Correction of the Ekaterinburg SuperDARN Data Mapping Using Ionospheric Vertical Sounding

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Abstract— We study a possibility of the Ekaterinburg SuperDARN (Ekb; 56.4°N, 58.5°E) data mapping improvement in both quiet and disturbed geomagnetic conditions. To take into account refraction, we apply the simulation of the HF wave propagation using the technique based on waveguide approach. International reference ionosphere model (IRI-2012) is used as a propagation media. In order to overcome IRI shortcomings at high-latitudes, we make an adaptation of IRI predictions using ionospheric vertical sounding data (critical frequency) recorded by a set of high- and mid-latitude ionosondes (Arti, Norilsk, Amderma, Salekhard, Dikson). We present the simulation results obtained using the original and corrected IRI and compare them with observational data.

1. INTRODUCTION

One of the effective tools to investigate the ionosphere dynamics are SuperDARN radars which operate in the high frequency (HF) band of 8–20 MHz. High temporal resolution and wide azimuthal field-of-view (FOV) allow SuperDARN radar to perform effective monitoring of the ionosphere in a large spatial region. However, the standard SuperDARN data mapping technique is based on a simple approach which does not take into account HF wave refraction in the Earth's atmosphere. This could lead to systematic errors of the mapping up to several hundred kilometers with regard to the true HF reflection/scattering region. Such accuracy is often insufficient for ionospheric dynamics investigation especially at high-latitudes (auroral and subauroral) where ionosphere is characterized by high degree of variability in both time and space.

The purpose of the current paper is to study a possibility for the Ekaterinburg (Ekb) SuperDARN HF radar (Ekb; 56.4°N, 58.5°E) data mapping improvement. The map of the radar location and its FOV are shown on Figure 1. The Ekb antenna system represents a phased array which forms a narrow radiation pattern (beam) in one of the 16th azimuthal directions. The radar FOV-width is about 50° with a boresite azimuth of 20° (clockwise from North). At present time the Ekb radar has no additional interferometer phased array antenna which is standard for SuperDARN radars and could provide the elevation angle measurements. This further reduces the accuracy of the Ekb data mapping. The only way to overcome the shortage is to provide HF wave propagation simulation. Such a simulation should include the ability of HF amplitude estimation and realistic ionosphere model.

We use a technique for HF wave propagation calculation based on waveguide approach [1]. The technique enables to effectively calculate HF ground backscatter (GB) amplitude taking into

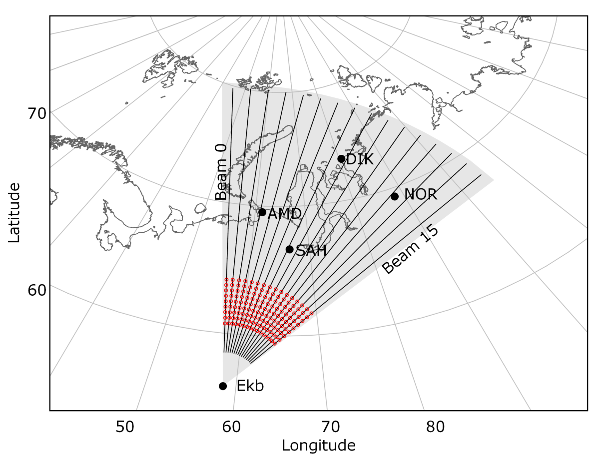

Figure 1: Ekb HF radar location and FOV. Vertical ionosonde locations are shown by black circles with labels.

account ionospheric absorption as well as antenna and scattering surface properties. We use a well-known global ionosphere model IRI-2012 [2] as a propagation media. In order to overcome IRI shortcomings at high-latitudes, we make a correction of IRI predictions using ionospheric vertical sounding data recorded by a set of high- and mid-latitude vertical ionosondes (see Figure 1): Arti (Ekb; 56.4°N, 58.5°E), Norilsk (69.4°N, 88.1°E), Amderma (AMD; 69.60°N, 60.20°E), Salekhard (SAH; 66.52°N, 66.67°E), and Dikson (DIK; 73.52°N, 80.68°E).

2. THE METHOD OF IRI-2012 CORRECTION

IRI-2012 model has a built-in mechanism for flexible correction by user input of main ionospheric parameters. For example, if we have measured critical frequencies at several points we can make an adaptation of electron density profiles calculated by IRI at these points. However, in case of HF propagation simulation we should provide an adaptation along the entire propagation path. This problem can be solved by two-dimensional interpolation with a known scattered set of points. Our method of IRI-2012 correction is based on the inverse distance weighting (Shepard's method).

We have a set of observed critical frequencies, $foF2(i)$, where i is a number of ionosonde with coordinates (θ_i, φ_i). Using IRI-2012, we calculate model critical frequencies for these ionosondes, $foF2(i)_{IRI}$, for certain date and time (UT). Then we calculate a correction factor for all the ionosondes, $r_i = foF2(i)/foF2(i)_{IRI}$. The value of correction coefficient in a arbitrary point is determined as weighted average between calculated values as,

$$r(\theta,\varphi) = \begin{cases} \dfrac{\sum_{i=1}^{N} w_i(\theta,\varphi) r_i}{\sum_{i=1}^{N} w_i(\theta,\varphi)}, & \text{if } d(\theta,\varphi,\theta_i,\varphi_i) \neq 0 \text{ for all } i \\ r_i, & \text{if } d(\theta,\varphi,\theta_i,\varphi_i) = 0 \text{ for some } i \end{cases} \tag{1}$$

The weight of each known correction factor is equal to the inverse of the squared distance between the two points, $w_i(\theta,\varphi) = 1/d(\theta,\varphi,\theta_i,\varphi_i)^2$. Further we calculate model critical frequency, $foF2_{IRI}$, for this arbitrary point and multiply it by the obtained correction factor (1). At final step we calculate electron density profile using IRI-2012 with corresponding user input.

3. TECHNIQUE FOR HF GROUND BACKSCATTER AMPLITUDE SIMULATION

Technique for HF GB simulation [1] is based on adiabatic approach of eigenfunction method [3]. In case of azimuthally symmetric Earth-ionosphere waveguide electromagnetic field induced by arbitrary emitter is expressed by a series of eigenfunctions as,

$$E(\vec{r},t) \sim \mathrm{Re}\left\{\sum_n I_n(\varphi) A_n(\vec{r}) g_0\left(t-\tau_n(\vec{r})\right) e^{i\Phi_n(\vec{r})-i\omega_0 t}\right\}. \tag{2}$$

where $\tau_n(\vec{r})$, $A_n(\vec{r})$ and $\Phi_n(\vec{r})$ are the time lag, amplitude and phase of eigenfunction with number n respectively, $g_0(t)$ is envelope of the transmitted signal, ω_0 is a cycle frequency. Excitation coefficient $I_n(\varphi)$ is related with the characteristics of emitter, or with scattering properties of rough ground surface. In the latter case the relation can be expressed as,

$$I_n(\varphi) \sim A(r_s)_i \sqrt{\frac{\sigma(\alpha_i,\alpha_s) S \cos\alpha_i}{4\pi}}. \tag{3}$$

where $\sigma(\alpha_i,\alpha_s)$ is a scattering coefficient, $A(r_s)_i$ is an incidence HF field amplitude on the surface, α_i and α_s are the incidence and scattering angles accordingly, S is an area of scattering region at certain time moment. We used an analytical expression for scattering coefficient derived by small perturbation method [4]

$$\sigma(\alpha_i,\alpha_s) \sim k^4 \cos^2\alpha_i \cos^2\alpha_s W(-k(\sin\alpha_i + \sin\alpha_s)). \tag{4}$$

where k is a wave number and $W(x)$ is one dimensional spectral density of roughness height distribution.

4. CALCULATION RESULTS AND DISCUSSION

Figure 2(a) shows standard SuperDARN range time intensity (RTI) plot, obtained by the Ekb radar on beam #4 (azimuth 8.7°) during February 8, 2014. The day is characterized by moderate geomagnetic activity ($Ap = 23$). Minimum slant range calculated using the original and corrected IRI-2012 is shown by black and red crosses respectively. Correction is performed taking into account $foF2$ recorded by three ionosondes (AMD, DIK, and SAH). There are time intervals where correction cannot be provided due to the absence of $foF2$ measurements (for example, there was F2-layer screening by distinct Es in the interval from 9 to 10 UT). However, it's clearly seen from the Figure 2(a) that correction sufficiently improves the correspondence between observed and simulated slant ranges.

Figures 2(b) and 2(c) present the HF GB amplitude calculated using the original and corrected IRI-2012 respectively. (The jumps on Figure 2(b) are explained by inability of correction). As we can see the correction of critical frequencies affects also the amplitude, the length and duration of GB echo. Even when there is a calculated minimum slant range value the echo amplitude can be low. In general the correspondence between simulated and observed RTI plots is good. So that the coordinates of the ionospheric reflection points obtained in the simulation can be used for further radar data mapping.

Figure 3(a) presents RTI plot obtained by the Ekb radar on beam #12 (azimuth 34.6°) during December 30, 2013. The day is characterized as geomagnetic quiet ($Ap = 2$). The red crosses show the minimum slant range calculated using corrected IRI. As we can see in spite of correction the agreement between simulated and observed slant ranges is very pour. Model significantly overestimates the slant range. Overestimation of the GB minimum slant range is often caused by the underestimation of critical frequency. The possible reason of the disagreement is that the radar recorded the GB echoes which came not in the front, but mainly from behind the radar where the critical frequency might be sufficiently higher. To check this suggestion we calculated GB amplitude for direct- and rear-FOV beams (azimuth 34.6° and 185.4°) using the corrected IRI.

The results are presented on Figures 3(b) (direct) and 3(c) (rear). As we can see on Figure 3(b) the amplitude of the GB echo coming in the front of the radar is somewhat 15–20 dB. However, the amplitude for GB echo coming from behind the radar is about 40 dB or even more. Thus the "front" echo is weaker than "back" echo by ∼20–25 dB. We used the same antenna gain characteristics in both simulations (the boresite azimuth only was changed) therefore the effect is related only to ionospheric conditions. As indicated in [5] for the SuperDARN antenna system the back lobe ∼20 dB down on the main lobe. Thus the simulated "back" echo is comparable with "front" echoes

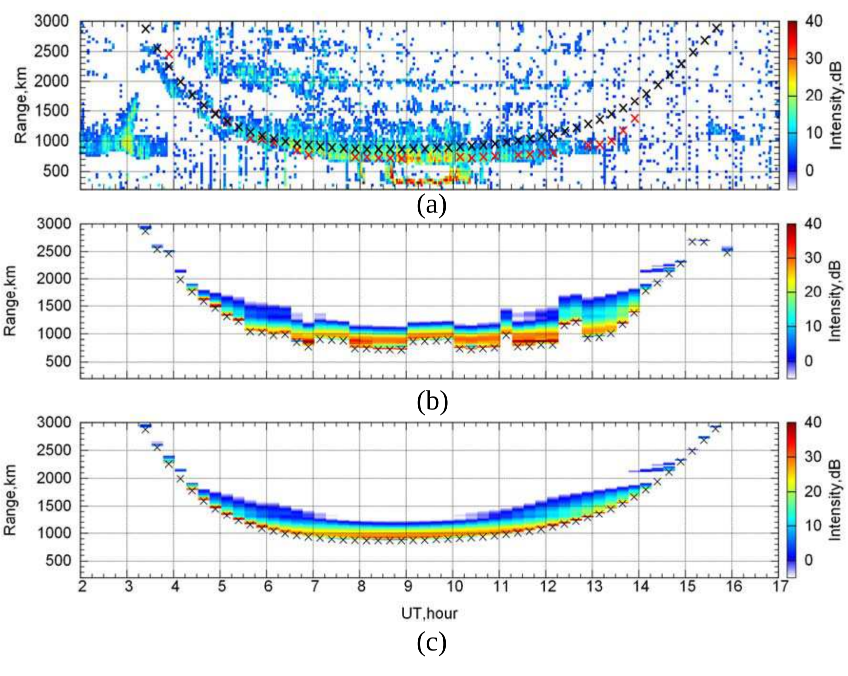

Figure 2: (a) Ekb HF radar RTI plot for beam #4 (azimuth 8.7°) for February 8, 2014. Simulated GB amplitude using (b) adjusted and (c) original IRI-2012. Crosses denote minimum slant range for adjusted and original IRI-2012 (red and black respectively).

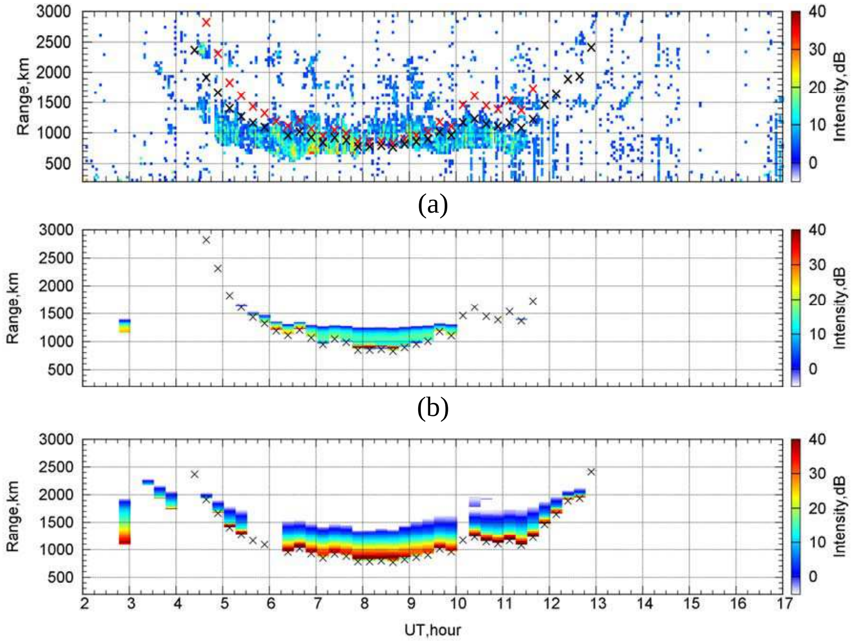

Figure 3: (a) Ekb HF radar RTI plot for beam #12 (azimuth 34.6°) for December 30, 2013. Simulated GB amplitude using adjusted IRI-2012 for (b) front and (c) rear FOV. Crosses denote minimum slant range for front and rear FOV (red and black respectively).

or even stronger on amplitude. Finally it is more likely that for the case under consideration the Ekb radar recorded the GB echo which came from behind the radar during the whole day.

Black crosses on Figure 3(a) represent the "back" minimum slant range. Their correspondence with observed minimum slant range is better than for red crosses, but not ideal. It seems that additional vertical sounding data is needed for achievement of better correspondence for case of "back" beams.

5. CONCLUSIONS

Described IRI-2012 correction technique using vertical sounding data both with HF amplitude calculation technique based on waveguide approach could provide a realistic simulation of GB echoes registered by the Ekb HF radar. The correction technique is very simple and flexible as it allows us to include unlimited number of observational data. Presented simulation results show a good agreement with observations. This can be useful for improvement of the Ekb data mapping under different geophysical conditions.

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