doi: 10.3724/SP.J.1085.2013.00001
March 2013 Vol. 24 No. 1: 1-11

The Super Dual Auroral Radar Network (SuperDARN): An overview of its development and science

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Received 2 March 2013；accepted 19 March 2013

Abstract The Super Dual Auroral Radar Network (SuperDARN) is a network of HF coherent scatter radars. At the end of 2012 there were 31 operational radars of which 22 were in the northern hemisphere and 9 in the southern hemisphere. The radars are operated by 17 different research groups from 11 different countries. In this paper we give an overview of the network and its development over the last twenty years, concentrating on the nature of the collaboration. We describe the data parameters that are available, radar operational modes, and the structure of the SuperDARN collaboration. A brief, "light touch" review is also given of the science achieved with the network. Finally we give a brief look to future science directions.

Keywords **ionosphere, magnetosphere, SuperDARN**

Citation: Lester M. The Super Dual Auroral Radar Network (SuperDARN): An overview of its development and science. Adv Polar Sci, 2013, 24:1-11, doi: 10.3724/SP.J.1085.2013.00001

1 Introduction

The Super Dual Auroral Radar Network (SuperDARN) is a network of HF coherent scatter radars which, at the end of 2012, consisted of 31 operational radars, with 22 in the northern hemisphere and 9 in southern hemisphere. The first radar to be deployed was at Goose Bay in 1983[1] and was subsequently followed by the Halley radar in Antarctica in 1988[2]. Together, these two radars formed the Polar Anglo-American Conjugate Experiment (PACE). However, SuperDARN, which included the Goose Bay and Halley radars, can be considered to have started operations in 1993 when new radars were deployed in Canada, at Saskatoon and Kapuskasing, soon to be followed by systems in Iceland and Finland[3]. Radar operations are currently conducted by 17 different research groups in Australia, Canada, China, Finland, France, Italy, Japan, the Russian Federation, South Africa, United Kingdom and the United States of America.

SuperDARN radars are coherent scatter radars which receive scatter from magnetic field-aligned irregularities in both the E- and F-regions of the ionosphere. The radars can operate at frequencies between 8 and 20 MHz, although typical operational frequencies are between 10 and 14 MHz. At these frequencies the radar signal is also refracted back down to the ground as a consequence of the ionospheric ionisation from where it can also be scattered both in the forward direction as well as back along the direction of the path. In the forward direction it can of course again be scattered back along the path by ionospheric irregularities. Hence the radars can receive not only direct backscatter from ionospheric irregularities, referred to as half hop, but also from one and a half hop propagation via the surface, as well as potentially, although rarely, two and a half hop propagation. This refraction greatly increases the potential size of a SuperDARN radar field of view, especially when compared with similar radars which operated at higher frequencies such as STARE[4] or SABRE[5]. The radars therefore receive scatter from two different regions, the ionosphere and the surface of the planet, either ground, sea or ice, but collectively known as ground scatter. The difference between the two types of scatter is that ionospheric scatter will have had a Doppler shift imposed upon the signal by the motion of the ionospheric irregularities in the ionosphere, while ground scatter has little or no Doppler shift. In addition the spectrum of the signal is often broadened by the scatter from ionospheric irregularities which is

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not the case for ground scatter. Both types of scatter can be used for scientific purposes, as can other types of scatter such as that from meteor ionisation trails or polar mesosphere summer echoes (PMSEs).

There have been several reviews[6-8] of the science that SuperDARN can achieve and has achieved. We do not propose to review in detail the science here but simply to provide an overview not just of the network but also the philosophy behind the operations as well as the manner in which the network runs. We do, however, close with some thoughts on the science problems that the network has addressed and will also be able to tackle in light of the recent expansion.

2 SuperDARN development

Although two radars were operational beforehand, the start of SuperDARN can be attributed to the year 1993, which means that the network celebrates its twentieth anniversary in 2013. At the end of 1993 there were 4 operational radars, 3 in the northern hemisphere and 1 in the southern hemisphere. By the end of 2012 there were 31 operational radars, 22 in the northern hemisphere and 9 in the southern hemisphere. Figure 1 provides a time history of the development of the radar network by plotting the geographic latitude of the radars as a function of time from their operational start for both the northern hemisphere (Figure 1a) and the southern hemisphere (Figure 1b). The start of the interval is 1993 as this can be considered the initial start of the network. Table 1 also provides the locations and start dates of each radar in the network.

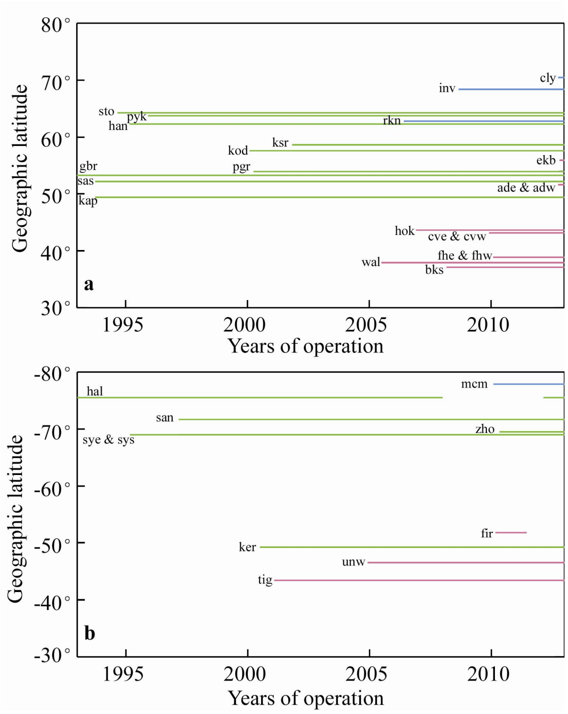

Figure 1 A presentation of the time development of the SuperDARN radars. Each radar or radar pair is represented by a horizontal bar starting at the start date of the radar operations with the radar bar located at its geographic latitude. The interval presented is from 1993 to the end of 2012. Panel **a** is for the northern hemisphere and Panel **b** is for the southern hemisphere.

Table 1 The locations and start dates of each radar in the SuperDARN

Current SuperDARN radars				
Radar name	Code	Commenced operations	Geographic co-ordinates	
			Latitude	Longitude
Northern Hemisphere				
Goose Bay	gbr	Oct 1983	53.32°N	60.46°W
Kapuskasing	kap	Sep 1993	49.39°N	82.32°W
Saskatoon	sas	Sep 1993	52.16°N	106.53°W
Iceland West (Stokkseyri)	sto	Aug 1994	63.86°N	22.02°W
CUTLASS Finland (Hankasalmi)	han	Feb 1995	62.32°N	26.61°E
CUTLASS Iceland East (Pykkvibaer)	pyk	Nov 1995	63.86°N	19.20°W
Kodiak	kod	Jan 2000	57.60°N	152.20°W
Prince George	pgr	Mar 2000	53.98°N	122.59°W
King Salmon	ksr	Oct 2001	58.68°N	156.65°W
Wallops Island	wal	Jun 2005	37.93°N	75.47°W
Rankin Inlet	rkn	May 2006	62.82°N	93.11°W
Hokkaido	hok	Nov 2006	43.33°N	143.61°E
Blackstone	bks	Feb 2008	37.10°N	77.95°W
Inuvik	inv	Aug 2008	68.42°N	133.50°W
Fort Hays East	fhe	Jan 2010	38.86°N	99.39°W
Fort Hays West	fhw	Feb 2010	38.86°N	99.39°W

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Christmas Valley E	cve	Nov 2011	43.27°N	120.36°W
Christmas Valley W	cvw	Nov 2011	43.27°N	120.36°W
Adak E	ade	Sep 2012	51.88°N	176.62°W
Adak W	adw	Sep 2012	51.88°N	176.62°W
Clyde River	cly	Sep 2012	70.49°N	68.50°W
Ekaterinberg	ekb	Dec 2012	56.44°N	58.57°E
Southern Hemisphere				
Halley (SHARE)	hal	Jan 1988	72.52°S	26.63°W
Syowa South	sys	Feb 1995	69.00°S	39.58°E
Sanae (SHARE)	san	Feb 1997	71.68°S	2.85°W
Syowa East	sye	Feb 1997	69.01°S	39.61°E
Kerguelen	ker	Jun 2000	49.35°S	70.26°E
TIGER Tasmania	tig	Jan 2001	43.38°S	147.23°E
TIGER Unwin	unw	Nov 2004	46.51°S	168.38°E
McMurdo	mcm	Jan 2010	77.88°S	166.73°E
Falkland Islands*	fir	Feb 2010	51.83°S	58.98°W
Zhongshan	zho	Apr 2010	69.38°S	76.38°E

* Note: The Falkland Islands radar ceased operations in October 2011.

The network was initially developed to provide observations of the high latitude convection pattern. Hence radars were originally placed such that their fields of view looked into the auroral regions. The initial auroral network comprised 16 radars in total, with 9 in the northern hemisphere and 7 in the southern hemisphere, with the last to be deployed being TIGER Unwin in 2004. However the bulk of these radars had been deployed prior to 2001, which meant that in the period following solar maximum the coverage in both hemispheres was excellent.

The original idea for the radar coverage was to have overlapping fields of view following on from the successful VHF radars such as STARE[4] and SABRE[5]. Such a configuration would allow for the 2 dimensional vector velocity perpendicular to the magnetic field in the ionospheric F-region to be determined. Moving to the lower frequency range from VHF, meant that the radars had larger fields of view. However, in the early part of the SuperDARN programme it became clear that, while there was plenty of ionospheric scatter measured by both radars at the same time, overlapping measurements by both radars happened rarely. Consequently other techniques were needed to provide the global ionospheric convection that was required. This resulted in the development of the “map potential” technique[9] which used all ionospheric measurements of velocity by the existing radars with a spherical harmonic representation of the ionospheric electrostatic potential, to produce a unique representation of the ionospheric convection pattern once every 2 min. An example of the output from this technique from 2002 is shown in Figure 2.

The next major development in the radar network began in 2005, when the first mid-latitude SuperDARN radar was deployed at Wallops[10]. This mid-latitude radar has a field of view looking north into the fields of view of two auroral radars in Canada, Kapuskasing and Goose Bay. Being at mid latitudes was important as it had become clear that the radars were missing part of the ionospheric convection due to the location of a number of the auroral radars being at relatively high latitudes. This is particularly the case when magnetic storms occur. While the auroral radars do still observe scatter during such events there are periods when the radar scatter does disappear either due to absorption of the HF signal or lack of ionisation for propagation. Moving to mid-latitudes enables the network to make measurements of the convection during such storm periods and hence the mid-latitude radars are often referred to as StormDARN. The Wallops radar was followed by the deployment of the Hokkaido radar in Japan in 2007 and then a second radar in the US, at Blackstone, in 2008.

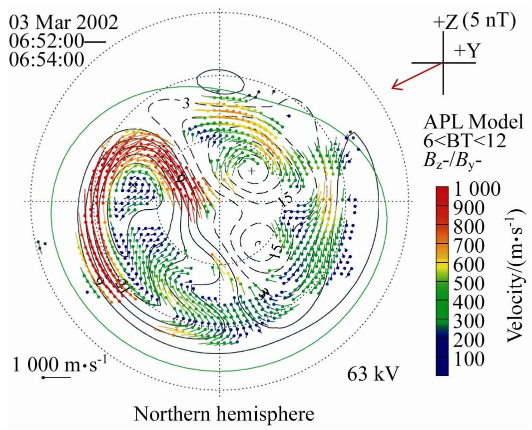

Figure 2 An example of ionospheric convection pattern derived from the map potential analysis technique[9].

While these were important developments, the real expansion at mid-latitudes came in 2010 with the deployment of the first pair of Mid Size Infrastructure (MSI) funded radars in the US at Fort Hays, Kansas. The MSI radars will include 8 radars with pairs of radars in the Aleutian Islands, Oregon, Kansas and the Azores. Of these the first three pairs are now built, with the Christmas Valley, Oregon, radars becoming operational in 2011 and the Adak radars on the Aleutian Islands in 2012. These radars developed the concept whereby a pair of radars each with at least 16 beam directions in a fan located at the same site would cover a significant range in azimuth. This had previously been done with two auroral radars in the southern hemisphere at the Japanese Antarctic Syowa Station. To do this a second antenna array is needed with a main bore sight in a direction nearly orthogonal to the other. Together with the first three mid-latitude radars, these 8 MSI radars will provide mid latitude coverage from Japan to the UK. These are not the only mid latitude SuperDARN radars, however. In 2012 the first of 4 such radars in Siberia was deployed and became operational in December 2012 at Ekaterinberg. This development is important as it is the first time that SuperDARN has had radars in the Siberian local time sector, a gap which in the past had been significant.

In the southern hemisphere the move to mid latitudes has not been as extensive, partly due to the lack of land area on which radars can be built. The two TIGER radars at Bruny island, Tasmania and in New Zealand (Unwin) could be described as hybrid radars as they are not quite auroral and not really at mid latitudes. At the time of writing the only true mid latitude radar in the southern hemisphere had been a radar deployed at Goose Green on the Falkland Islands[11] in 2010 and which was operational for nearly 18 months. This radar was short lived as the electronics from the Halley radar were removed from the site due to the site base being re-built. The electronics were returned to Halley in 2012 and this radar continues to function.

At the time of the move to mid-latitudes there was also a new development of radars at much higher latitudes, PolarDARN. Three such radars have been deployed in the high latitude Arctic regions in Canada, at Rankin Inlet in 2006, Inuvik in 2008 and Clyde River in 2012. The first two of these radars proved to be very influential at the time of the unusually extended solar minimum during which there was a reduced level of ionospheric scatter at the SuperDARN and StormDARN radars. In the southern hemisphere two PolarDARN radars were also deployed, at the Chinese Antarctic Zhongshan Station, in 2010, and McMurdo, in 2011. Further expansion of the network in both hemispheres is expected in 2013 and 2014.

3 SuperDARN operations

Early in the development of SuperDARN it was clear that in order to get the best from the network, a clear planning structure for the operations of the network was needed. Having all radars operational in the same mode providing essentially the same data set was seen as a critical element of the network. Indeed this aspect remains central to the scientific success of the network. To do this, therefore, a structure through which the network would run was required, albeit an informal structure to reduce the burden of administration.

The main structure consists of an Executive Council, which consists of each of the individual SuperDARN radar Principal Investigators, with several working groups which have responsibility for various aspects of the radar operations. In 1995, the 7 members of the Executive Council formalised the collaboration by each signing a PI agreement which set out the terms of reference of membership of the network. The Executive Council meets once per year, at an annual SuperDARN workshop, which has been held every year since 1993. The PI agreement was revised and re-signed by the current 15 PIs in 2012 at the annual meeting in Shanghai. This agreement covers all aspects of the radar programme, including the radar operations, the basic data sets expected from each radar, the operational schedule, data availability.

In addition to the Executive Council, there are working groups which are responsible for the operations schedule, data distribution, spacecraft co-ordination and software. The Scheduling Working Group (SWG) allocates time through a monthly operating schedule which is based on requests of time to the SWG from the community and other scientists. Assessment of the time allocation requests is done on a monthly basis and time allocated according to the request, ability of the radar to undertake the required measurements. As input to the SWG, the Spacecraft Scheduling Working Group also provides input on the need for certain experimental modes in support of spacecraft missions. There have been three main space missions with which the network has run co-ordinated campaigns, Cluster, THEMIS and, since November 2012, the Van Allen probes. Other working groups include the Data Distribution Working Group which ensures that there are clear guidelines on how the data should be distributed and the Software Working Group which looks at ways in which the radar operational software and analysis software can be improved.

SuperDARN radars are remarkably flexible in operation. The standard, or common mode, is to steer the radar in 16 successive directions integrating along each direction for a fixed time, either 3 s, 6 s, or 7 s, and starting each scan either on a 1 min or 2 min boundary. The individual beam direction has a 3 dB beamwidth of typically 3.25° and so the full azimuthal scan of a single radar is 52°. This synchronisation of the radars ensures that a full scan for each radar is completed in typically 1 min or 2 min. Initially the scans were fixed at 2 min, with 7 s integration times along each beam, but in the mid part of the last decade the decision was taken to operate 1 min scans with 3 s integration along each beam. Based on the PI agreement the common mode operates for at least 50% of each month. In 2012 the PIs agreed to run modes in support of the van Allen probes which include a responsive mode based on the scientific conditions. SuperDARN also operates an open data policy.

Other types of radar time, special and discretionary, are also allocated, with special time being run for at most 20% of each month and discretionary time at most 30% of the month. In the case of special experimental modes, the radars all run essentially the same mode, but not a common mode. Early examples of this mode would be the insertion of a single special beam which would be interleaved between each of the individual beams, thereby giving higher time resolution on a single beam. More complicated modes were also proposed. Discretionary modes are operated when individual experimenters require a different mode on an individual or small subset of radars. Such discretionary modes can be useful for supporting experimental work requiring just one radar, for example in support of experiments involving high power radio transmitters such as the "heater" at Tromso[12-13], or experiments designed to study only E-region ionospheric irregularities with range resolution 15 km[14].

Typically SuperDARN radars operate a seven pulse code with individual pulse lengths of 300 microseconds. The interpulse sequence varies such that an auto correlation function (ACF) can be computed from the integrated returned signal. From the ACF the Doppler velocity and spectral width parameter are calculated. The individual pulse length determines the range resolution which is typically 45 km but can be reduced below that depending upon the radar. Most radars for example can only go to 100 microseconds, equivalent to 15 km, but new developments enable systems to reach range resolutions of 5 km or even less. Typically the range coverage is between 180 km and 3 230 km, although the furthest range does depend on the number of range gates and the range resolution. A second development is to store all the data rather than to integrate the data. This allows subsequent re-analysis of the data and can result in sub second time resolution[15-16].

4 Science

As mentioned above, it is not the purpose of this paper to review the science that has been done with SuperDARN or its capabilities. Detailed reviews can be found elsewhere[6]. However, for the purposes of this overview paper, it does seem reasonable to provide some discussion of the science that has been done and where future directions may take the network. It should be noted that given there are over 600 papers which have been published with SuperDARN data, it is not feasible to cover all aspects nor in detail. Consequently the overview below is very much a "light touch" approach.

4.1 Ionospheric convection

SuperDARN was originally designed to make large scale, near global, and interhemispheric measurements of the ionospheric convection which is driven by the interaction of the solar wind with the magnetosphere. In this, the network has been extremely successful and has made several new discoveries. The main driver for ionospheric convection is magnetic reconnection, either at the dayside magnetopause between the interplanetary magnetic field (IMF), or more accurately the magnetosheath magnetic field and the geomagnetic field, or in the geomagnetic tail between open field lines nominally in the two tail lobes.

Dayside reconnection and its consequences for ionospheric convection have been studied extensively with SuperDARN. Transient convection flow enhancements were initially found to be related to the ionospheric footprint of the dayside cusp[17-18]. While the flows had significant poleward velocities, the region of scatter was also found to move polewards, and have become known as Poleward Moving Radar Auroral Forms (PMRAFs). Subsequently, the relationship between PMRAFs and flux transfer events, examples of transient and patchy reconnection at the dayside magnetopause, was demonstrated in a series of joint space and radar studies[19-24]. Measurements by the radars can allow estimates of the flux content which has been opened by the flux transfer event to be made[20]. However, there is a conundrum since it appears that the amount of flux opened during such events as measured by the radars is an order of magnitude higher than the normal values estimated from spacecraft *in situ* measurements.

Global scale observations of the ionospheric convection have allowed the response to changes in the direction of the IMF to be determined, although this at first was somewhat contentious. In an initial early study the flows in the noon sector appeared to respond rapidly to a northward turning of the IMF (of order 2 min) while at other local times, the response to a complete change in the pattern was much longer[25]. Other studies[26-27], in contrast, showed an almost simultaneous response at all local times to a southward turning of the IMF. The differences were later reconciled when it became clear that both were correct, with an instantaneous response at all local times, but a gradual change to the completely new pattern[28-29], an observation supported by simple modelling results[30]. Large scale statistical ionospheric convection patterns have also been created using the radar data[31-34].

An alternative way of using the global ionospheric convection has been reviewed[7] where a technique to calculate the reconnection electric field as a function of local time was described. This is undertaken by measuring the ionospheric flow across the boundary between open and closed magnetic flux in the ionosphere. This technique which utilises the model of the expanding and contracting polar cap for the generation of ionospheric flows[35] requires the large scale continuous observations made possible by SuperDARN. Thus, SuperDARN is the only technique that can currently estimate the reconnection electric field as a function of local time over a range of local times at time scales of a few minutes.

One of the real discoveries with SuperDARN is the observation of large scale ionospheric flows in the nightside ionosphere during relatively quiet magnetic conditions[36-41].

These flows occurred during extended periods of northward IMF and the direction of the flow differed depending upon the orientation of the IMF B_y component, dawnward (duskward) across midnight for B_y positive (negative) in the northern hemisphere and opposite in the southern hemisphere. The proposed mechanism for the formation of such large scale flows is a twisted magnetic field in the tail resulting from the extended period of IMF conditions[41].

As mentioned earlier a key aspect of the initial SuperDARN array and radar locations was that during disturbed, or storm time conditions, the radars often received little or no backscatter either as result of ionospheric absorption or as the convection pattern expanded across the network. The addition of the first mid-latitude radar at Wallops demonstrated that during such disturbed conditions (K_p>3) the ionospheric cross polar cap potential with Wallops was of order 76 kV compared with 61 kV when Wallops data were not included[42]. This comparison was based on an eleven month data set in 2005 and 2006.

Another aspect of the mid-latitude observations of ionospheric convection is the large scale, large electric field driven flows during storms, often referred to as sub-auroral polarization streams, SAPS[43]. The first observations of some of the two-dimensional sub-auroral ion drifts within the SAPS were made in 2006 by the Wallops radar[10]. In this study the two dimensional nature appeared to vary on timescales of a few minutes. More recently the extensive nature of the SAPS has been revealed by the extension of the mid-latitude radars across the USA[44]. Here the SAPS are seen across 6 h of local time and for 3 h of UT. Furthermore, interhemispheric observations of storm time electric fields in the sub-auroral latitudes have been made with the Falkland Islands and Blackstone radars[11,45].

4.2 Magnetospheric substorms

Ionospheric convection is also driven by magnetospheric substorm processes, although the process is much more complex on the nightside due to the presence of enhanced ionospheric conductivities. A number of studies have utilised SuperDARN observations of convection, either through statistical studies[46-49] or through individual case studies[50-52].

The recent statistical studies have centred on using the onset location of magnetospheric substorms to determine the convection relative to the initial brightening. Superposed epoch analysis of such events have demonstrated that the flows in the vicinity of the enhanced conductivity are often reduced, but with enhanced flow surrounding this region of suppressed velocity[46], while the transpolar voltage nearly doubled from just prior to onset to 12 min after onset (40 kV to 75 kV). Further study using a larger data set indicated that the flow response to substorm onset was dependent upon the latitude of the initial onset[48]. All latitudes demonstrated an enhancement in the flows some 60 min after the substorm onset, with the lower latitude onset events having more enhanced convection than higher latitude events. However, the convection during onsets at lower latitudes do have localised reduced convection in the midnight-sector.

4.3 Magnetospheric boundaries and ionospheric structure

The above discussions have focussed on the use of the Doppler velocity from the radar observations. There are two other routine parameters which are measured, the backscatter power and the spectral width. The spectral width parameter has been used in a variety of ways. One of the critical ways has been to indicate the ionospheric footprints of magnetospheric boundaries. Two examples have been the identification of the ionospheric footprint of the cusp region by enhanced spectral width and the boundary between open and closed magnetic flux by a boundary between high (open) and low (closed) spectral width. In the former case, the cusp, the observations are typically of large values of spectral width being associated with the footprint of the cusp[53]. These observations demonstrated two particular regions of spectral width, a higher latitude, higher spectral width region and a lower latitude, lower spectral width region, with often a well defined boundary between them, the so-called spectral width boundary (SWB). Such boundaries were found to be located elsewhere, e.g. in the pre midnight sector[54] and the post midnight sector[55], the latter case related to auroral boundaries. A series of studies[56-59] then demonstrated that the SWB is a good proxy for the boundary between open and closed magnetic field lines in two main regions, the pre-midnight sector (18–24 MLT), and the noon sector (08–12 MLT). Elsewhere the SWB is offset by 2° equatorward of the boundary between open and closed magnetic fields in the 02–08 MLT region, and could be a proxy for the boundary only at latitudes greater than 74° magnetic latitude. Knowledge of the boundary between the open and closed magnetic fields is important for the determination of reconnection rates as detailed in section 4.1.

The backscatter power is also an important indicator of the regions of scatter. Often these will also be associated with enhanced electron density[60]. Enhanced electron density in the polar regions will be related to polar cap patches[61]. Using the radars to identify the regions of enhanced density and the convection measured simultaneously led to predictions[60] of the motion of the patches from the dayside creation region in the throat of the convection flow all the way across the polar cap and into nightside located radars in Canada. Other reports of coincident GPS observations of TEC have demonstrated that polar patches can be formed due to the modulation of nightside reconnection during the substorm cycle[62].

4.4 ULF waves

SuperDARN has also proven to be a successful tool for the study of ultra low frequency (ULF) magnetohydrodynamic (MHD) waves with periods typically in the 45–600 s range. Such waves are an important means of energy transfer within the magnetosphere. ULF waves can be caused by external mechanisms, for example the flow of the solar wind across the magnetopause which creates Kelvin-Helmholtz waves. Such waves will typically have large scale sizes within the magnetosphere. Internally driven waves, which typically have smaller azimuthal scale sizes are also observed by SuperDARN and these waves are typically generated by drifting energetic particle populations in the magnetosphere. Due to the typical scan time for the radars of 1 min or 2 min, it has tended to be long period waves which have been observed by SuperDARN, that is in the Pc5 band (150–600 s). Specific experiments have been used where the scan time is shorter, for example with experiments with high power transmitters which create patches of scatter from which the radars can receive backscatter. Small-scale waves can be seen with such experiments[63] and in conjunction with theoretical analysis have lead to a deeper understanding of the interactions of the waves with the particle populations responsible for generating them[64]. Alternatively, the implementation of new systems such as the Stereo technique[65] can enable the radars to operate two different experimental modes simultaneously, such that one mode can be a high time resolution, e.g. a single beam.

SuperDARN observations are typically of the modulated ionospheric electric field associated with the waves[66], but also the waves can cause changes in the reflection altitude and so can be seen in the ground scatter[67]. MHD waves in the solar wind can also directly modulate the reconnection rate at the dayside magnetopause, resulting in modulation in the Pc5 band (150–600 s) of the velocity fluctuations in the cusp region[68]. There is also evidence that Pc5 field line resonances which are related to similar Alfvenic fluctuations in the solar wind, can be observed equatorward of the cusp region on closed magnetic field lines[69-70].

4.5 Atmospheric Gravity Waves

Atmospheric gravity waves (AGW) propagating in the thermosphere create disturbances in the ionosphere often referred to as travelling ionospheric disturbances (TIDs). Such TIDs essentially move the reflecting layer of the ionosphere up and down and consequently the ground scatter received by the radars can be modulated in power and range. The TID essentially focuses and defocuses the radar signal at the reflection height resulting in the modulation of the ground scatter[71-72]. In addition the range to the first ground scatter, often referred to as the skip distance, can be modulated[73]. Dual frequency observations of such waves using the Stereo technique[65] have also proven useful in determining accurately the source location[74] TIDs with wavelengths 150 to 350 km are referred to as Medium Scale (MSTIDs) and these features are often related to source mechanisms in the auroral zone[75].

The expansion of the network to mid latitudes has given greater opportunity for the study of such waves as it becomes easier to remove any contamination of the source region on the propagation conditions. The Hokkaido radar has been successful in observing MSTIDs in particular in conjunction with all-sky imager and GPS observations[76]. This work was followed by observations by the Falkland Islands radar[77] which found not just a population of waves propagating equatorward but also a smaller population of westward travelling waves that may have been associated with AGWs which have been generated by winds over mountains such as the Andes or those of the Antarctic peninsula mountains, or the Antarctic Polar Vortex.

Large scale TIDs also exist and these waves are believed to have similar auroral sources, but here the wavelengths are of order several thousand kilometres and the periods of the waves are several hours. The radar network is well placed to make such observations in particular with the motion of the skip distance. In one case study the source is believed to be Joule heating in the magnetospheric cusp region associated with enhanced convection[78]. An example of a LSTID was also reported in conjunction with Total Electron Content (TEC) measurements by GPS receivers, demonstrating the relationship between downward ionospheric motion and increasing TEC[76].

4.6 Meteor winds

As meteors move through the Earth's upper atmosphere they create ionisation trails and such trails are ideal targets for radar scatter. Dedicated meteor radars have been developed but SuperDARN is also capable of receiving scatter from such targets[80]. Subsequent observations have used the data from these targets to study long period planetary waves, such as the semi-diurnal tide[80], quasi two day waves[81-82] and 10 h and 16 h waves caused by the interaction of the two day waves and the semi-diurnal tide[81]. These were then followed by measurements of winds in the mesosphere[83-85].

4.7 Polar Mesosphere Summer Echoes

Another form of near range scatter observed in SuperDARN data is the unusual echoes between 180 and 315 km range from the radar which occur during quiet magnetic conditions and typically in the altitude range 80 km to 100 km[86]. First reported for the Antarctic summer periods, the scatter differed from meteor scatter in that it was characterised by being present for longer periods, up to 80 min in some cases, and had quasi-periodic variations in scatter power. The initial proposal was that these were related to Polar Mesosphere Summer Echoes (PMSE) which had at that time rarely been observed at HF frequencies, although reports at higher frequencies were numerous[87]. Subsequent observations demonstrated that similar echoes in the northern hemisphere in Scandinavia were from between 80 and 100 km and were consistent with simultaneous MST radar observations[88].

5 The future directions for SuperDARN

The last twenty years have been considerably successful in terms of the scientific exploitation of SuperDARN. Recent developments indicate that the future will also be very successful in bringing new results on a range of different scientific problems. Exact predictions of what areas of science will be impacted most often can be difficult. Consequently we shall just indicate areas where we expect the network to make significant progress in the next 5 years.

Two aspects of the development of the network over the last few years that will dictate to some extent the new science are (i) the development of the network into new areas and (ii) new technical developments of the radars. The extension of the network to both mid and polar latitudes over the last 5 years has opened up new regions which we can investigate. The mid-latitude radars in both the American sector and the Siberian sector will be very important. These radars will enable large scale observations of the impact of storm events and extend the studies already started with 6 mid-latitude radars to be extended to almost all local time sectors. This in turn will enable universal time effects at mid latitudes during storm time conditions to be determined. For example, do sub auroral polarization streams occur in a preferred universal time sector or at all universal times? If there is a preferred sector, then why is this?

At auroral latitudes there has been a gap in the coverage east of Finland. This gap will start to be covered with the extension of mid latitude radars into the Siberian sector and the deployment of a radar on Svalbard in 2014. We will, therefore, be able to determine the ionospheric convection at all local times over much larger ranges of latitudes. These extensions are important not only for studies of ionospheric convection but also MHD waves, TIDs, magnetospheric substorms.

PolarDARN radars have already demonstrated that they receive significant scatter, indeed at times these radars often contributed a large percentage of the data to the overall global analysis. This was particularly the case during the recent extended solar minimum. However, the performance of the radars has also been strong during the recent solar maximum. The presence of this scatter in the polar regions is important as it can be difficult to instrument the very high latitude regions. The coverage of the existing PolarDARN radars in both hemispheres will be extended in the southern hemisphere in 2013 with new radars at South Pole and Dome-C and in 2014 with a radar on Svalbard, thereby further enhancing the network.

New developments in the radar systems will enable improved performance of the systems. Critical here is to ensure that we get the best temporal resolution possible. We have started to develop this but not routinely and the challenge for the SuperDARN community is not only to maintain the existing radars but to upgrade them to ensure that all radars have the same capability. This is not a challenge which will be easy to overcome. The increase in data processing power together with new data mining techniques also have the potential to enable new science to be undertaken. For example, they will enable the capacity to draw together different and complementary data sets to give detailed physical quantities, e.g. Joule heating from electric field and conductance measurements. Data assimilation into models is another area where the SuperDARN data will be critical.

Finally we are now starting to look at ways in which we can respond to events rather than simply operate a planned schedule. We have started this in conjunction with the van Allen probes but such developments could be used for a range of different types of event. For example, northward IMF conditions might require different modes from the ones that we would employ during storm conditions.

Acknowledgements ML would like to thank all the scientists, students and engineers over the last 25 years who have contributed to SuperDARN in many and diverse ways. ML would also like to thank Suzie Imber for help with Figure 1. ML acknowledges the use of SuperDARN data. SuperDARN is a collection of radars funded by national scientific funding agencies of Australia, Canada, China, Finland, France, Italy, Japan, the Russian Federation, South Africa, United Kingdom and United States of America.

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