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Model calculations of possible ionospheric backscatter echo area for a mid-latitude HF radar

Nozomu Nishitani[1]* and Tadahiko Ogawa[1]

[1]*Solar-Terrestrial Environment Laboratory, Nagoya University, Toyokawa 442-8507*
**Corresponding author. E-mail: nisitani@stelab.nagoya-u.ac.jp*

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Abstract: HF ray path calculation is performed in order to identify possible ionospheric backscatter echo area for an HF radar at mid-latitude. The calculation is made on the basis of the R.M. Jones and J.J. Stephenson (U.S. Dept. of Commerce, OT Rep. 75–76, 1975) HF ray path tracing algorithm plus the IRI-2001 ionosphere model. It is shown that depending on the local time and geomagnetic activity, the possible ionospheric backscatter regions have different distributions. In any case the backscatter region is large enough, indicating the capability of a planned HF radar in Hokkaido (43.5°N, 143.6°E), Japan.

key words: ionospheric echoes, SuperDARN, mid-latitude, ray-path tracing

1. Introduction

Super Dual Auroral Radar Network (SuperDARN) (Greenwald *et al*., 1995) is a powerful tool for monitoring the ionospheric plasma dynamics over a global extent. Figure 1 shows the coverage of the present SuperDARN network as of January 1, 2005. Each radar has spatial resolution of 15 to 45 km in radial direction and up to about 100 km in azimuthal direction, temporal resolution of 1 s to 2 min per one beam, operating frequency of 8 to 20 MHz, peak output power of 10 kW and 16 beam directions. There are total of 16 radars operating in the polar ionosphere (9 in the northern and 7 in the southern hemisphere), under the international cooperation of 11 countries.

Although all of the present radars are located at geomagnetic latitudes higher than 54°, there are plans to expand this network to lower latitudes, in United States, Europe, Japan, and so on. One of these proposals is a mid-latitude HF radar in Hokkaido, Japan (43.5°N, 143.6°E in geographic coordinates), which is designed to monitor the upper atmosphere with the geomagnetic latitude between 38° to 63°. The field of view of the radar is shown in Fig. 2. With this radar we expect to deal with a wide variety of scientific topics, ranging from the magnetosphere, ionosphere, thermosphere to upper mesosphere.

There are several points which should be considered when deploying mid-latitude HF radars to observe ionospheric backscatter echoes. The most important point is that the ambient geomagnetic field lines at mid-latitudes are not vertical to the ground, but rather inclined to the horizontal direction. This may greatly affect the receiving con-

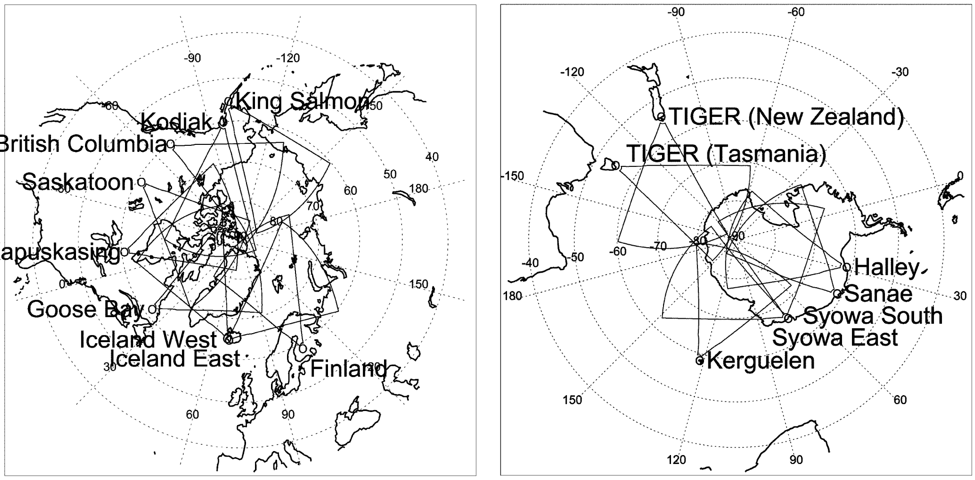

Fig. 1. Fields of view of the existing SuperDARN radars in both hemispheres. The plots are given in Altitude Adjusted Corrected Geomagnetic (AACGM) coordinates, which is an updated version of the PACE geomagnetic coordinate system (Baker and Wing, 1989).

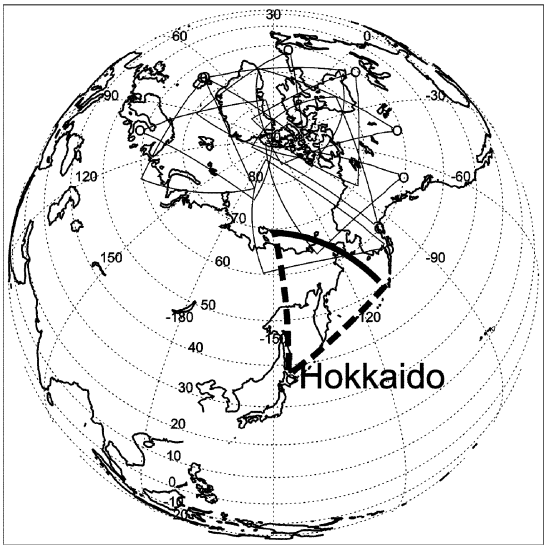

Fig. 2. Field of view of the planned Hokkaido HF radar.

ditions of ionospheric backscatter echoes, because the radar wave propagation vector should be normal to the geomagnetic field vector in order to detect echoes from ionospheric field-aligned irregularities (Greenwald *et al.*, 1995). For the HF radar the situation is complicated because the radar waves are highly deflected when they pass through the ionosphere, and the amount of deflection depends on the ionospheric plasma densities, which is highly variable as a function of several parameters. In order to estimate the echo receiving conditions for the mid-latitude HF radar accurately, it is necessary to execute HF ray path tracing by using reliable ionospheric models.

Ogawa *et al.* (1990) calculated the possible ionospheric backscatter regions for the Syowa South HF radar, by using the Chapman model ionosphere, but things might be completely different for mid-latitude radars. In this paper, we show examples of the calculation of the HF ray path tracing under a model ionosphere (IRI-2001) and estimate ionospheric backscatter for the planned Hokkaido HF radar.

2. Model description

The HF ray path tracing program used in this study was originally developed by Jones and Stephenson (1975). With this program we can calculate the ray paths of HF radio waves under a simple model ionosphere such as Chapman layer with a limited number of ionospheric parameters. In the present study we introduced International Reference Ionosphere-2001 (IRI-2001) model ionosphere (Bilitza, 2001) to this HF ray tracing program. With the IRI model we can use various parameters as input, so that we can estimate the echo reception under variable conditions such as geomagnetic/solar activities, season and local time, and can perform more realistic calculation. For the geomagnetic field modeling, the International Geomagnetic Reference Field (IGRF) model is used.

3. Result of calculation

Figure 3 shows examples of the model calculation result of the echo receiving situation for the Hokkaido HF radar. The horizontal axis is the ground distance from the radar site, and the vertical axis is the ground height (both axes have the same scale). The calculation was made for the central beam of the planned Hokkaido radar, at a horizontal angle of 30° clockwise from the geographic north and the elevation angles of 10° to 40°, every 5 degrees. The vertical antenna pattern of standard SuperDARN radars depend on radar HF frequency, but at 10 MHz the maximum sensitivity occurs between 20° and 30° elevation angle, and the sensitivity is −5 to 0 dB for 10° to 40° (Y. Kato, unpublished data). In order to observe ionospheric backscatter echoes, it is required that the radar wave vector is normal to the ambient magnetic field vector; the × labels indicate the points where the angles between these two vectors are within the range of 90°±1°. The calculation was made by using the IRI-2001 model ionosphere for quiet nighttime (2003/03/26, 00 JST, JST=UT+9 hours, Ap=4), disturbed night-time (2003/05/30, 00 JST), quiet daytime (2002/04/23, 0900 JST) and disturbed daytime (2002/04/18, 09 JST) conditions, and the IGRF geomagnetic field model. The Ap geomagnetic indices indicate 3-hour averaged mid-latitude geomagnetic activity level with a linear scale. The calculation was made for various radar HF wave frequencies (9, 11 and 13 MHz).

It can be seen that the distribution of × points highly depends on local time, geomagnetic activity and radar HF frequency. In the nighttime, the 9 MHz case seems to be most suitable for observing ionospheric backscatter echoes over wide range, both

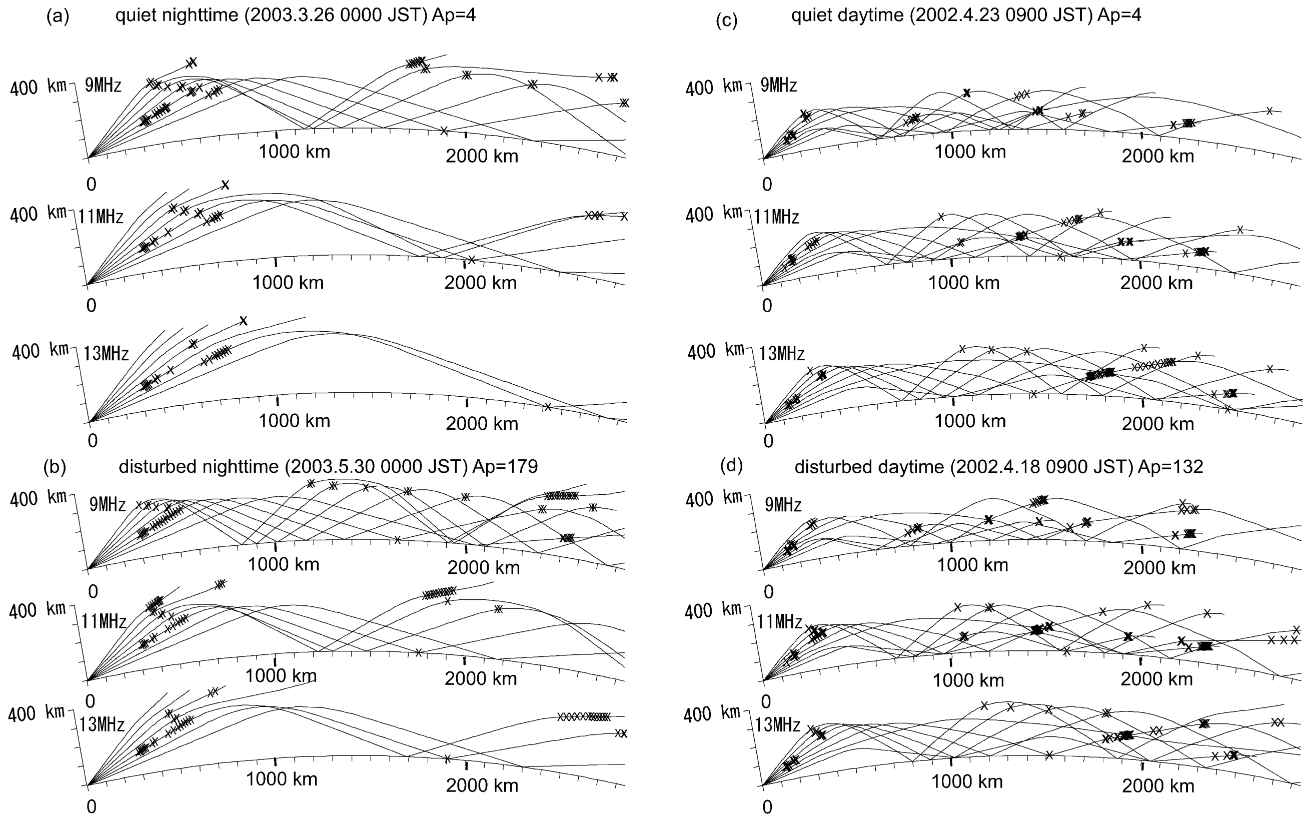

Fig. 3. *Vertical profile of HF ray paths (solid curves) in the model ionosphere. The horizontal axis is the distance from the radar antenna, and the vertical axis is the height. The radar wave is emitted at a horizontal angle of 30° clockwise from the geographic north. At × points, where the angle between radar HF ray vector and the ambient magnetic field vector is within the range of 90°±1°, HF waves are expected to be backscattered by ionospheric field-aligned irregularities (if they exist). Four sets of 3 panels show the results for (a) quiet nighttime (2003/03/26, 00 JST), (b) disturbed nighttime (2003/05/30, 00 JST), (c) quiet daytime (2002/04/23, 09 JST) and (d) disturbed daytime (2002/04/18, 09 JST) conditions respectively, with 3 different frequencies.*

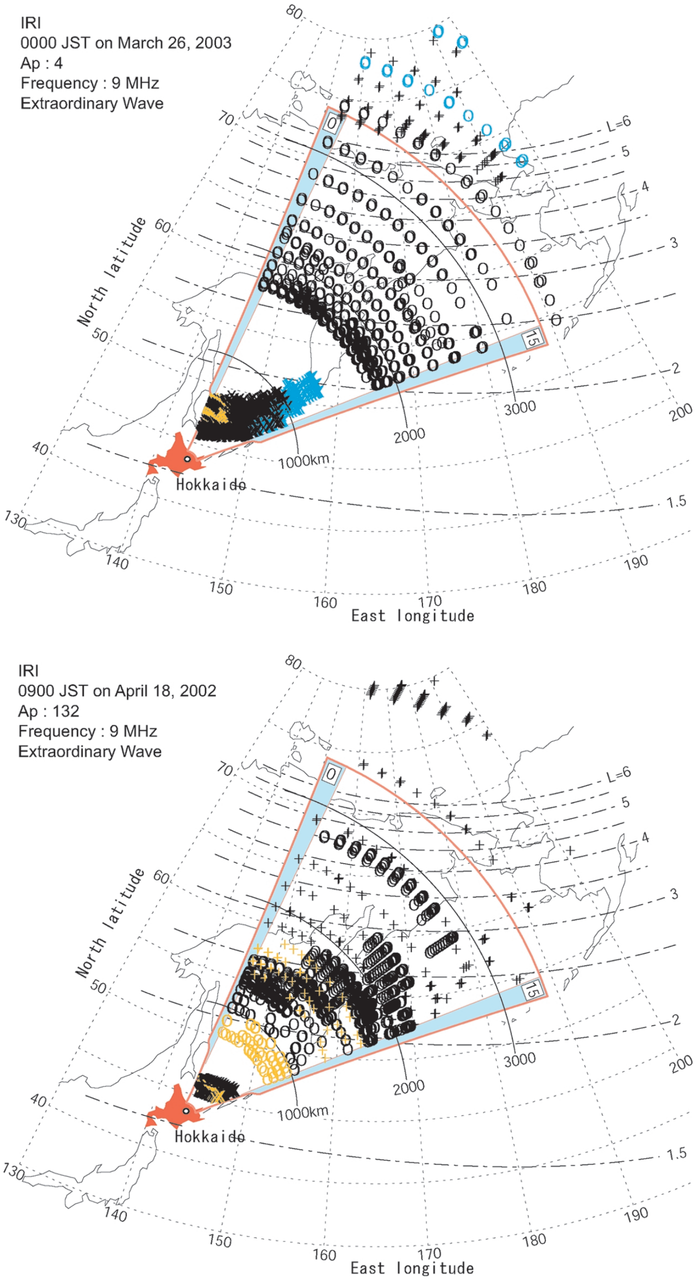

Fig. 4. Horizontal profile of possible HF ionospheric backscatter receiving points where the angle between radar HF ray vector and the ambient magnetic field vector is within the range of 90°±1°. The upper and lower panels show the results for nighttime (2003/03/26, 00 JST) and daytime (2002/04/18, 09 JST) conditions. The points labeled '×', '○' and '+' are for 0.5-hop, 1.5-hop and 2.5-hop propagation modes, respectively. The black points are for initial elevation angles 10° to 40°, blue are for elevation angles 5° to 10°, and yellow are for elevation angles 40° to 50°. The calculation is made for every 2.5° elevation angle.

for quiet and disturbed periods. For the higher radar frequencies (11 MHz and 13 MHz) most of the ray-paths tend to penetrate the ionosphere and go to infinity without satisfying the perpendicularity criterion. In the daytime, the propagation conditions do not depend very much on radar HF frequency and geomagnetic activity, although the distribution of x points changes slightly.

Figure 4 shows the horizontal distribution of possible ionospheric backscatter echo regions for both nighttime and daytime conditions with the radar HF frequency of 9 MHz. The calculation was made for all 16 beams of the planned HF radar. The '×', '○' and '+' points show the ground projection of the points where the angle between radar HF ray vector and the ambient magnetic field vector is within the range of $90^\circ \pm 1^\circ$. Possible ionospheric backscatter points with 0.5, 1.5 and 2.5-hop propagation modes are labeled '×', '○' and '+' respectively. Black points are for initial elevation angles 10° to 40°, where the antenna sensitivity is -5 to 0 dB, and most of the transmitter power is radiated. Blue and yellow points are for initial elevation angles 5° to 10° and 40° to 50°, where the sensitivity is -10 to -5 dB, so we still have some opportunities to receive ionospheric backscatter echoes. It can be seen that the possible echo region within the 2000 km range is broader during daytime (lower panel) than the nighttime (upper panel). The big gap of the nighttime distribution in the western field of view in the 500–1700 km range is due to the gap between ionospheric points with 0.5 and 1.5-hop propagation modes, and to the lack of points where perpendicularity condition is satisfied. (Please recall that the geomagnetic field vector in the mid-latitude region is not vertical.) However, even the nighttime distribution covers more than 2/3 of the total field of view. This result clearly indicates the capability of the new mid-latitude HF radar.

4. Discussion and conclusions

We have demonstrated the possible ionospheric backscatter echo areas based on the calculation by using HF ray path tracing algorithm. In the present calculation we used the IRI-2001 model. It is based on the statistical observation, so that the model has several limitations. Most important point is that the model does not precisely describe the short-time variations of ionospheric plasma densities affected by auroral particle precipitation with relatively short-time changes such as substorms. However, such precipitation will not have significant effect on the field of view of the Hokkaido HF radar because this region is located usually at lower latitudes than the auroral precipitation region. Consequently, the actual ionospheric plasma density distribution in the field of view of the Hokkaido HF radar is expected not to differ much from the distribution in the IRI-2001 model ionosphere, except for extremely large geomagnetic storms.

There are other conditions which affect the ionospheric backscatter receiving conditions. The most important factor is the presence/absence of ionospheric field-aligned plasma irregularities of the spatial scale of $\lambda/2$, where λ is the wavelength of the radar HF wave. Without such irregularities, the radar HF waves are not backscattered even if the perpendicularity condition is satisfied in the ionosphere. Since plasma irregularities are often observed in the *F*-region ionosphere at sub-auroral and mid-latitude regions (Hosokawa *et al*., 2001; Fukao *et al*., 1988), we can expect to observe *F*-region echoes at mid-latitude regions. The occurrence of mid-latitude *F* region irregularities is one of the key scientific questions we hope to address with the new HF radar.

The actual ionospheric echoes are also affected by the HF ray absorption in the D-layer ionosphere at high latitudes, which are enhanced by particle precipitation during high geomagnetic activity such as substorms (Milan *et al*., 1996; Gauld *et al*., 2002). However, such effects are weaker for the mid-latitude radar than the existing high-latitude radars, because the HF ray paths cross the D-layer ionosphere at much lower latitudes than the auroral oval where the significant particle precipitation is expected. It is interesting to examine whether this hypothesis is true or not, by analyzing the actual data of the planned mid-latitude HF radar.

It should be noticed that the daytime D-layer ionosphere is produced by solar photoionization, which at mid-latitudes will lead to high absorption. This might have some impact on dayside observation of the HF radar, but the amount of absorption highly depends on the selection of HF radar frequency. It should be important to select proper radar HF frequency for observation.

In the present study we have estimated the possible ionospheric backscatter echo regions by using HF ray path tracing algorithm. This ray path tracing algorithm is applicable for various other purposes. Here are some examples: (1) estimation of the HF ray path refraction in the high-latitude D-region and E-region ionosphere during geomagnetically active periods and during solar proton events. (2) estimation of the change of HF ray paths due to the sporadic E layer in the ionosphere, which is often observed in Japan area during summer. Moreover, although we have discussed here only the ray paths of the radar HF waves, we can also the estimate the rate of attenuation, phase shift and Doppler shift of the HF waves.

The mid-latitude HF radar also aims at detecting two-dimensional images of thermospheric phenomena such as MSTIDs (Samson *et al*., 1990). When we employ SuperDARN radars for the measurement of TIDs, ground scatter echoes become important. Figure 3 shows that for the quiet nighttime ionosphere and 9 MHz frequency, 1.0-hop ground scatter echoes have ionospheric reflection points for 500 to 1500 km range continuously. For daytime and disturbed periods these ranges become shorter, but this highly depends on the selection of radar HF frequency. Again, the selection of proper radar HF frequency is important, as in the case of suppressing dayside D-layer absorption.

With mid-latitude HF radars we expect to deal with a wide variety of scientific topics, ranging from the magnetosphere, ionosphere, thermosphere to the upper mesosphere. Mid-latitude HF radars such as Hokkaido HF radar will provide many important parameters for studying particle transport/acceleration in the inner magnetosphere, response of ionospheric convection to changes in solar wind parameters, generation/propagation/decay of gravity waves in the upper atmosphere, and many other dynamic processes in the geospace environment.

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