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SuperDARN Radars – Introduction

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1. INTRODUCTION

SuperDARN radars are coherent scatter radars which use the Bragg scattering phenomenon on structures characterised by a certain spatial periodicity whose distances are comparable to the sounding wavelength. For a certain range of the probe's wavelength, in the case of objects with a periodic structure and constant distances between the elements of the structure, a coherent echo superposition occurs, which results in the amplification or weakening of the signal by interference. In this way, an echo signal gain towards the radar receiver can be obtained. We have such a case to deal with a specific ratio of the probe's wavelength to the distance between the elements of the structure of the observed object:

$$d = \frac{\lambda_t}{2 \cdot cos\theta} \tag{1}$$

where:

d – distance between elements of the structure,

λ_t – length of incident wave,

θ – incident angle (here, the angle between the parallel to the element of the structure and the direction of the incident radiation).

In the case of used frequencies from 8 to 22 MHz, it gives a size from several to over a dozen meters.

A characteristic feature of ionospheric irregularities is their orientation along the lines of the magnetic field. For this reason, the incoming wave emitted by the radar should be orthogonal to the geomagnetic field in order for the scattered signal be able to return to the antenna. This poses certain requirements for the regions of the ionosphere that can be observed by coherent scatter radars. For example, at high latitudes, where the field lines are almost vertical, it is impossible to meet the orthogonality condition above layer E (90–130 km). At VHF frequencies and higher, the signal propagates towards space. Using the frequencies from the HF band, ionospheric refraction allows to achieve the orthogonality criterion for layers E and F. In the case of ionosphere irregularities in this region, the radar signal will be scattered in the direction of transmission. The construction and operation of SuperDARN radars has been thoroughly presented in the works of Greenwald (2012) and Lester (2013).

2. A BRIEF HISTORY OF DARN RADARS

The first cases of using coherent scatter radar to observe ionospheric convection took place at the end of the 1970s using the STARE (Scandinavian Twin Auroral Radar Experiment) installation in northern Scandinavia (Greenwald *et al*. 1995). It consists of two bistatic pulse radars with phase control, located in Malvik (Norway) and Hankasalmi (Finland). Their common field of vision covers an area of around 400 × 400 km. The radar measures the intensity and speed of the Doppler ionospheric irregularities in layer *E*. The device offers a spatial resolution of 20 × 20 km and a time resolution of 20 seconds. At the time of its creation it was the only radar allowing two-dimensional observation of convection paths of the ionospheric plasma.

The effects of the research conducted using the STARE radars were an impulse to build further analogous installations operating in the VHF band. They were SABER, located in Wick (Scotland) and Uppsala (Sweden) and BARS located in Red Lake and Nipawin (Canada). These radars were part of the planned Dual Auroral Radar Network (DARN) which was the answer to NASA's project Origins of Plasmas in the Earth's Neighborhood (OPEN). The field of view of each radar covered the sector 4° magnetic width and 1 hour MLT.

The first radar using coherent scattering is the Goose Bay installation constructed by Johns Hopkins University Applied Physics Laboratory. The radar uses a phase-controlled antenna and operates on a frequency of 8÷20 MHz (HF band). Its field of view is 52° around the axis running along 5°E and the range from a few hundred to over 3000 km. Reflections in *F* layer are usually recorded in the range of 10–60% of this range. Radar operates continuously and provides measurement data since its launch in 1983.

The next HF radars were the French-Canadian SHERPA (located in Quebec) and the American-British radar in Antarctica, built as part of the Polar Anglo-American Conjugate Experiment (PACE) project. The experience gained during the tests using the above installations showed the benefits of observations made simultaneously on two radars. This configuration has been particularly helpful when tracking convective plasma motions. PACE radars were able to provide information about plasma flows in adjacent hemispheres and changes in the routes of these flows within minutes. SHERPA radar, observing in parallel with the radar from Goose Bay (to which it is similar in design), also showed the usefulness of observations from two directions. It was possible to monitor time changes with a 90 second time resolution.

In 1990 in Lindau (Germany) at the DARN Investigation Team meeting, a decision was made to expand the global network of HF radars to widen the coverage and measurement capabilities of the DARN system. The new network gained the name SuperDARN which was supposed to indicate a significant development of the DARN concept. Another important step in the development of the SuperDARN network was 2005, when the first mid-latitude radar was launched in Wallops (Oksavik *et al.* 2006). This radar has a field of view facing north between the two auroral radar fields of Goose Bay and Kapuskasing (both in Canada). The location of radars on mid-latitudes is particularly important in the case of observing magnetic storms (Lester 2013). During these phenomena there occur periods when the radar echo disappears due to absorption of the HF signal or insufficient ionization of the medium for wave propagation. Mid-latitude radars do not have that inconvenience, hence they are often referred to as StormDARN.

The next installation was Japanese radar on Hokkaido (2007) and American radar in Blackstone (2008). A big step in the development of a mid-latitude network of radars took place in 2010 with the start of the construction of a set of 8 radars as part of the MSI (Mid Size Infrastructure) initiative. The first pair of radars was installed in Fort Hays (Kansas USA). The next ones were located in Christmas Valley (Oregon USA), Aleutes and Azores. In 2012, the first of four Siberian radars in Yekaterinburg was launched. This is an important supplement to the SuperDARN network in a geographic area long ignored in research.

3. SCIENTIFIC GOALS

The example areas of research on which coherent scatter radars are applicable are presented below:

Analysis of ionospheric convection

The main goal that guided the SuperDARN radar concept were large-scale (almost global) measurements of ionospheric convection caused by the interaction of the solar wind with the magnetosphere. In particular, it is a magnetic reconnection between the field of the magnetic sheath and the geomagnetic field on the dayside and between the open field lines belonging to two lobes of the Earth's magnetic tail. SuperDARN radars have contributed to learning about the mechanisms governing the phenomenon of Poleward Moving Radar Auroral Form (PMRAF) (Milan *et al*. 2000, Neudegg *et al*. 1999, Wild *et al.* 2001, Wild *et al*. 2003) – increasing the intensity of ionospheric plasma flows induced by the particle stream from the magnetosphere. Radar observations have allowed also to create global maps of ionospheric convection and to study the reaction of the ionosphere to changes in the interplanetary magnetic field (IMF) (Taylor *et al.* 1998, Cousins and Shepherd 2010). SuperDARN radars, as the only tool, allow for continuous measurements to estimate the field of electric reconnection as a function of time for many timezones with a resolution of several minutes (Chisham *et al.* 2008). Another of the discoveries made using radar are large-scale plasma motions on the nightside in relatively calm geomagnetic conditions, probably caused by the twisting of magnetic field lines in the Earth's magnetic tail by the action of IMF (Grocott *et al.* 2005, Walker *et al.* 2002). SuperDARN observations also concern convection in the ionosphere caused by processes associated with magnetospheric substorms (Bristow and Jensen 2007, Grocott *et al.* 2006, Yeoman *et al.* 2000). In particular, among the observed on mid-latitudes SuperDARN radar forms of ionospheric irregularities, we can distinguish plasma motions called SAPS (Sub-Auroral Polarization Streams), caused by strong electric fields occurring during magnetic storms (Clausen *et al.* 2012, Oksavik *et al.* 2006).

Monitoring of the magnetosphere and ionosphere structure

The ionospheric convection tests mentioned in the previous chapter are based on measurements of Doppler velocities performed with radar. In addition, it is also possible to measure the power of the received echo and the width of its spectrum. This is useful in determining the position of polar cusp based on observations of widening the spectrum of the scattered signal (Baker *et al.* 1995) and determining the boundary between the region where the magnetic field lines are closed (narrow spectrum) and those in which they are open (widened spectrum). The border region is called in the literature (Lester 2013) Spectral Width Boundary (SWB). Its knowledge is important in determining the speed of reconnection, which is required in the measurements described in the previous point.

The measurement of the signal power reaching the receiver, in many cases, can be an indicator of the distribution of electron density in the ionosphere (Oksavik *et al.* 2010). This applies, while measuring convection, to forecasting ionospheric plasma movements (polar patches) in the polar region (Milan *et al.* 2002, Oksavik *et al.* 2010).

ULF waves

SuperDARN radars are also a useful tool in studies on magnetohydrodynamic (MHD) ultra-low frequency waves, with periods on the order of 45÷600 s. They constitute a significant means of energy transfer within the magnetosphere. They are caused by external phenomena, such as, for example, solar wind flows through a magnetopause that evokes Kelvin-Helmholtz waves. These waves have a relatively large size. Waves of smaller sizes in the azimuth are generated by internal mechanisms, like drift of large sets of high-energy particles in the magnetosphere. The tests were carried out, during which high-power transmitters had generated regions of increased ionization from which the radar signal was then scattered. During the experiments, small-sized waves were observed (Yeoman *et al.* 1997). These studies have contributed to a better understanding of the mechanisms of the wave-particle interaction responsible for the induction of these vibrations (Yeoman *et al.* 2012). In this group of tests, a certain modification is the Stereo technique (Lester *et al.* 2004) allowing simultaneous operation of radars in two different modes, one of which can offer high time resolution. Observations of SuperDARN radars usually involve modulated electric fields in the ionosphere that are related to waves (Ruohoniemi *et al.* 1991). However, sometimes the impact of waves is manifested in change at the point of dispersion, which can be seen in echoes from the ground (Ponomarenko *et al.* 2003).

4. SIMULATION RESULTS

One of the key issues when choosing a location for a new SuperDARN station is to determine its potential for observation. It depends on the local configuration of the geomagnetic field, the current ionosphere structure and the operating frequency of the transmitter. One can use the ray tracing software by Jones and Stephenson (1975) to track the propagation path of the pulse emitted by the radar and determining points in which the wave vector is perpendicular to the local magnetic field of the Earth. Such a condition will allow for the scattering of the radar signal emitted by the antenna back in the direction of transmission. Simulations do not include such parameters of the probe signal as the shape of the pulse and its time parameters.

Figure 1 shows examples of calculation results for the conditions of echo formation for a signal sent from hypothetical radar located in the area of Wierzbowa (51°23’N 15°45’E). The location was initially considered in the plans of Polish scientists for the SuperDARN infrastructure in Poland (*e.g.* Popielawska *et al*. 2011, Góral *et al*. 2013). The horizontal axis represents the distance from the transmitter and the vertical axis the distance from the surface of the Earth. The results shown correspond to the beam at an angle of 66° to the geographic north and elevation angles in the range from 5° to 60° with a step of 5°. The transmitter’s operating frequency was set to 9 MHz. The observation point was 16/03/2015, 22:00 UT. Marked points are regions where the wave vector is orthogonal to the local geomagnetic field vector, which would allow observation of ionospheric irregularities in these places. Figure 2 shows the effect of increasing the operating frequency up to 16 MHz. As you can see, this results in a given tendency to penetrate the ionosphere by the emitted wave and “escape” without meeting the criterion of orthogonality. Figure 3 illustrates the horizontal distribution of potential sources of strong ionospheric echo (marked with crosses places in which the wave vector is orthogonal to the local geomagnetic field vector) for the orientation of the radar axis in the direction of 30°. The sounding beam’s azimuth angle changed from -3° to 66° with a step of 3°. The rest of parameters remained as in the case of Figure 1. Figure 4 shows the horizontal echo distribution for the orientation of the radar axis in the -40° direction and changing the operating frequency to 9 MHz. In this case sounding beam’s azimuth angle changed from -73° to -4° with a step of 3°. In the calculations the IRI (Bilitza 2014) ionosphere model in the 2012 version and the IGRF (Thebault *et al*. 2015) geomagnetic field model were used.

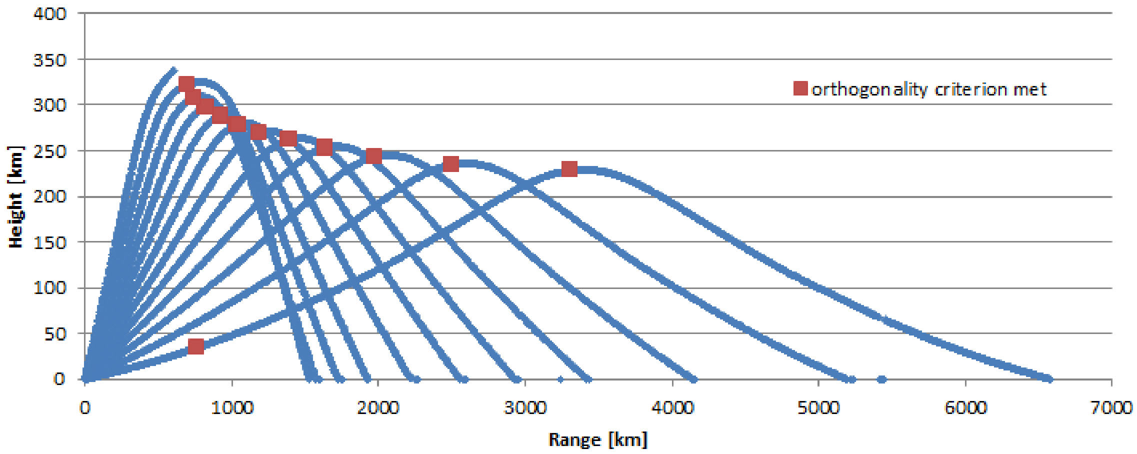

Fig. 1. Ray paths for the HF radar simulation described in the article. Operating frequency 9 MHz, radar axis 30° (*own calculations*).

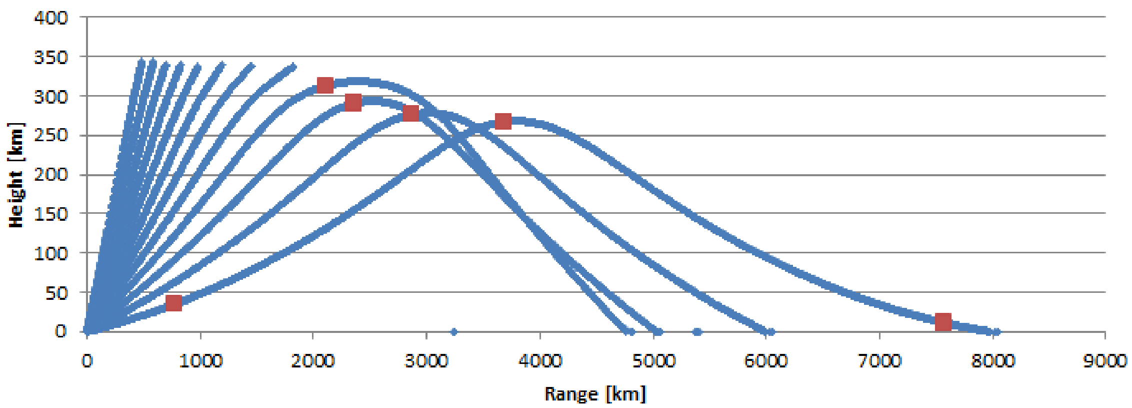

Fig. 2. Ray paths for the HF radar simulation described in the article. Operating frequency 16 MHz, radar axis 30° (*own calculations*).

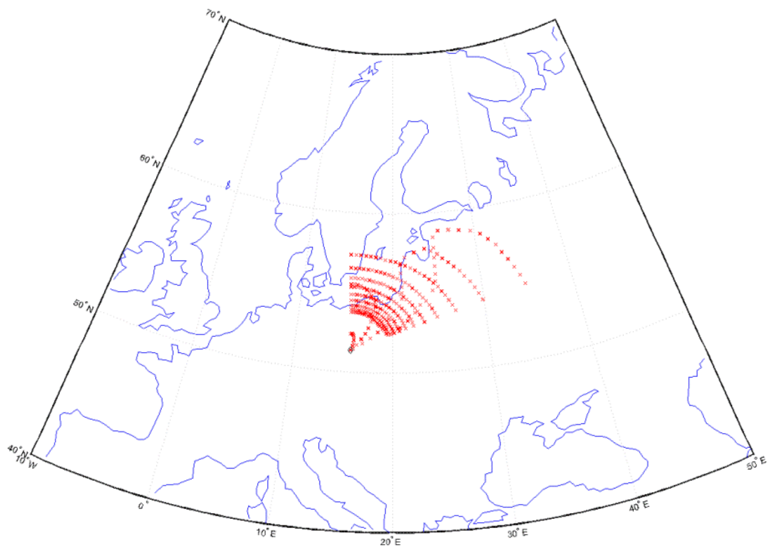

Fig. 3. Horizontal distribution of potential places of formation of a strong radar echo from ionospheric irregularities. Operating frequency 9 MHz, radar axis 30°. Red points are regions where the wave vector is orthogonal to the local geomagnetic field vector, which would allow observation of ionospheric irregularities in these places. (*own calculations*).

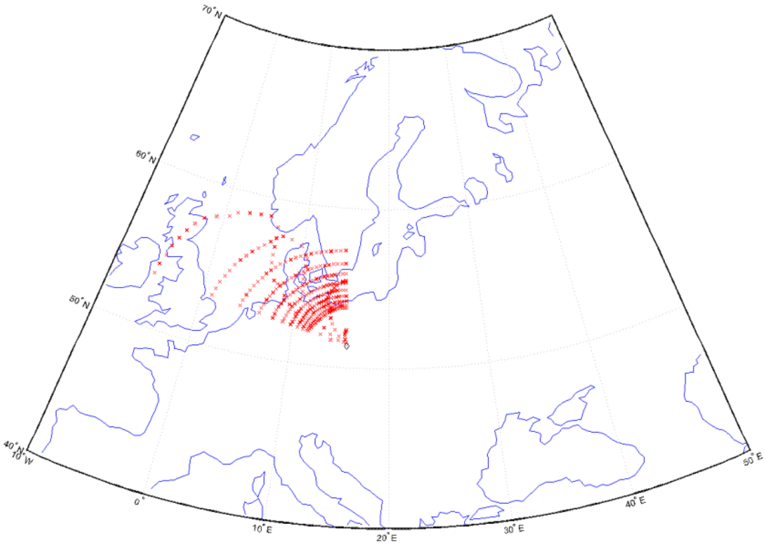

Fig. 4. Horizontal distribution of potential places of formation of a strong radar echo from ionospheric irregularities. Operating frequency 9 MHz, radar axis -40°. Red points are regions where the wave vector is orthogonal to the local geomagnetic field vector, which would allow observation of ionospheric irregularities in these places. (*own calculations*).

5. CONCLUSION

A condition for the existence of ionospheric echoes is, next to the fulfillment of the orthogonality criterion, the occurrence of ionospheric irregularities in the *F* layer. Otherwise, the radar signal will not be scattered. Observations of these phenomena on mid-latitudes have been confirmed in a number of works (Clausen *et al*. 2012, Hosokawa and Nishitani 2010, de Larquier *et al.* 2011, Ribeiro *et al*. 2012). The simulations show that by choosing the appropriate frequency it is possible to obtain favorable conditions for observing irregularities occurring in the ionospheric *F* layer (in geomagnetically quiet conditions) at a distance of 500 to 3500 km from the transmitter.

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RADARY SUPERDARN – WPROWADZENIE

S t r e s z c z e n i e

Radary SuperDARN powstały jako narzędzie do badań górnych warstw atmosfery i ich związków z magnetosferą i wiatrem słonecznym (np. Greenwald i in. 1995, Chisham i in. 2008, Lester 2008, 2013). Pracują w zakresie częstotliwości HF (High Frequency), pomiędzy 8 a 20 MHz. Ich zasada działania opiera się na wykorzystaniu rozpraszania Bragga na periodycznych strukturach przestrzennych o skalach odległości porównywalnych z długością fali sondującej. Radary te umożliwiają obserwacje formacji jonosferycznych zorientowanych wzdłuż linii pola geomagnetycznego.

W pracy przedstawiono powstanie i rozwój sieci SuperDARN z uwzględnieniem działających obecnie na świecie radarów na średnich szerokościach, które są szczególnie interesujące w kontekście potencjalnej lokalizacji w Polsce.

Jedną z kluczowych kwestii przy wyborze lokalizacji dla nowopowstającej stacji SuperDARN jest określenie jej potencjalnych możliwości obserwacyjnych. Można wykorzystać do tego oprogramowanie dokonujące śledzenia dróg propagacji impulsu emitowanego przez radar i określania punktów w których wektor fali jest prostopadły do lokalnego pola magnetycznego Ziemi. Warunek taki pozwoli na uzyskanie rozproszenia wyemitowanej przez antenę radaru fali z powrotem, w kierunku nadawania.

W artykule przedstawiono wyniki symulacji dla hipotetycznej stacji SuperDARN, zlokalizowanej w południowo-zachodniej Polsce. W obliczeniach użyto programu do ray tracingu, bazującego na algorytmie Jones i Stephenson (1975), modelu jonosfery IRI-2012 (Bilitza 2014) oraz modelu pola geomagnetycznego IGRF (Thebault *et al*. 2015).