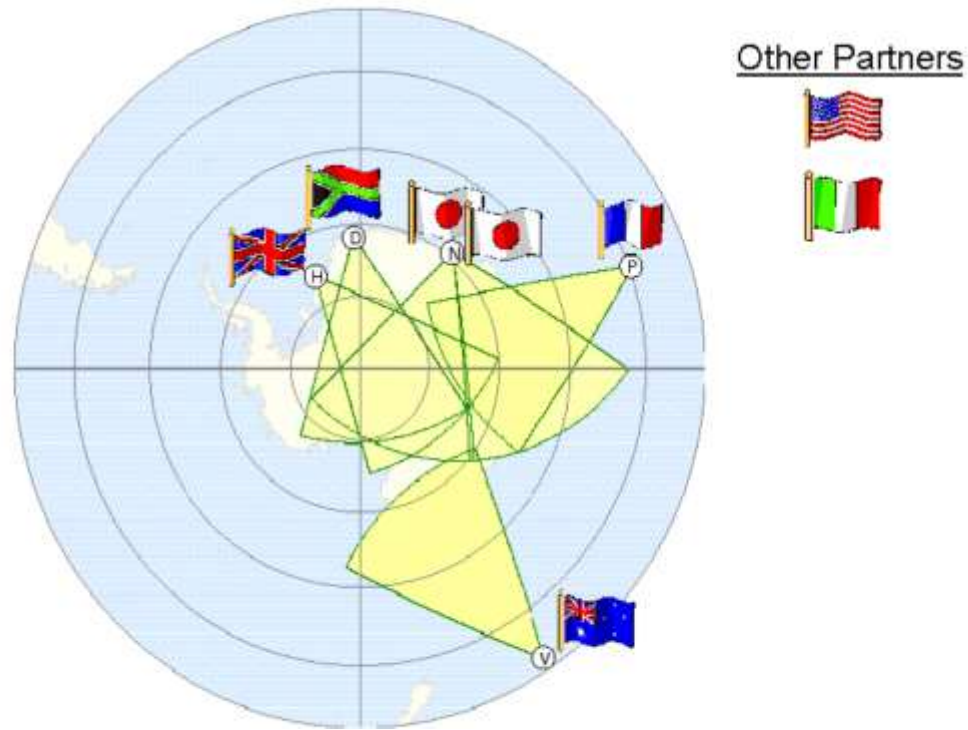
SuperDARN

The Space Weather Adaptation of Goose Bay

North



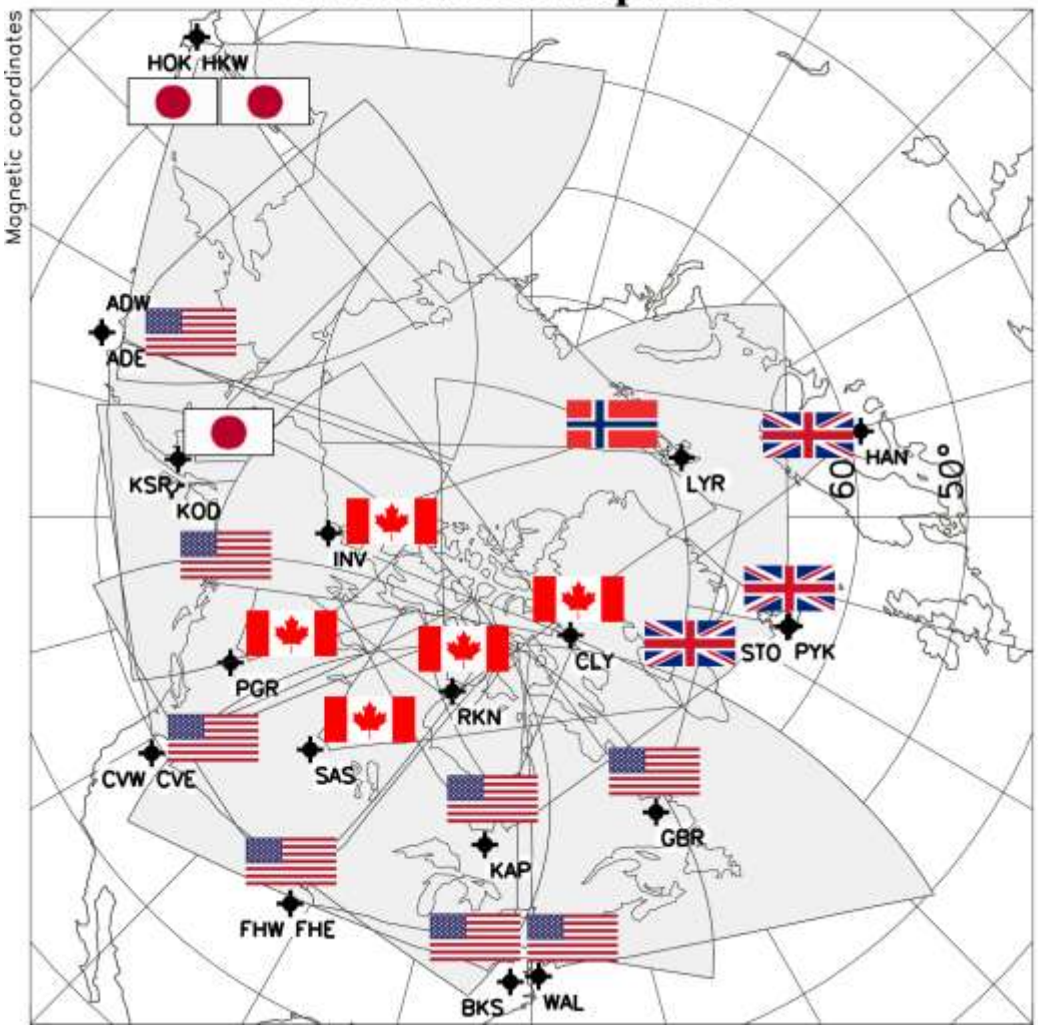
South



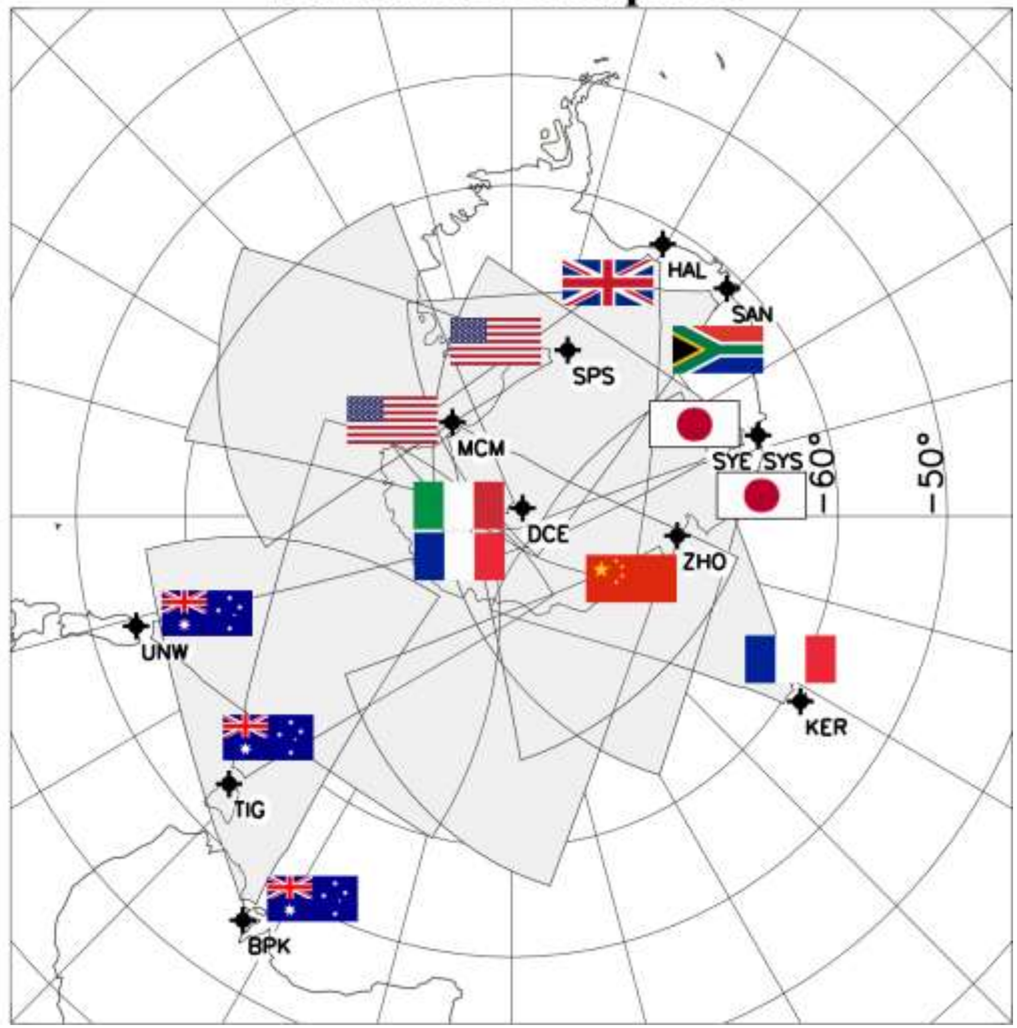
These radars contributed to numerous NASA and ESA spacecraft missions between 1995 and 2015.

Current SD Radars

Northern Hemisphere

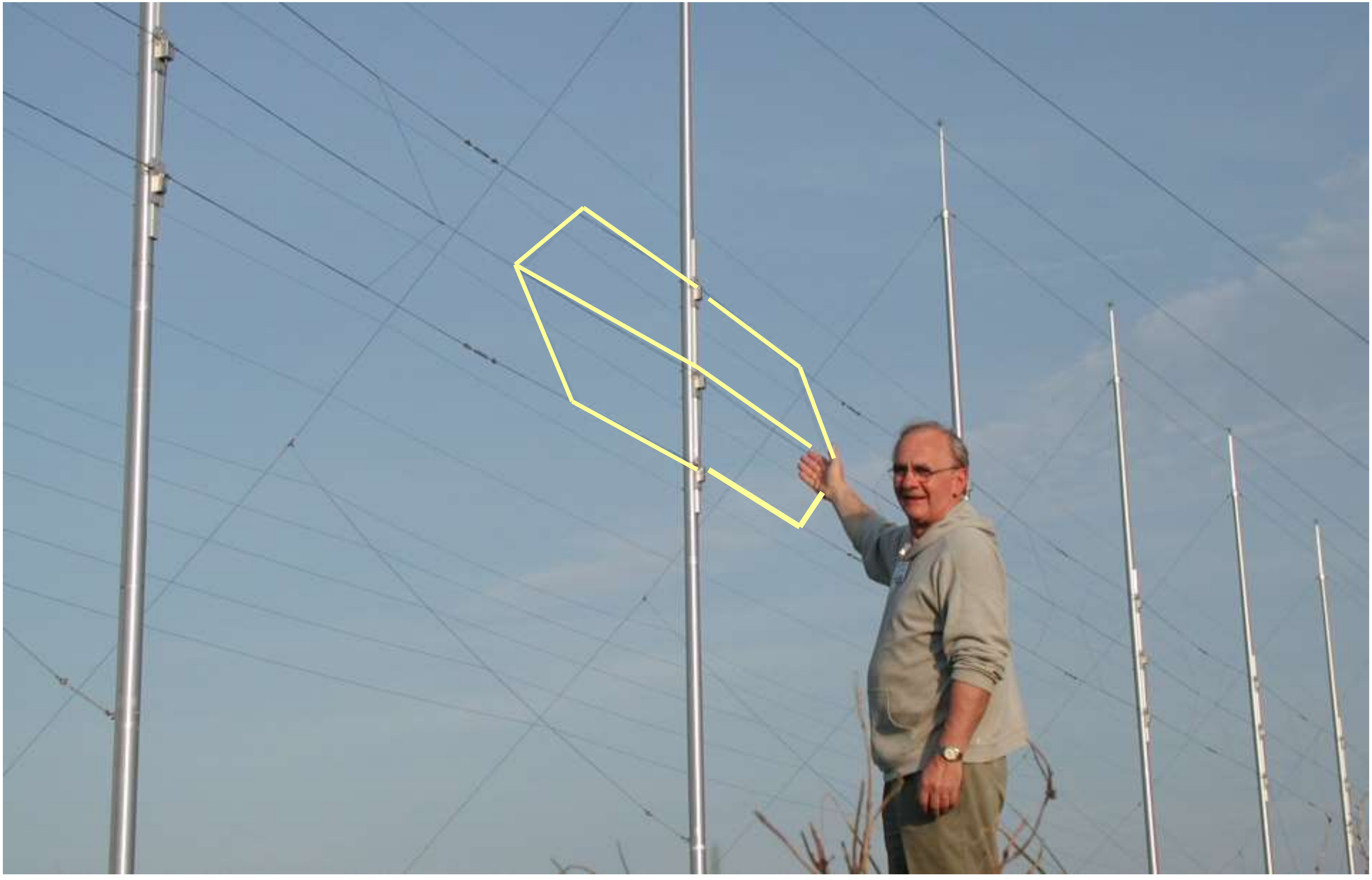


Southern Hemisphere



TTFD Antenna Array

Wallops Island, VA

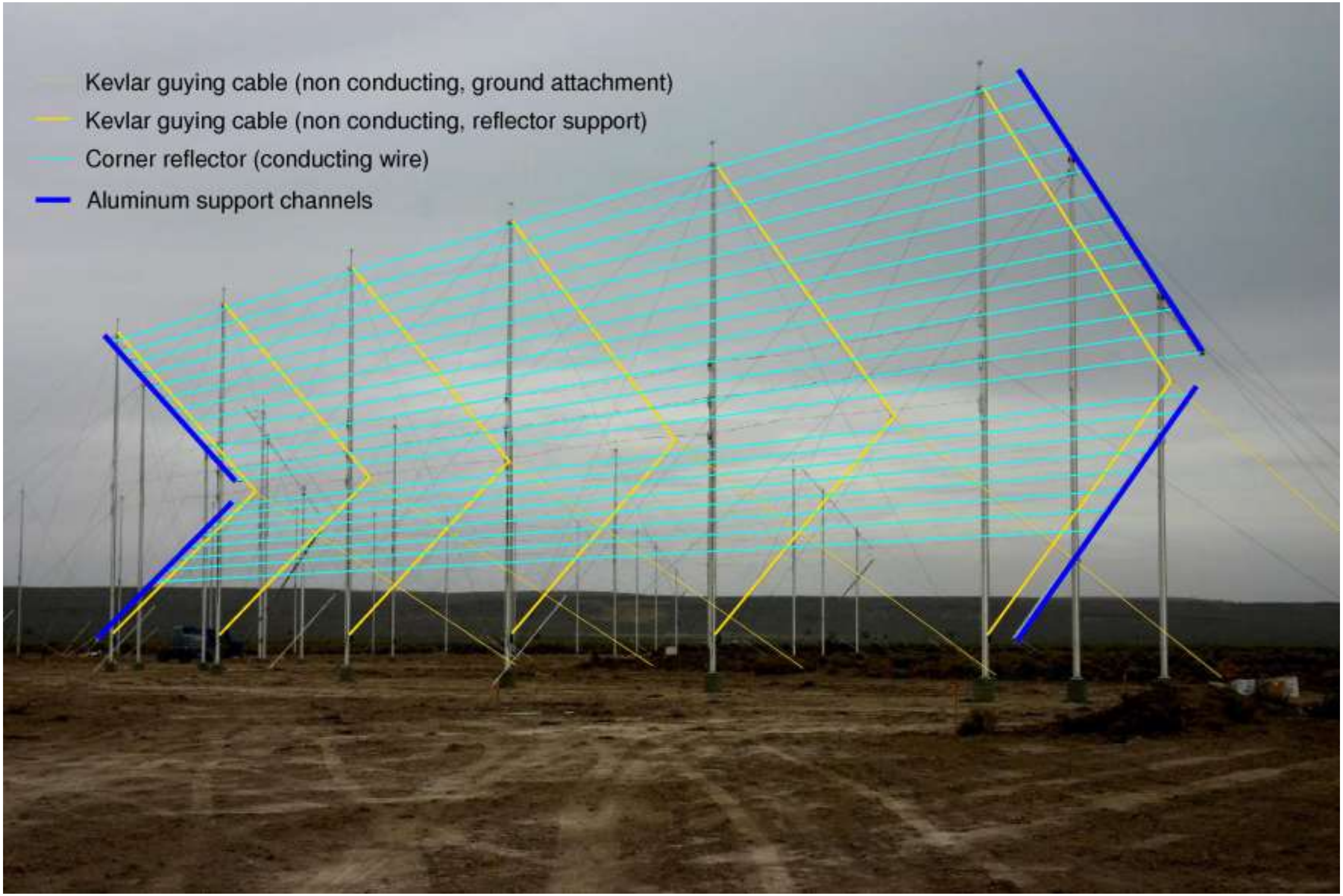


CVE Main Array

Christmas Valley, OR

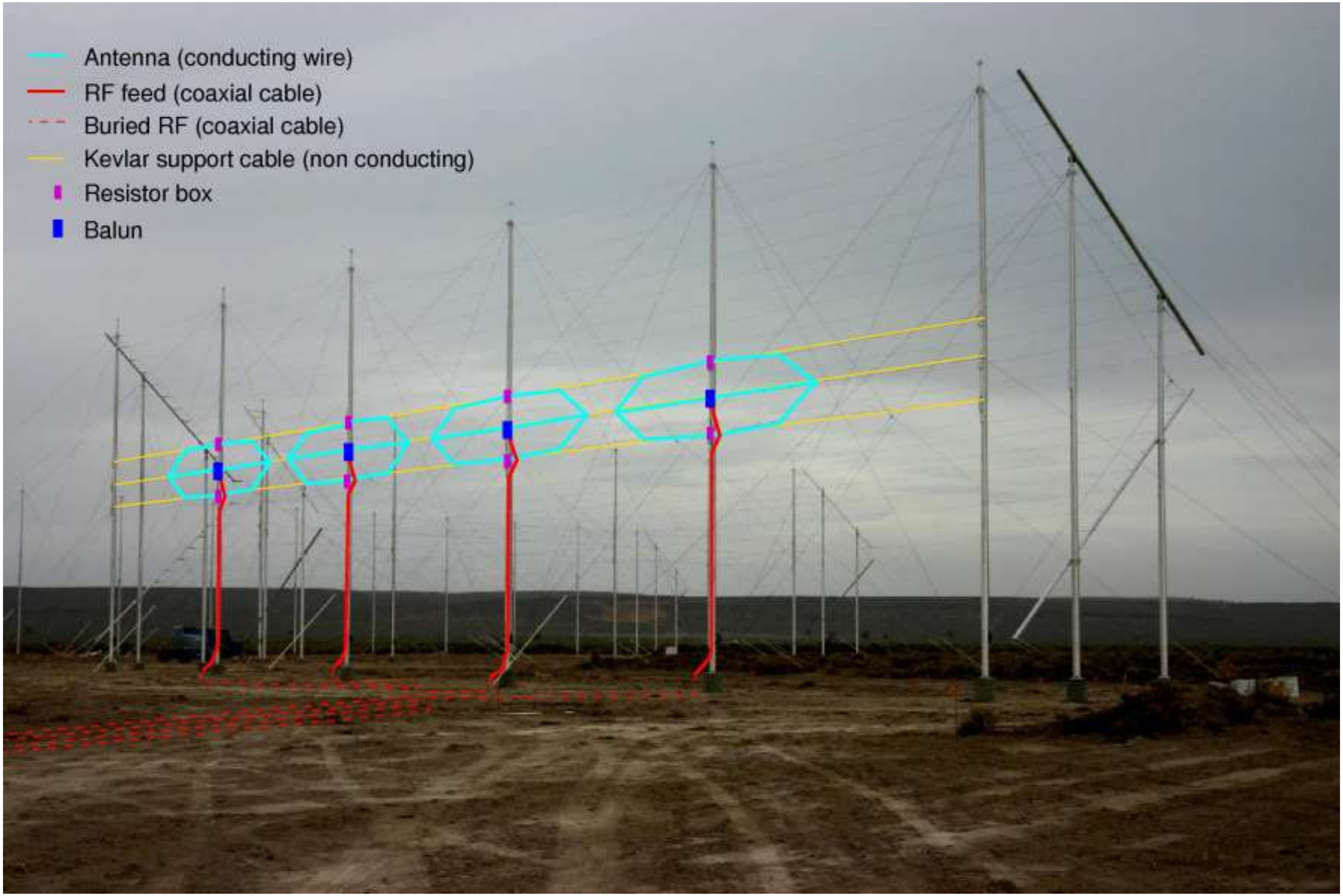
CVW Interferometer Reflector

Christmas Valley, OR



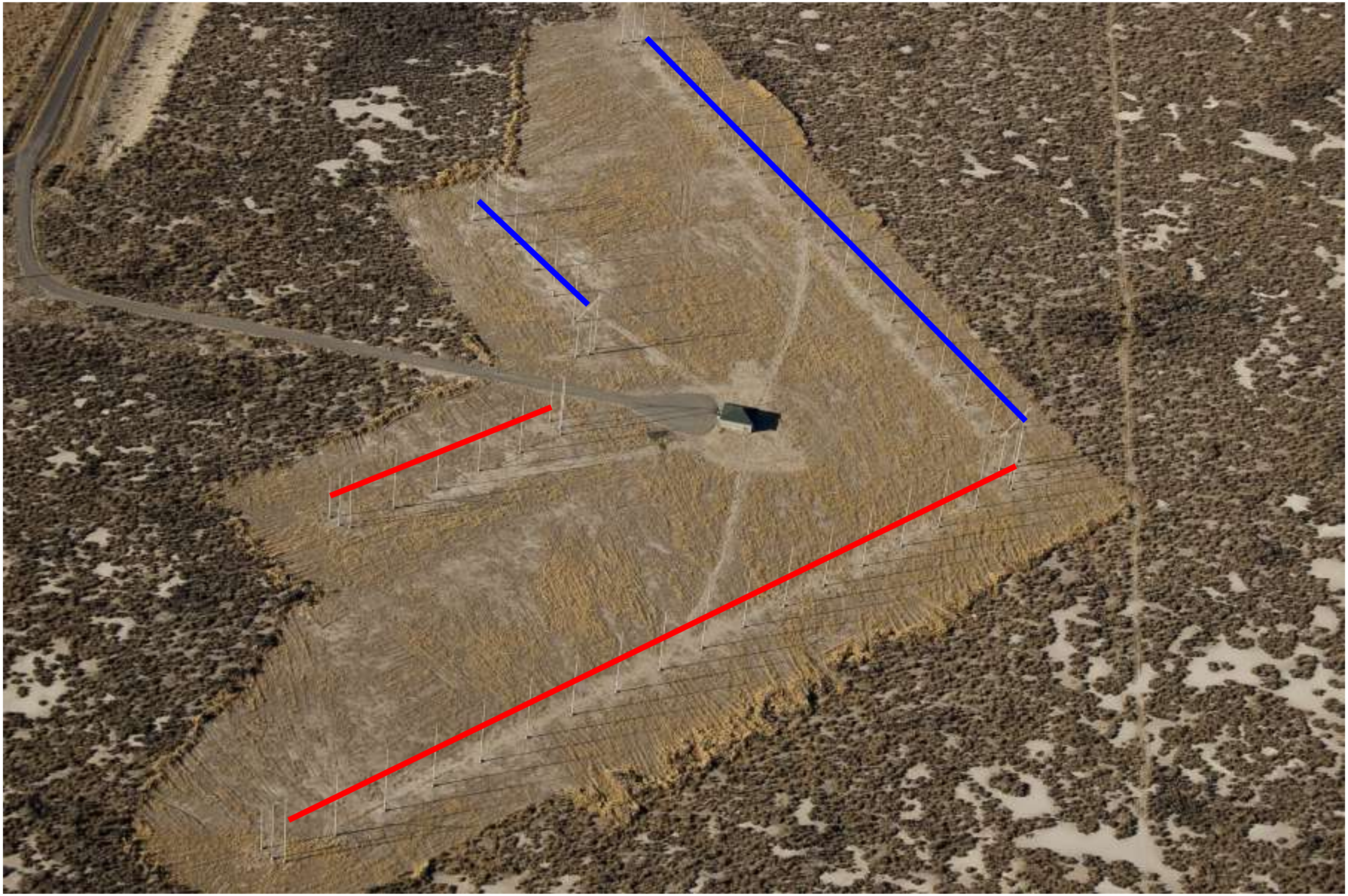
CVW TTFD Radiators

Christmas Valley, OR

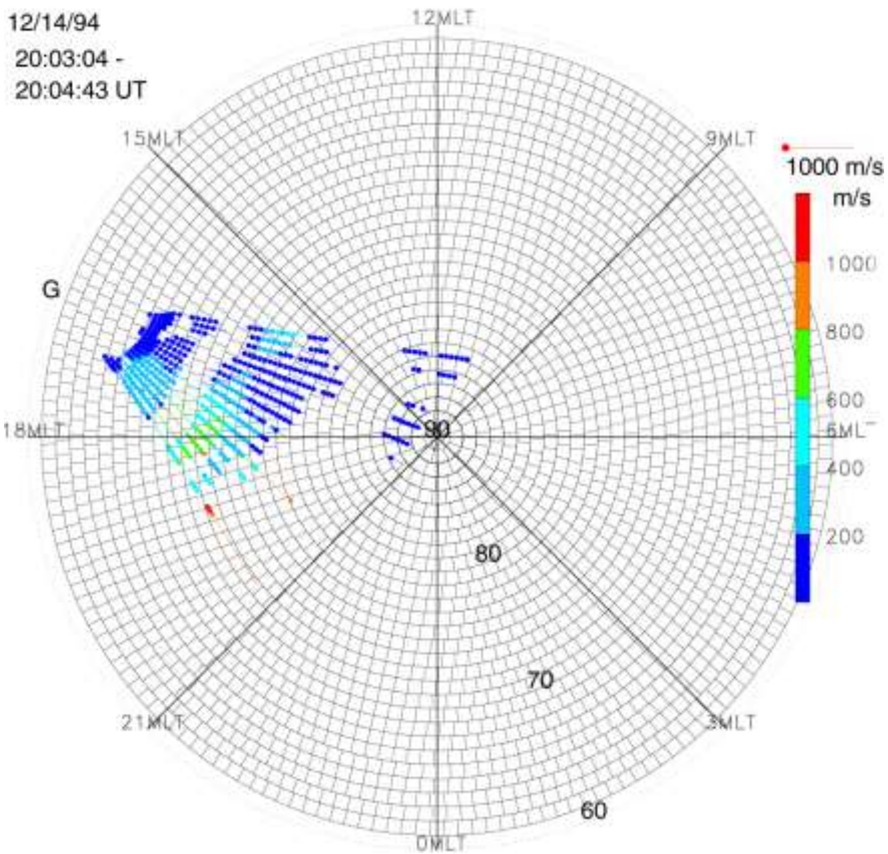


Full Antenna Configuration

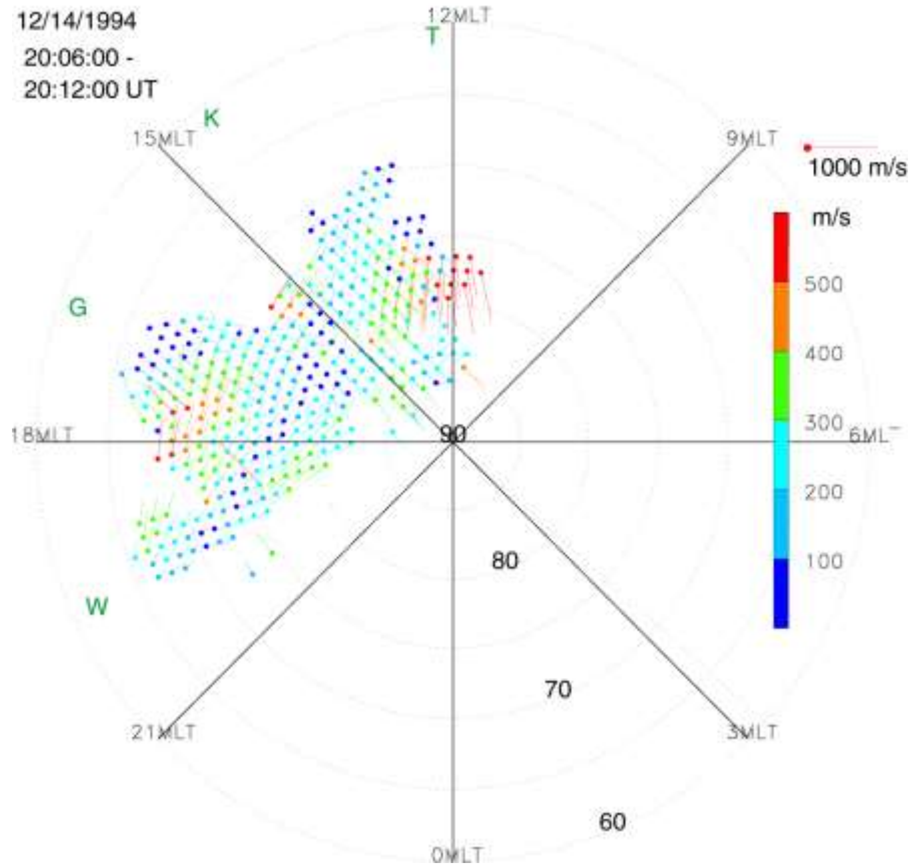
Christmas Valley, OR



Determination of SuperDARN Potential Maps

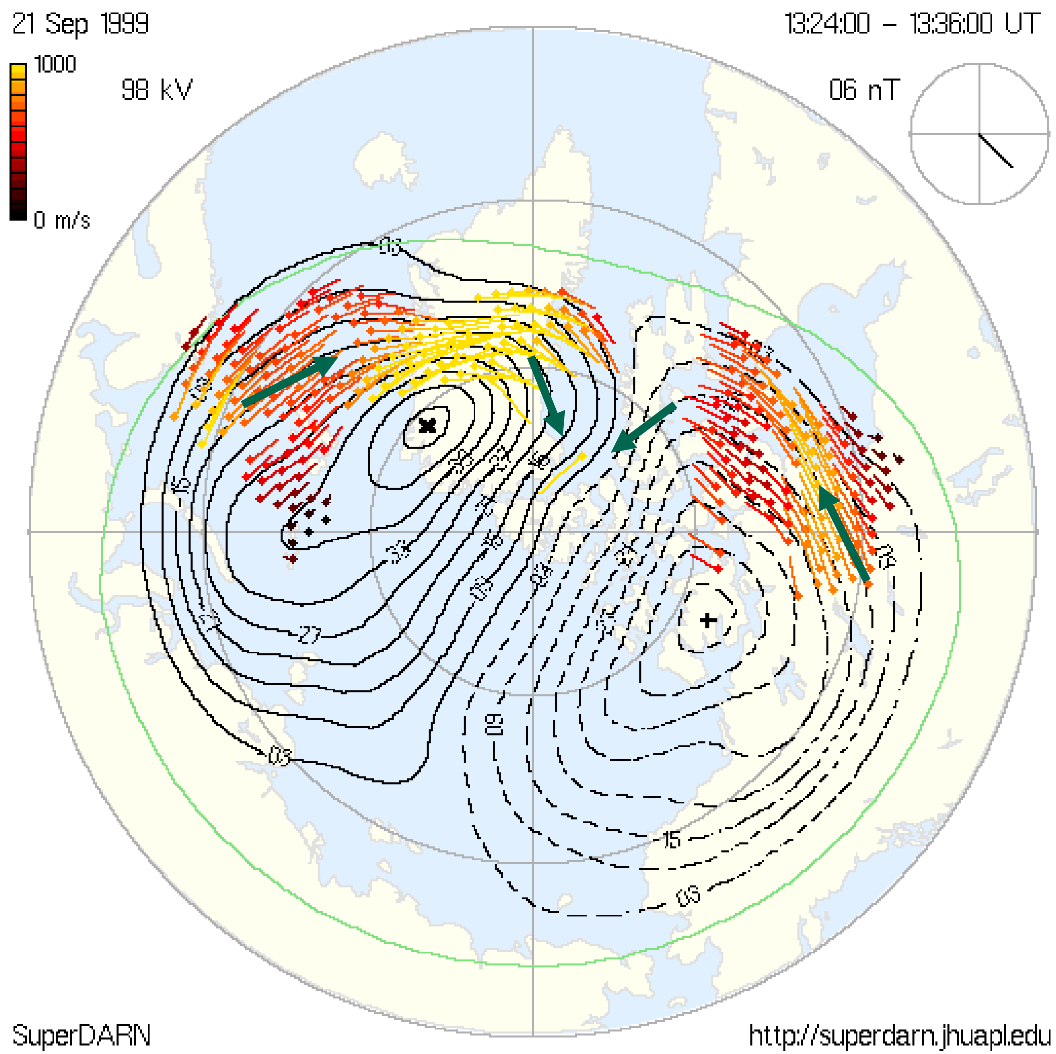


Doppler data from Goose Bay radar overlain on analysis grid.



Doppler data from four radars ready for spherical harmonic analysis.

Determination of SuperDARN Potential Maps

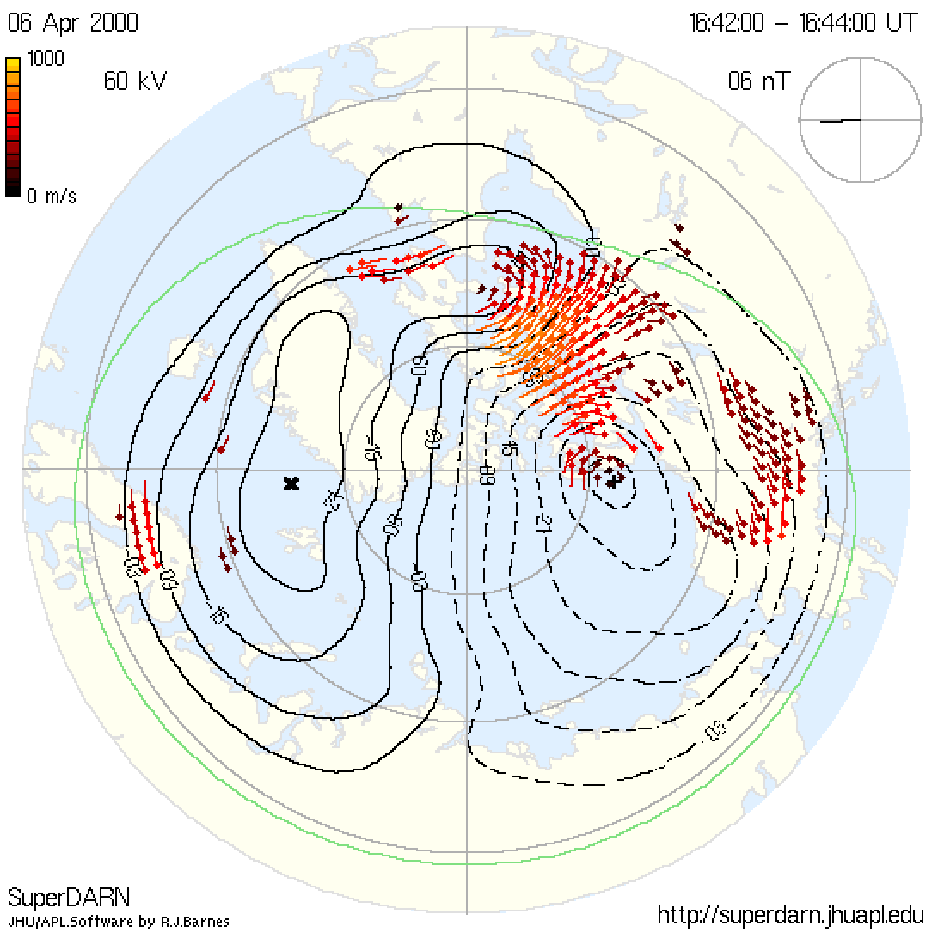


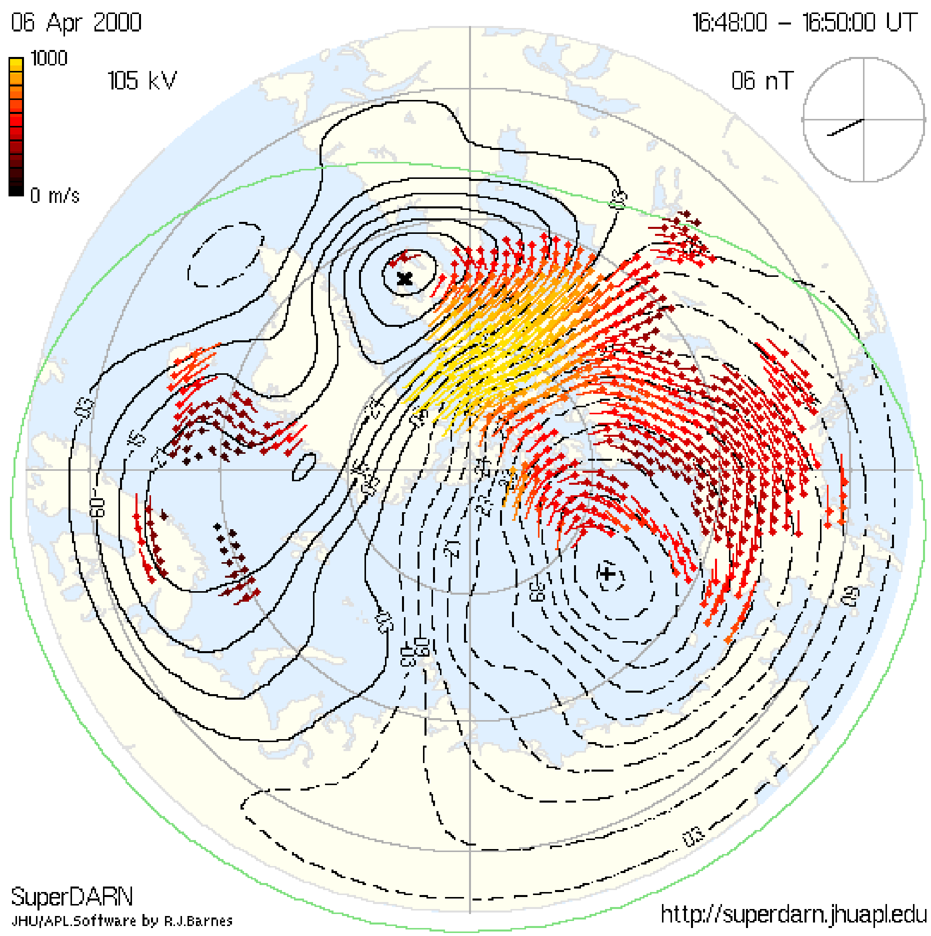
The solution is very good where observations are made. Where there are no observations, it is impacted by the model

Plasma wind direction: Controlled by electrical potential gradient.

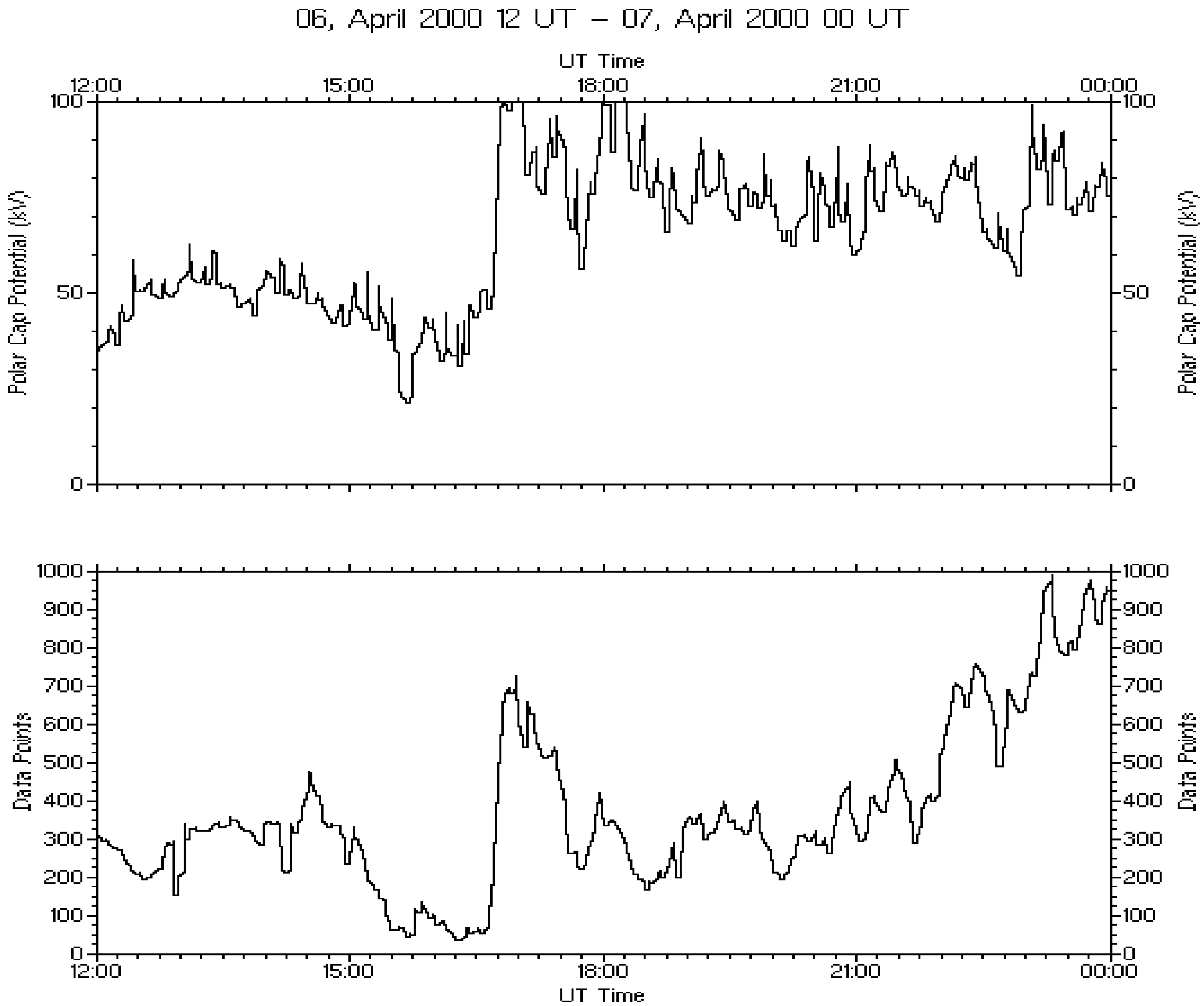
How Quickly Does the Potential Change?

April 6, 2000 Storm Event: Ace magnetometer data not synchronized





How Quickly Does the Potential Change?



Summary

- Space weather prediction will eventually be made through large-scale coupled models describing the many domains of the solar-terrestrial environment.
- The quality of these models will be validated through space-based and ground-based observing networks.
- The observing networks will most likely provide inputs to the models to keep them on track. This is done in terrestrial weather forecasting.
- We have a long way to go!
  - Many processes, known to be important, are not yet included.
  - Current models are not well coupled.
- **Weather in not climatology!** We are not interested in average conditions, but rather in the dynamics.