# Space Weather Products from SuperDARN

Raymond A. Greenwald
Johns Hopkins University Applied Physics Laboratory
Laurel, MD   USA

The SuperDARN network of HF radars offers the unique capability of providing a coordinated set of observations of the high-latitude ionosphere that can be combined to yield global-scale views of many auroral-zone and polar-cap phenomena. The recent addition of Internet connectivity to all of the northern-hemisphere SuperDARN radars has extended this global overview to the near real-time domain and hence has made them adaptable to "Space Weather" applications. The coverage of the existing northern-hemisphere radars is shown in Figure 1. It can be seen that the SuperDARN coverage area will extend over approximately three-fourths of the polar ionosphere. The only sector left uncovered is that over central Asia. The basic observations obtain with these HF radars are oblique backscatter returns from the ionosphere and from the ground. The ionospheric returns are primarily from electron density irregularities produced by plasma instabilities in the altitude regime from 100-400 km and secondarily from meteor trails at altitudes from 90-95 km. The ground backscatter returns are due to signals that have been reflected obliquely off of the ionosphere and then backscattered from the ground or sea surface at some distant location. In all cases, the returning signals are processed to yield their amplitude, Doppler velocity, Doppler spectral width, and vertical angle-of-arrival as a function of time delay. In addition, each radar can steer its antenna array horizontally into any of 16 viewing directions within the fans indicated in Figure 1. Thus, there is a wealth of information that is collected at each radar site and returned via the Internet to a central processing location such as the Applied Physics Laboratory (APL).

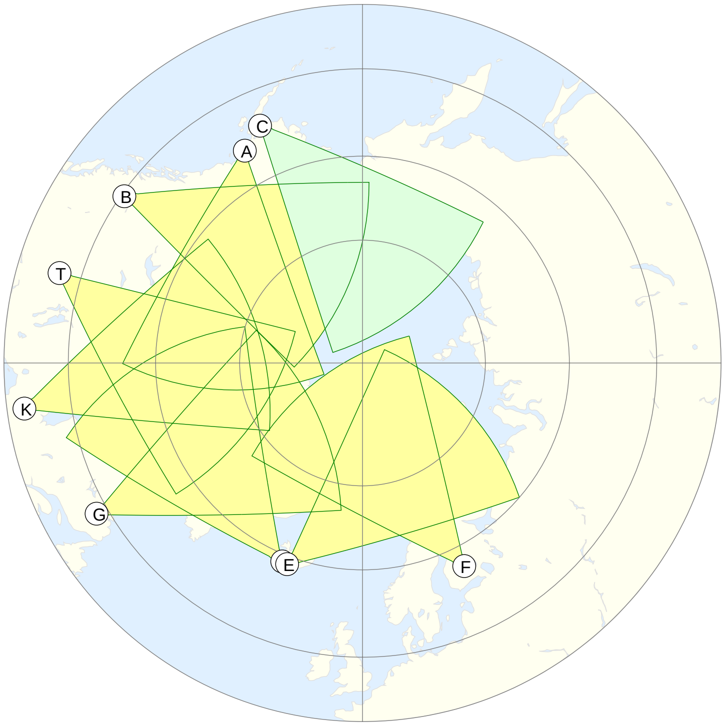

Figure 1. Viewing areas of northern-hemisphere SuperDARN radars. Radars in yellow are in operation and have Internet connections. Radar in green is under development.

The first usage of real-time data from the SuperDARN radars was to produce displays of radar parameters – amplitude, velocity, and spectral width – over a radar scan. These data were made available, again via the Internet, through the Space Physics Research

Collaboratory (SPARC) of the University of Michigan as part of multi-institutional real-time studies of high-latitude ionospheric processes. Subsequently, as data from more SuperDARN radars became available in real time and new processing techniques were developed to integrate these data and derive global patterns of high-latitude convection, it became possible to produce global images of the convection pattern and display these images on the Internet in near real time.

At the present time, the Real-Time Data selection on the APL SuperDARN web site -- [http://superdarn.jhuapl.edu/](http://superdarn.jhuapl.edu/) -- provides three options: 1.) displays from real-time radar scans from the northern hemisphere SuperDARN radars, 2.) near real-time convection maps that are updated every 2 minutes, and 3.) daily time-series plots from the northern hemisphere radars (updated every 15 minutes). The most important of these from the space-weather perspective is the convection maps. The information in these maps help to specify the energy flow through the magnetosphere-ionosphere-atmosphere system. They also describe the circulation of the high-latitude ionosphere and they identify regions of significant heating of and momentum coupling to the neutral atmosphere. Two examples of convection maps seen on the APL web site are shown in Figure 2. These convection maps describe the circulation of the ionosphere under the influence of ionospheric electric fields. The dark contours in the figure, show the paths that the ionospheric plasma follows. In regions where the contours are closer together, the circulation is more rapid. Also shown in the figure are flow velocity vectors at locations where SuperDARN observations were made. The colored lines extending from the dots indicate the magnitude and direction of the flow vectors. The most important characteristic to be gleaned from these two maps is the rapidity with which the global pattern changes on short time scales.

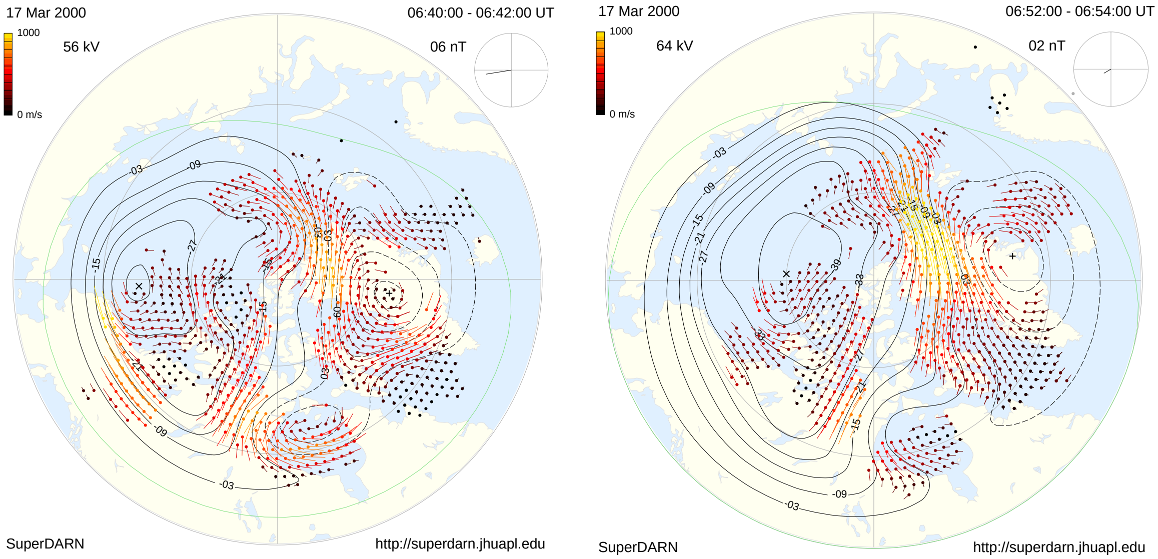

Figure 2. Two convection maps observed in real time on the SuperDARN web site. Each map is derived from 2-minutes of data and the observations are separated by 12 minutes in time. These examples demonstrate the rapidity with which the high-latitude convection pattern changes. The convection patterns are related to the electrostatic potential pattern in the Earth's polar ionosphere and magnetosphere. In this case, the potential drop associated with this pattern increased from 56 kV to 64 KV.

In addition to the convection patterns, the APL web site displays plots of the cross polar cap potential drop and the number of SuperDARN data points contributing to each map for the previous 24-hour interval. An example of a more-limited 12-hour plot from an interval in April 2000 that was associated with the onset of a major storm is shown in Figure 3. It can be seen that the polar cap electrical potential drop rapidly increased from 50 kV to more than 100 kV. The number of SuperDARN data points contributing to these measurements is typically in excess of 200 per convection map.

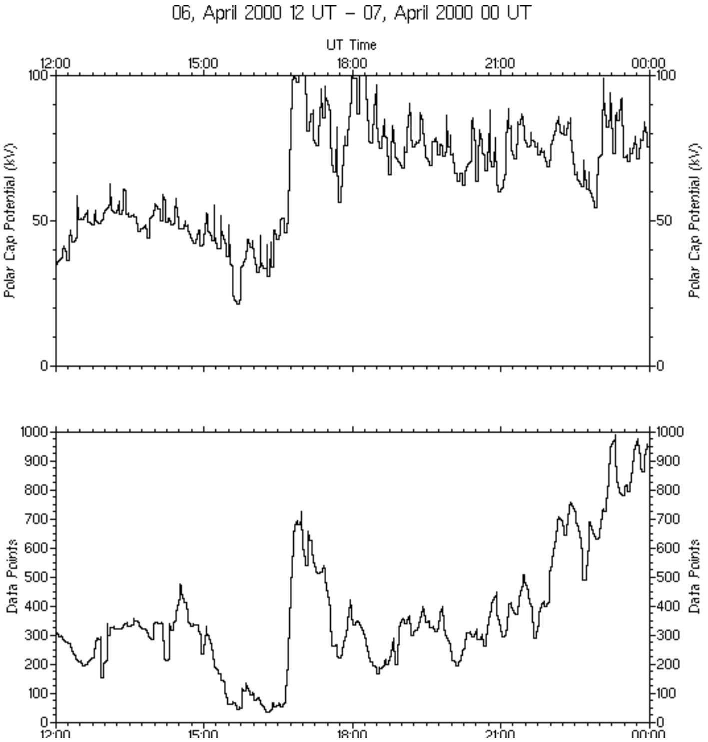

Figure 3. Upper panel displays cross polar cap potential drop for a 12-hour interval on April 6, 2000 associated with the onset of a major geomagnetic storm. The lower panel shows the variation in the number of SuperDARN observations over the period.

The nature of SuperDARN as a global network of observatories with real-time data access inherently allows other space-weather products to be obtained. Some of these are consequential to the types of observations that the radars make, whereas others are consequential to the frequency band that the SuperDARN radars use. Over the past year, we have examined a number of potential products and identified a number of candidates that are particularly important to the specification of the current state of the radiowave environment. It is highly likely that these products will be important to space-weather forecasters and to the SuperDARN community as we attempt to operate our radars in a manner that maximizes the number of ionospheric observations that are obtained. The specific products that have been identified are:

- Low-latitude boundary of the auroral zone
- Polar-cap boundary
- Low-latitude boundary of auroral radar clutter
- Low-latitude boundary of auroral-zone/polar-cap scintillations
- High-latitude propagation specification
- High-latitude absorption specification

## Low-Latitude Boundary of the Auroral Zone

Studies carried out at APL during the past year have shown a surprisingly close relationship between the location of precipitating particles as observed with the U.S. Air Force Defense Meteorological Satellites (DMSP) and the location of HF ionospheric backscatter as observed with SuperDARN. The full details of this relationship are described elsewhere in these proceedings. For the present discussion, we show a single comparison that illustrates the close spatial relationship between high-latitude ionospheric irregularities and particle precipitation. Figure 4 shows overlays of DMSP particle observations on SuperDARN maps of high-latitude convection and Doppler spectral width. The data are plotted in a geomagnetic polar coordinate system with noon at the top. SuperDARN data were only obtained in regions where velocity vectors are plotted in the panel on the left and spectral width information is plotted in the panel on the right. There were no radar observations in the pre-noon local-time sector. Note that the duskside data show that the strongest particle precipitation is collocated with irregularity regions having significant sunward motions. Poleward of the precipitation band, the convection velocity changes from sunward to antisunward indicating that the ionospheric irregularities in the poleward region are located in the polar cap. The irregularities in the precipitation regions also display large spectral widths, whereas those located poleward and equatorward of the precipitation display much narrower spectral widths. Finally, equatorward and poleward of the band of significant particle precipitation, the convection velocity either diminishes and/or reverses direction. These general relationships appear to be valid for a large number of DMSP overflights that have been examined. When the SuperDARN radars are located in the late morning local-time sector similar results are obtained. Thus, we can generally conclude that the equatorward boundary of the auroral precipitation is closely related to the equatorward boundary of the ionospheric backscatter, that the precipitation is largely confined to regions of sunward-convecting irregularities, and that a more poleward zone of irregularities having

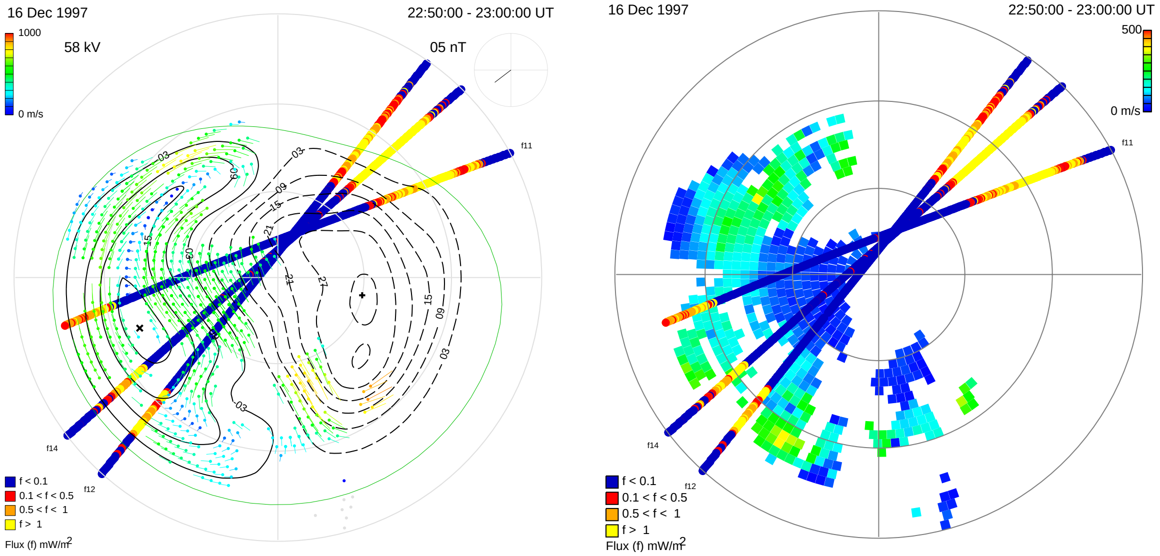

Figure 4. DMSP orbit tracks showing precipitating-particle energy flux superposed on Super-DARN convection pattern and spectral width data. Note that strong precipitation is generally located in regions of sunward convection and larger Doppler spectral width.

narrow spectral width and moving antisunward is located on polar cap field lines. These results lead us to believe that global observations with SuperDARN may be useful in identify the global low-latitude boundary of the auroral oval. This is an important result since it indicates that the locations of ionospheric irregularities derived form real-time SuperDARN observations can be used to provide a warning as to when and where high-latitude propagation will be impacted by auroral precipitation.

## Polar Cap Boundary

The preceding discussion also indicates that the polar cap boundary may be identified using SuperDARN observations. The poleward edge of auroral precipitation is approximately collocated with the poleward edge of larger spectral widths and the flow reversal boundaries identified in the SuperDARN convection analysis. This boundary is useful for identifying the poleward edge of where the auroral zone impacts propagation as well as the equatorward boundary of direct entry of very energetic solar particles into the ionosphere. The latter phenomenon is related to polar cap absorption events (PCAs) that can severely degrade HF communications at high latitudes.

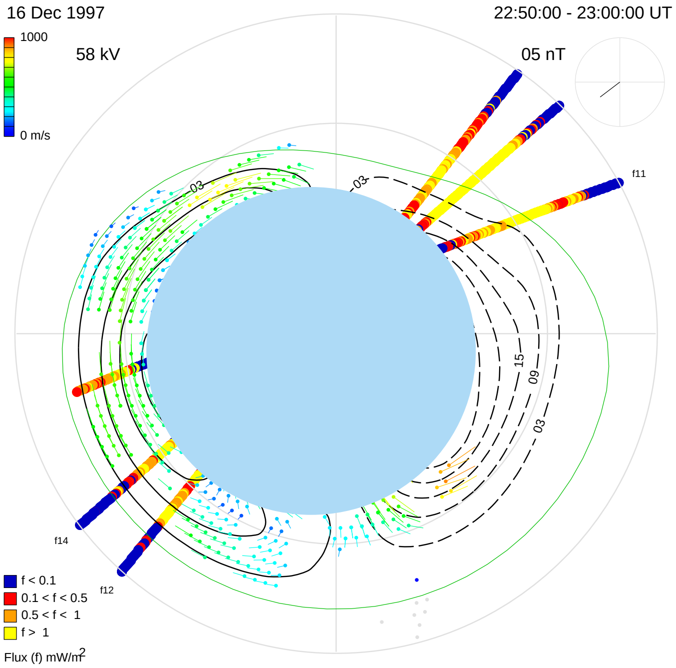

Figure 5. SuperDARN high-latitude convection pattern overlaid with DMSP particle measurements and circular polar cap. The polar cap is determined from the flow reversal boundaries in the SuperDARN observations and/or the poleward boundaries of the DMSP precipitation. The green curve is the low latitude boundary of the auroral oval.

We have developed some preliminary algorithms to identify the preceding two boundaries. The polar cap is defined by a circle fit to the location of the flow reversal boundary at all local times. The low latitude boundary of the auroral oval is identified by the Heppner and Maynard boundary to the high-latitude convection pattern. This curve bounds the high-latitude convection cells and is shown in green on the left-hand panel of Figure 4. Its location is determined by the lowest latitude at which ionospheric irregularities were observed to have significant Doppler velocities,. Figure 5 shows an example of how these to curves might be combined. The polar cap is identified by the blue circular region, while the low-latitude boundary of the auroral zone is identified by the green curved line. The region in between is the auroral oval. When these boundaries are placed over a geographic map, one should be able to identify communications paths that would be affected by high-latitude ionospheric disturbances.

## Low -Latitude Boundary of Auroral Clutter

Ionospheric irregularities produce clutter on radar systems that can severely affect their operations. The nature of the problem is that ionospheric irregularities move and, often, their Doppler-shifted backscatter returns cannot be distinguished from those of conventional radar targets. Under these conditions, the auroral clutter masks conventional radar targets or create false targets (e.g. flying saucers). Until the development of SuperDARN, there was no way to estimate the instantaneous global distributions of clutter-producing ionospheric irregularities at high latitudes. With SuperDARN, and the techniques used in the Heppner-Maynard boundary determination, it is possible to directly observe clutter producing irregularities over much of the high-latitude ionosphere and estimate its probable occurrence elsewhere.

Since clutter-producing ionospheric irregularities are generally created by plasma streaming instabilities in the auroral E-region and gradient-drift type instabilities at higher altitudes, a first-order estimate of the probable extent of this clutter is the region poleward of the Heppner-Maynard boundary to the high-latitude convection pattern. Poleward of this boundary, the ionospheric electric field increases rapidly and maintains high values over most of the polar region. The Heppner-Maynard boundary is identified by the closed green curve bounding the high-latitude convection pattern in Figure 5.

## Low-Latitude Boundary of Auroral-Zone/Polar-Cap Scintillations

While centimeter to decameter wavelength ionospheric irregularities produce clutter on radar systems through Bragg scattering, longer wavelength structures produce small angle scattering of radiowave signals passing through the ionosphere. After passing through the ionosphere, the signals scintillate in amplitude and phase, which effectively reduces or scrambles their information content. The problem is most important for satellite-to-ground communications and can lead to reductions or even loss of communications. Long-wavelength and short-wavelength irregularities are collocated as the plasma instabilities producing the irregularities generally involve turbulent cascading processes in which energy generally flows form long-wavelength to short-wavelength structures. Thus, not only can short-wavelength auroral backscatter be used as a tracer of scintillation producing regions of the ionosphere, but also the strength of this backscatter can be used as an estimator of the probable intensity of scintillations on satellite communications systems.

The Heppner-Maynard boundary is again used as the proxy for the equatorward limit to high-latitude scintillations. A needed topic of investigation is to determine the level of backscatter that is require for concurrent strong scintillations to be observed on satellite communications systems.

## High-Latitude Propagation Specification

The SuperDARN radars operate continuously, providing observations of HF backscatter and propagation over much of the high-latitude ionosphere. These multipoint data sets represent a sampling of propagation conditions over large segments of the high-latitude ionosphere and include the effects of propagation through the ionospheric trough and the auroral oval. For these reasons, the data set is highly valuable for validating HF propagation models and three-dimensional ionospheric density models in regions where accurate prediction is particularly difficult. Most countries have offices for ionospheric prediction and frequency management. These offices use models that they realize are limited in their applicability and accuracy, particularly at higher latitudes. SuperDARN offers the possibility to identify the limitations of these models on both temporal and spatial bases. Modifications in radar operation that will enable these global specifications are generally minimal, while the effort would most likely benefit society, in general, and the SuperDARN community in particular.

As a simple example, two neighboring SuperDARN radars might share a common field of view and be operating at similar frequencies. Yet one radar will observe ionospheric backscatter from a particular region of space and the other will observe ground scatter or nothing at all. Better understanding of the propagation condition operative at the two radars site may enable an alternative frequency selection at the second radar site that will provide better overlap of regions of ionospheric scatter.

### High-Latitude Absorption Specification

Ionospheric absorption is a phenomenon whereby an electromagnetic wave transiting a highly collision-dominated ionosphere is subject to severe energy loss. The problem is most severe in regions where the frequency of electron collisions with the neutral atmosphere becomes significant with respect to the frequency of the electromagnetic wave. Typically this occurs in the D-region of the ionosphere for very energetic particle precipitation (>20 keV electrons or > 100 keV ions). The impact is most important at HF frequencies. Typically, forecasting agencies are most concerned about polar-cap absorption (PCA) events which occur in association with major geomagnetic storms, are very wide spread, and last for extended periods of time. Under a PCA, all high-latitude communications at HF frequencies comes to a halt. PCAs are rare, but high-latitude absorption in the auroral zone is much more common. Auroral zone absorption is generally much more spatially confined and endures for periods of minutes to hours. It can also impact communications, but there have been no means whereby it can be detected on a global basis as it occurs.

Recent studies at APL have shown that SuperDARN data, when combined with available riometer data, may provide a global specification of auroral zone absorption. Figure 6 shows a sequence of four global sets of riometer observations taken over an hour time interval. The large circles represent absorption determined from the background noise levels obtained with the SuperDARN radars. The small circles represent absorption measurements obtained in central Canada with the CANOPUS riometers operated by the Canadian Space Agency. Unfilled circles represent sites were no data were available. The upper left panel shows little absorption with the exception of some of the riometers along the Churchill chain and the Saskatoon radar. The upper right panel, obtained 20 minutes later, shows somewhat increased levels of absorption, but little else. In the lower left panel, obtained 10 minutes later, the absorption has intensified considerably and spread over a larger spatial area. Finally, in the lower right panel, the absorption has intensified still more. In this event, which continued for an additional two hours, the absorption is intense over a fairly large spatial region and HF communications through this region would have been degraded or interrupted. The probable cause of this event was a fairly significant magnetospheric substorm, which injected very energetic particles into the inner magnetosphere. The particle drifted through the dawnside magnetosphere and eventually precipitate into the ionosphere in the late morning hours.

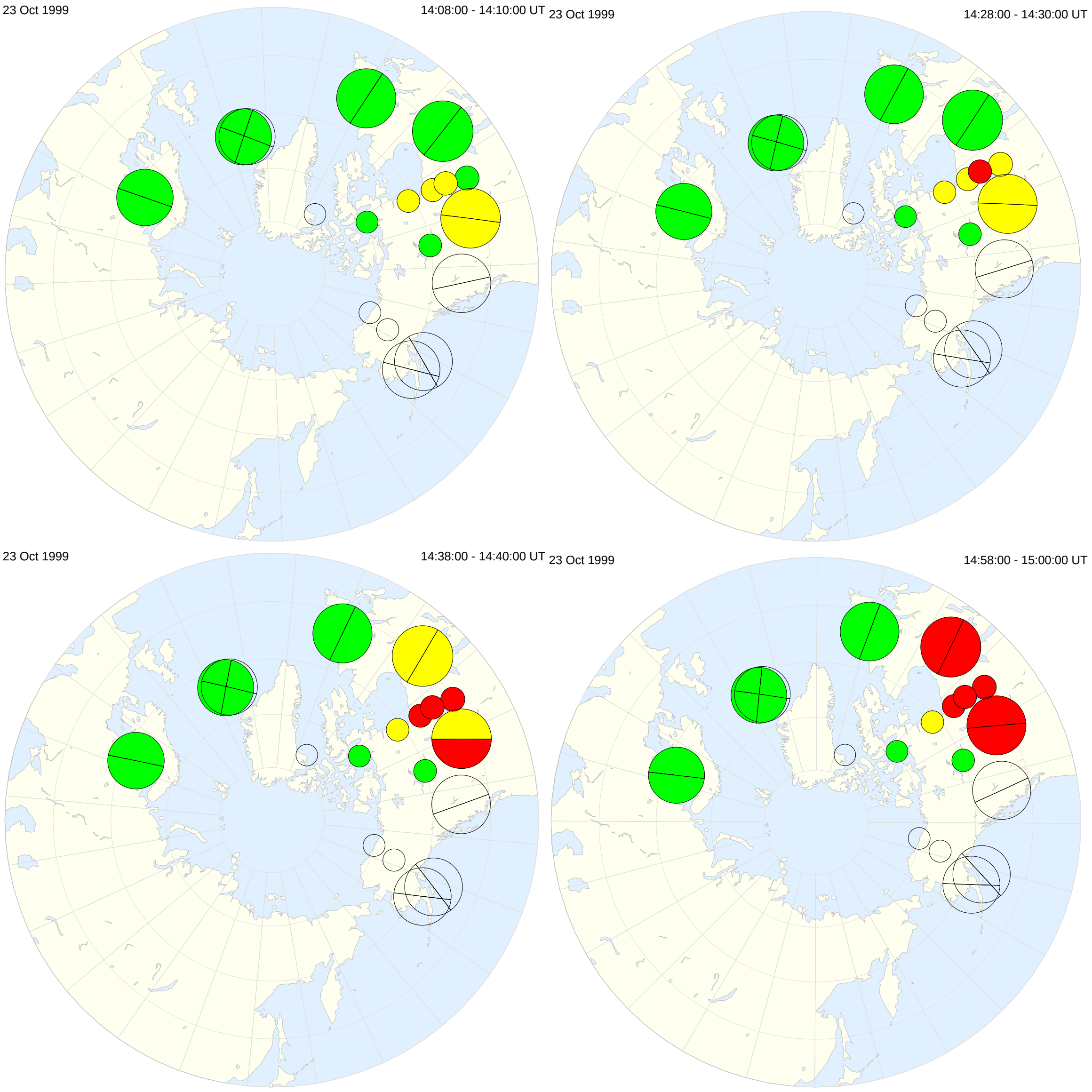

Figure 6 Four images of auroral zone absorption as observed with the SuperDARN radars and CANOPUS riometers. Red Circles indicate strong absorption, yellow circles indicate modest absorption, and green circles indicate no absorption. Open circles mean no data available. The data were obtained on 21 October 1999. Upper Left: 1408-1410 UT, Upper Right: 1428-1430 UT, Lower Left: 1438-1440 UT, Lower Right: 1458-1500 UT.

## Summary

The examples represent a few of the ways in which the global array of SuperDARN radars with their real-time Internet connectivity can contribute to human awareness of the dynamic nature of the high-latitude ionosphere and aid forecasters in the specification and prediction of the high-latitude ionosphere and its impact on radiowave propagation. By setting up and improving these specification products, we would be providing a service to a broad community of users, including HF broadcasting services, radio amateurs, and organizations that are forced to use HF as their primary means of communications. Most importantly, these space weather products will enable us to do a better job of optimizing the operation of the SuperDARN network.