Historical Overview of Mid-latitude SuperDARN

Following the successes of the Scandinavian Twin Auroral Radar Experiment (STARE) (Greenwald et al. 1978) and the Sweden and Britain Auroral Radar Experiment (SABRE) (Nielsen et al. 1983; Waldock et al. 1985) in the 1970s and 1980s which operated at very high frequencies (VHF), a new coherent scatter radar operating at HF was built at Goose Bay (GBR) (Greenwald et al. 1985) by Johns Hopkins University Applied Physics Laboratory (JHU/APL) with assistance from the British Antarctic Survey (BAS) and the Centre National de la Recherche Scientifique (CNRS). Prior work on HF in Europe with the Scandinavian and French Auroral Radar Investigation (SAFARI) had given a basis for expecting that scientifically valuable measurements would be obtained (e.g., Villain et al. 1985). The advantage of the new radar (GBR) was the extension of the field of view over that offered by the earlier VHF radars (note also that accurate $\mathbf{E} \times \mathbf{B}$ measurements cannot be made using the VHF radars) but more importantly this new radar was the first in a series of developments that would ultimately lead to the development of SuperDARN. The radar site was chosen in part for its geomagnetically high latitude (~60° N) which allowed for coverage of the bulk of the auroral oval under quiet to moderately active conditions. Common-volume measurements became possible with the construction of a radar at Schefferville, Canada, in 1986 although the geometry was not optimal for creating vector flows (Hanuise et al. 1993) and the radar ceased operation in 1995. This shutdown was followed, however, by a more successful development, the deployment of the first southern hemisphere radar at the BAS research station at Halley (HAL) in 1988 with a field of view approximately conjugate to that of GBR. The overall effort was referred to as Polar Anglo-American Experiment (PACE) (Baker et al. 1989). It is generally agreed that GBR and HAL were the first two in what would become SuperDARN.

The next major development occurred early in the 1990s when ideas about a Dual Auroral Radar Network (DARN) first began as a ground-based experiment for the Opportunity for the Origins of Plasmas in the Earth's Neighborhood (OPEN) concept, although this was really a mix of HF and VHF coherent scatter radars as well as the available incoherent scatter radars. A meeting held in Cambridge, UK, in 1991 provided the impetus for the creation of SuperDARN, at which point it became clear that radars would be developed with Principal Investigators (PIs) in France, Canada, Japan, South Africa, UK, and the US. The first radars inspired by the SuperDARN concept were built at Saskatoon and Kapuskasing (SAS and KAP) in 1993 by the University of Saskatchewan and JHU/APL, respectively. This activity was followed by builds in 1994 at Stokkseyri (STO) by CNRS and in 1995 by University of Leicester at the Collaborative UK Twin Located Auroral Sounding System (CUTLASS) sites in Hankasalmi and Pykkvibaer (HAN and PYK). The year 1995 is now considered to be the start of SuperDARN in its current form for three reasons: (i) the first tranche of radars was now operational in both hemispheres such that a true network could be considered to be in place, (ii) the formal agreement between the radar PIs was signed at a workshop in Cambridge, UK, in 1995, and (iii) the first paper describing SuperDARN as an experiment appeared (Greenwald et al. 1995). The PIs agreement formalized the operations of the radars in such a way that not only did a network exist but the way the radars would operate together - the allocation of time, the sharing of data, and how and on what time scales - had all been finalized.

The next decade saw the rapid deployment of radars at high latitudes in both the northern and southern hemispheres and the formation of new SuperDARN groups. By the early 2000s the high-latitude chain in the northern hemisphere had reached its current configuration, anchored in the east by the radars in Finland and Iceland and in the west by radars in Alaska. In the southern hemisphere the choice of sites was more constrained by logistical considerations and most sites were placed on the coast of Antarctica. The radars of the northern high-latitude chain were placed within a few degrees of the 60° N geomagnetic latitude (MLAT) contour with the exception of the sites in the Atlantic sector where only the landmass of Iceland was available resulting in radar sites nearer 65° N MLAT. The coverage of the F region ionosphere with the northern chain thus lies generally poleward of 65° N and backscatter is routinely generated up to 80° N MLAT, defining an annular region that encompasses the quiet-time Feldstein oval (Feldstein and Starkov 1967). In the southern hemisphere the latitudinal coverage is more variable but still aims to encompass the oval. A notable exception occurs in the Australian sector where the search for sites not in Antarctica led to the southern coasts of Tasmania and South Island (New Zealand) with MLAT nearer 55° S. The coverage of the F region ionosphere with the two Tasman International Geospace Environment Radars (TIGER, TIG and UNW) thus begins nearer 60° S and so a larger portion of the mid-latitude ionosphere is accessible to them.

Soon after the first SuperDARN radars were built it became clear that although the radars would see common-volume backscatter, the reliance on propagation conditions meant that the level of such overlapping scatter was not as high as had been expected from the earlier VHF experiments. This situation resulted in a significant data analysis development whereby the data are brought together and constrained by a spherical harmonic fit and a model of ionospheric convection to produce global maps of plasma convection (Ruohoniemi and Baker 1998; Shepherd and Ruohoniemi 2000). In addition, new technical developments were being added to the radars. Examples include a different antenna design for the radar at the King Salmon site (KSR), the concept of Stereo whereby radars run in two modes nearly simultaneously (Lester et al. 2004), digital receiver cards in place of the analogue receivers that had been part of the original design, and new pulse codes.

The scientific accomplishments of SuperDARN as a high-latitude network were reviewed by Chisham et al. (2007). It was noted that the equatorward expansion of the auroral oval and convection pattern during storm periods lessened the ability of SuperDARN to image the entire pattern. Moreover, storm-time suppression of backscatter due to enhanced D region absorption at high latitudes impacted the availability of measurements. Within the U.S. and Japan, the idea formed that the HF technique could be scientifically productive at lower latitudes. The JHU/APL group was strongly motivated by a desire to map the expansion of storm-time convection while researchers in Japan were interested in extending observations of medium-scale Traveling Ionospheric Disturbances (TIDs) (e.g., Samson et al. 1990; Bristow and Greenwald 1996) to include mid-latitude TIDs as reported, for example, by Shiokawa et al. (2003), and also in extending the coverage provided in the Japanese sector by Global Positioning System (GPS) Total Electron Content (TEC) receivers and all-sky airglow imagers to the ionosphere north of Hokkaido.

The JHU/APL group arranged to construct a radar site on the grounds of the NASA Wallops Flight Facility in eastern Virginia which corresponds to about 50° N MLAT. Limited resources were stretched by designing and building in-house a new type of antenna (the Twin-Terminated Folded Dipole or TTFD) and transmitter and control electronics. A further re-design of the standard radar layout involved reducing the separation of the antennas in the arrays from 50 feet to 42 feet (15.24 to 12.80 m). The radar was oriented to look primarily eastward over the Atlantic Ocean. After some iteration of the antenna design the first purpose-built mid-latitude SuperDARN radar (WAL) went on the air at Wallops in the spring of 2005. As expected, daytime ground scatter and storm-time auroral backscatter were observed; unexpectedly, a new and persistent type of backscatter was observed on the nightside that appeared to be from the sub-auroral ionosphere. The low velocities (tens of meters) and narrow spectral widths of this type of backscatter caused it to be confused initially with ground scatter. Greenwald et al. (2006) described the properties of the backscatter and suggested that it was due to irregularities generated by the temperature gradient instability (TGI). New views of Sub-Auroral Polarization Streams (SAPS) electric fields were described by Oksavik et al. (2006) and a first model of convection using mid-latitude radar data was developed by Baker et al. (2007).

As of 2005, Japanese groups were operating radars at high-latitude sites in Alaska and Antarctica. A new group working out of the Solar-Terrestrial Environment Laboratory (later re-organized into Institute for Space-Earth Environmental Research, ISEE) at Nagoya University proposed to build a radar at a site near the Rikubetsu Observatory on Hokkaido (Hokkaido East, HOK) that corresponds to about 37° N MLAT which is more than 10° equatorward of WAL. In principle, the radar would form a common-volume pair with the high-latitude radar operating out of King Salmon, Alaska (KSR) by the group at National Institute of Information and Communications Technology (NICT) albeit with a challenging far-range requirement. The Nagoya University group proposed a special program "Energy Transport Processes in Geospace" containing the construction of a SuperDARN radar in Hokkaido. It was approved as Special Funds for Education and Research from the Ministry of Education, Culture, Sports, Science and Technology of Japan in 2005. The radar began operations in November 2006. The consistency in observations of TIDs between the radar looking over the ocean to the north of Hokkaido and TEC measurements over the Japanese home islands was soon demonstrated (Ogawa et al. 2009). The radar also demonstrated its capability for monitoring a wide variety of topics such as ionospheric disturbances triggered by a huge earthquake (Nishitani et al. 2011; Ogawa et al. 2012) and solar flares (Watanabe and Nishitani 2013).

The JHU/APL group explored the possibility of locating a second radar at the NASA Wallops Flight Facility to extend coverage westward over the North American continent. A lack of suitable land led to discussions with Virginia Tech concerning a site in central Virginia, and a radar was installed near Blackstone (BKS) in 2008 using transmitters and control electronics loaned by University of Leicester. A paper by de Larquier et al. (2013) used the interferometer capability of the radar to confirm that nightside sub-auroral backscatter is due to F region irregularities. The involvement of Virginia Tech in the build project at Blackstone contributed to the move of the senior leadership of the SuperDARN group at JHU/APL to Virginia Tech with the PI-ship of WAL remaining with

JHU/APL.

Within the U.S. community the idea formed to pursue the rapid development of a mid-latitude chain of radars anchored by the existing radars in Virginia and Hokkaido. A proposal to the National Science Foundation (NSF) Mid-Sized Infrastructure (MSI) program for 'StormDARN' was successful and a consortium of groups at Virginia Tech, University of Alaska Fairbanks, Dartmouth College, and JHU/APL proceeded to implement a new dual radar concept with two radars essentially sharing a site through careful coordination of transmit and receive functions. The first radar pair was built near Hays, Kansas ('Fort Hays') (FHE and FHW) in 2009, the second near Christmas Valley, Oregon (CVE and CVW) in 2011, and the third on Adak Island (ADE and ADW) in the Aleutians in 2012. A key aspect of the MSI dual radar configuration is the joining of adjacent fields of view resulting in a large fan-shaped area of combined coverage. (Although a pair of radars had been deployed at the Japanese Antarctic base at Syowa, the MSI project was the first time that such a planned development over many hours of LT had been undertaken.) An early triumph of the mid-latitude chain was the first multi-radar observation of a longitudinally extended SAPS channel (Clausen et al. 2012). This result dramatically demonstrated the value of extending the SuperDARN coverage to include the sub-auroral region. The Nagoya University group succeeded in deploying a second SuperDARN radar near Rikubetsu Town on Hokkaido in 2014, the Hokkaido West radar (HKW), with a field of view extending from the north to the northwest. Here also the combination of radar fields of view produces a large fan-shaped area of coverage.

As noted, the arc of radar sites in the North American sector roughly follows the 50° N MLAT arc. The radars built in Virginia, Hokkaido, and elsewhere in North America as a result of the NSF MSI project were dedicated to making observations in the mid-latitude ionosphere, that is, they were located to make observations over latitudes that are usually sub-auroral. In fact, some nominally high-latitude radars had reported on sub-auroral phenomena previously. Although sited at the relatively high MLAT of 65° N the field of view of KSR is rotated so far from poleward as to make this radar look in the westward zonal direction where it observes SAPS, e.g., Koustov et al. (2008). The Australian radars at 55° S MLAT were also reported to detect SAPS, e.g., Parkinson et al. (2006). It seems likely that all the high-latitude radars at times detect backscatter from equatorward of the auroral boundary that is not always acknowledged as such. The dusk scatter phenomenon first described by Ruohoniemi et al. (1988) for GBR and discussed comprehensively by Hosokawa et al. (2001) using high-latitude radars is an example of a boundary effect that required the deployment of a dedicated mid-latitude radar (to Hokkaido) to place in its proper spatial context (Hosokawa and Nishitani 2010). It should also be noted that during periods of enhanced geomagnetic activity the auroral oval expands out of the high-latitude radars fields of view into the mid-latitude radar field of view. For example, Carbary [2005] showed that the auroral oval expands to ~50º MLAT for Kp 8-9.

In the southern hemisphere a radar was briefly deployed on the Falkland Islands (FIR) from 2010 to 2011 owing to a temporary re-location of Halley electronics (this radar resumed operations in November 2017 with fully digital electronics, identical to the one at Buckland Park). This deployment made possible studies of SAPS in the southern hemisphere (Grocott et al. 2011) and conjugate studies of SAPS with WAL and BKS in the north (Kunduri et al. 2012). A new radar was deployed at Buckland Park, Australia (BKP) in 2014. This implementation was a significant technical development as it represented the first fully digital SuperDARN radar (see the "Technical Developments" subsection). Plans were also drawn up for SuperDARN radars to be deployed in Russia. New mid-latitude radars are planned for Europe and Eastern Asia (see the "Expansion of SuperDARN Coverage" subsection for details).

At much the same time as the first mid-latitudes radars were being deployed, the final (to date) major development of the overall network occurred as new radars were being built in the polar cap regions in both the northern and southern hemispheres thereby extending the coverage of SuperDARN to a much larger latitudinal range. In the North American sector, it is now possible to make out three latitudinal tiers of radar chains with coverage of the F region ionosphere extending continuously from 55° MLAT into the polar cap. The value of this expanded coverage has been demonstrated with large-scale mapping of the sources of high-latitude ionization structures in processes taking place at mid-latitudes (e.g., Thomas et al. 2013; Zhang et al. 2013).

We note that the occurrence of irregularities in the sub-auroral F region ionosphere was described at least as long ago as Bourdillon et al. (1982). Subsequent reports have included satellite observations of topside irregularities, e.g., Pfaff et al. (2008). SAPS phenomena have been studied for several decades using satellites and single radars, e.g., Anderson et al. (1991), Foster and Vo (2002). To these studies the SuperDARN mid-latitude radars have brought significant new capabilities for imaging effects on large spatial scales with high time resolution. With these capabilities SuperDARN community is moving beyond basic detection of irregularities to deeper analysis of the underlying causes of plasma instability and to utilization of the backscatter to make measurements of electric fields, conjugacy, magnetosphere-ionosphere coupling, and a host of other phenomena that are fundamental to improving our understanding of space science.

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