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Simulation of Near-distance Propagation of Artificial ULF Source in Anisotropic High Ionosphere

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Abstract

The numerical simulation of the near-distance propagation of the generated ultra-low frequency (ULF) virtual antenna by modulated heating of the high ionosphere is crucial for understanding and interpretating observations from various platforms including ships, aircraft and satellites. In this study, we establish a source that radiating ULF waves from the upper hybrid altitude to the ordinary (O-mode) wave reflection altitude, which can be considered as an antimagnetic circular antenna array. By employing the full-wave method, we obtain the spatial radiation distribution of ULF electromagnetic waves. Analyzing the ground radiation at high latitude EISCAT and low latitude Qingdao, it reveals symmetric concentric circles for horizontal magnetic fields received on the ground at high latitudes and asymmetric concentric circles at middle latitudes around the heater. Additionally, there exists an amplitude minimum around the heater at high latitude, which agrees with experimental results.

1. Introduction

Compared with other radio communication frequencies, ultra-low frequency (3-30 Hz, ULF) waves have low propagation attenuation and are widely used for long-distance communication. Currently, a novel method has been proposed to generate ULF source in the ionosphere using the ground-based high-power high-frequency transmitters. This method essentially modulates the anisotropic ionospheric plasma to stimulate a ULF oscillating current as a "virtual antenna" [1-3]. The resulting ULF waves can propagate simultaneously towards the magnetosphere and the ground-ionosphere waveguide, and these ULF waves can be detected by ground receivers and overflying satellites. In comparison to the ULF wavelength, the field structure detected from satellites and from the ground ULF receiver near the ground-based heater are within the near zone. Therefore, numerical simulations of the near-distance radiation field of generated ULF waves are important for the understanding and interpretation of the obtained result from the satellites and ground receivers.

The propagation of ULF waves from the source regions in the high ionosphere to the ground is a complex problem due to plasma inhomogeneity at different altitudes in the ionospheric background and the ground-ionospheric ULF wave waveguide [4]. Numerical simulations need to take into account the anisotropic characteristics of the high ionosphere and the numerical instability caused by evanescent waves [5,6]. Generally, when simulating artificial virtual antennas in the high ionosphere, researchers often consider them as an electric (magnetic) dipole. However, most of the studies have overlooked the stereoscopic structure of ULF radiated current source, which are generated by the complex nonlinear interactions between the heating waves with the ionospheric plasma, into consideration.

In this paper, we set up an antenna array consisting the multiple anti-geomagnetic circular antennas spanning from the upper hybrid altitude to the ordinary (O-mode) wave reflection altitude. To overcome the instability, we employed the full-wave method, and simulated the propagation of ULF in near-distance space. By analyzing spatial radiation distribution of generated ULF waves on the ground of the high-latitude EISCAT and the low-latitude Qingdao, we provide theoretical support for generation of the ULF source in the high ionosphere using powerful high-frequency transmitters.

2. Modeling

Consider ULF electromagnetic waves with time dependence $e^{-j\omega t}$ in a horizontally stratified ionosphere. Let us choose a three-dimensional model in Cartesian coordinates, depicted in Figure 1, where the ionospheric layer is located above the altitude $z = 80$ km, the atmosphere below 80 km and the perfectly conducting ground $z = 0$ km. Here, x denotes the geographic north direction, y denotes the geographic west direction, z denotes the vertical direction. We divide the calculated region into layers with boundaries z_i, in which i denotes i layer from the ground. I is the geomagnetic inclination, and A_{zB} denotes the angle between the z-axis and the geomagnetic field, with clockwise being positive and counterclockwise being negative. φ is the angle between the geomagnetic meridian plane and the geographic north direction.

Maxwell's equations for a source-free medium are written following

$$\nabla \times \mathbf{E}_i = j\omega\mu_0\mathbf{H}_i \qquad (1).$$

$$\nabla \times \mathbf{H}_i = -j\omega\hat{\varepsilon}_i\mathbf{E}_i \qquad (2).$$

where μ_0 is permeability constant, and $\hat{\varepsilon}_i$ is magnetized plasma dielectric tensor, which is describes the anisotropic properties of ionosphere.

$$\hat{\varepsilon}_i = \varepsilon_0(\mathrm{I} + \mathrm{M}_i) \qquad (3).$$

where ε_0 is the vacuum permittivity, I is a 3×3 unit matrix. M_i is the electric susceptibility tensor, determined by the electron density and collision frequency in the ionosphere, as well as the geomagnetic field.

$$\mathrm{M}_i = \mathrm{M}_0 \times \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix} \qquad (4).$$

where $\mathrm{M}_0 = -X/U(U^2 - Y^2)$,$M_{11} = U^2 - l_x^2Y^2$, $M_{12} = jl_zYU - l_xl_yY^2$, $M_{13} = -jl_yYU - l_xl_zY^2$, $M_{21} = -jl_zUY - l_xl_yY^2$, $M_{22} = U^2 - l_y^2Y^2$, $M_{23} = jl_zYU - l_xl_yY^2$, $M_{31} = jl_yUY - l_xl_yY^2$,$M_{32} = -jl_xUY - l_zl_yY^2$, and $M_{33} = U^2 - l_z^2Y^2$. We denote $U = 1 + j\nu/\omega$, $Y = \omega_{ce}/\omega$, and $X = \omega_{pe}^2/\omega^2$, where ω_{ce} is the electron cyclotron frequency, ω_{pe} is the plasma frequency. l_x, l_y and l_z are the direction cosine of the geomagnetic field. The electron collision frequency ν is divided in two parts, below 120 km part is determined by the atmospheric pressure, and above 120 km part is the sum of the electrons-neutral collision frequency and electron-ion collision frequency.

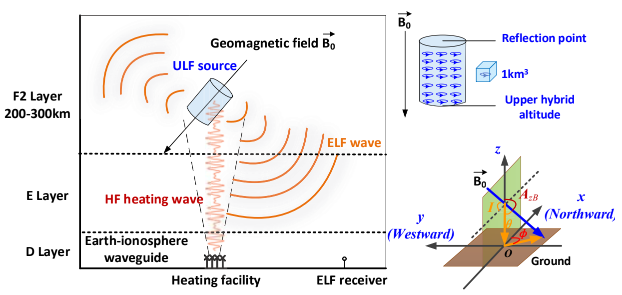

Figure 1. A schematic picture of the generated ULF source model as an antenna array consisting multiple anti-geomagnetic circular antenna in anisotropic high ionosphere.

Considering that the Alfvén speed at the F2 peak around the O-mode reflection altitude is at minimum region and is about 1×10^6 m/s [7], the wavelength of the ULF electromagnetic wave of 30 Hz is about 33.33 km. The spatial distribution of the radiated field is approximately the same as that of a magnetic dipole with circular antenna radius satisfies $a < 0.016\lambda$ [8]. For a 30 Hz circular antenna whose radius is shorter than 0.533 km, it can be equated to a magnetic dipole. Eliasson considered that the heated region exists within a radius of 40 km and an altitude of 20 km.

In this work, the heated region of the ULF source is considered an antenna array, which has m anti-geomagnetic circular antennas located from the upper hybrid altitude to the O-mode wave reflection altitude. Each circular antenna exists within 1 km^3 volume.

The current moment of each magnetic dipole representing circular antenna A_m

$$\mathrm{A}_m = \Delta J_m \cdot S_m \qquad (5).$$

where ΔJ_m and S_m denotes the current and the area of each dipole, respectively.

$$\Delta J_m = N_{em}k_B\frac{\mathbf{B}_0 \times \nabla T_{em}}{|\mathbf{B}_0|^2}e^{-j\omega t} \qquad (6).$$

N_{em} and ∇T_{em} are the electron density and temperature increment at the position of the mth dipole. $\mathbf{B}_0$ is the geomagnetic field.

3. Result and Discussion

The simulating time is 12:00 local time on June 9, 2023, and the simulating location are EISCAT (69.6°N, 19.2°E) and Qingdao (36°N, 120°E), respectively. The International Reference Ionosphere (IRI) model, the Mass Spectrometer and Incoherent Scatter Radar Model (MSIS) model, and the Geomagnetic Reference Field (IGRF) model are employed to establish the ionospheric background, the atmospheric background, and the geomagnetic field, respectively.

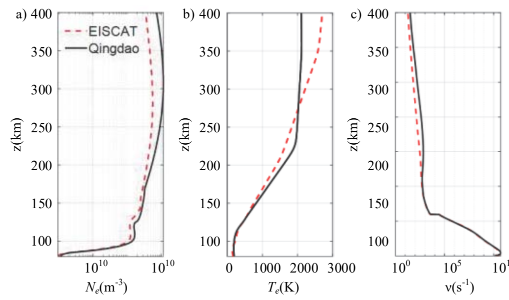

Figure 2. Vertical profile of (a) the electron number density $\boldsymbol{N_e}$ (m^{-3}), (b) the electron temperature $\boldsymbol{T_e}$ (K), (c) the collision frequency $\boldsymbol{\nu}$ (s^{-1}).

Figure 2 displays electron density, electron temperature and collision frequency with red dashed lines representing EISCAT and black solid lines representing Qingdao. Qingdao electron density is larger than that of EISCAT in the F2 region. The O-mode reflection altitude and the upper hybrid altitude of EISCAT are 278 km and 256 km. The O-mode reflection altitude and the upper hybrid altitude of Qingdao are 296 km and 273 km. Thus, the antenna array lengths of EISCAT and Qingdao are 22 km and 23 km, respectively, and the horizontal radius are both set at 40 km.

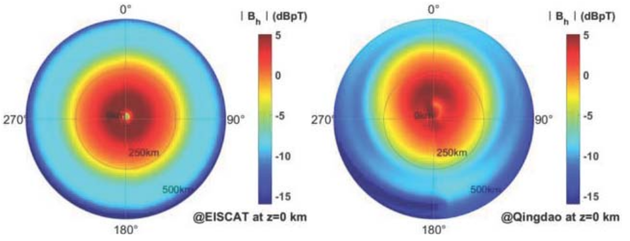

Figure 3. The horizontal magnetic field on the ground (a) @EISCAT; (b)@Qingdao.

The ground-based horizontal magnetic field within a range of 500km at EISCAT and Qingdao are shown in Figure 3. 0° corresponds to the direction of geographic north, while the geomagnetic meridians for EISCAT and Qingdao are situated at approximately 8.89° and 6.75°, respectively. The center is location of the high frequency transmitter.

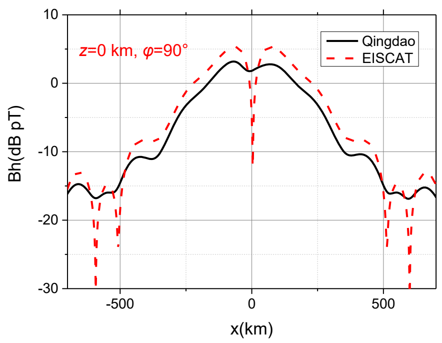

Figure 4. The horizontal magnetic field at $\varphi = 90°$ on the ground at EISCAT and Qingdao.

The difference of ground-based horizontal magnetic field between high latitude and low latitude regions is obvious. The reception of ULF signal's horizontal magnetic field at EISCAT exhibits a distribution characterized by concentric circles surrounding the heater. These concentric circles are caused by the interference of ULF waveguide modes in the Earth-ionosphere waveguide. However, at Qingdao the distribution of ground-based horizontal magnetic field is the asymmetric circles. The direction of asymmetric displacement from the center is the direction of the velocity of the ULF wave group. The ULF generated by the heated area is propagated downward along the geomagnetic field lines, and when it arrives at the low ionosphere, almost only the perpendicular direction of the propagation direction of the ULF wave can be transmitted into the Earth-ionosphere waveguide.

The ground-based horizontal magnetic field at $\varphi = 90°$ is presented in Figure 3. There is a minimum around the heater at high latitude EISCAT, which is distinguish it from the ELF/VLF wave generation by modulated heating of the auroral electrojet. The closer to the heater on the ground, the easier it is to detect the excitation ELF/VLF signal through the modulated auroral electrojet method. Therefore, the presence of a minimum horizontal magnetic field around the heater at high latitude can serve as one of the fundamental criteria for determining the cause of the ULF source. The presence of a minima is attributed to high ionospheric current driven, which is agree with the experimental results at HAARP [5]. The amplitude maxima at $x = \pm 80$ km and the amplitude decrease with increasing distance from the heater.

4. Conclusion

Based on the full-wave method, we have developed a model to calculate the propagation of artificial ULF sources in the anisotropic high ionosphere to study the spatial distribution of magnetic fields within the 500 km region on the ground. It has been observed that there is a noticeable disparity in the spatial distribution of horizontal magnetic field between high latitude and low latitude regions. Specifically, at high latitudes, the received ULF signal exhibits symmetric concentric circles around the heater, while at middle latitudes, it shows asymmetric concentric circles. There is a minimum around the heater at high latitude EISCAT, which is consistent with the experimental results of ULF waves generated in the high ionosphere in the high latitude region. These simulation results can provide a reference for relevant ground received experiment in the high-latitude and mid-latitude regions. The current studies are based on the conclusions in the steady state of the ionosphere, but the gradient of electron temperature in the non-saturated state is much larger, and the ULF sources produced will be different. Therefore, the establishing a model coupled the ionospheric heating model and the ULF propagation model is particularly important, which will be the primary focus of our future work.

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