The contribution of artificial D-region disturbances to the ionospheric VLF wave environment

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Abstract

Artificial ionospheric disturbances are created by intense high-frequency (HF) radiation from ground-based facilities and very-low-frequency (VLF) radiation from Navy transmitters. We apply Stanford Full-Wave Method (SFWM) to scattering of the VLF waves propagating in the Earth-ionosphere waveguide (EIW) by such ionospheric disturbances, using Born approximation. The waves are scattered both into the EIW (in the forward direction) and into the ionosphere (both forward and upward into a whistler "column"). In the case of HF heating, the upward-scattered wave intensity may significantly exceed the waveguide leakage into the ionosphere, while for the VLF-heated ionosphere, it is relatively small.

1 Introduction

Intense high-frequency (HF) electromagnetic radiation from ground-based facilities, as well as intense very-low-frequency (VLF) radiation from Navy transmitters, heat the D-region of the ionosphere, modifying the electron-neutral collision rate. The disturbed region scatters the VLF electromagnetic waves which propagate in the Earth-ionosphere waveguide and originate due to both human activities (from VLF transmitters) and natural phenomena (i.e., sferics emitted by lightning). The VLF perturbations on the ground were calculated previously, using the Earth-ionosphere waveguide (EIW) mode theory with both WKB and Born approximations, both for HF heaters [2,3] and for VLF transmitters [4,5]. The recently-developed Stanford Full-Wave Method (SFWM) [1] allows us to use only Born approximation, without the need of WKB approximation, and allows us to calculate waves scattered both into the EIW and into the ionosphere.

SFWM provides a full-wave 3D solution for monochromatic electromagnetic waves in an arbitrary stationary anisotropic plane-stratified medium with arbitrary dielectric permittivity and magnetic permeability tensors given in each layer of the medium. The electromagnetic radiation may be emitted by an arbitrary configuration of harmonically varying currents (both electric and magnetic). This method is stable against "swamping" of the solution by evanescent waves and is easily parallelized due to most of the calculations being performed in Fourier domain with independent partial waves.

In the present application, the Earth's atmosphere and D and E-region ionosphere are modelled as a horizontally-stratified magnetized plasma, with an arbitrary direction of the geomagnetic field. The VLF transmitter radiation which propagates in the EIW, is scattered by D-region disturbances, both into ionosphere as whistler waves and into the EIW. We apply SFWM to calculate both the EIW modes and the scattering on ionospheric disturbances in Born approximation. The waveguide modes are used to represent the oncoming wave which is being scattered. We consider two cases: (1) VLF waves from NLK transmitter scattered by the ionospheric disturbance above HAARP HF heating facility and (2) VLF waves from NAA transmitter scattered by the ionospheric disturbance above NAU VLF transmitter (see Figure 1).

EIW modes. We calculate the waveguide mode height gains and excitation factors using the SFWM in the way described in [6]. For the night-time ionosphere electron density profile, the modes that make the most contribution into the total field in the Earth-ionosphere waveguide at the distance of $R_0 = 2000$ km (which is of the order of great-circle path distance from the NLK transmitter to the HAARP heating facility) are the first few QTM modes, the strongest being the QTM1 (or QTEM) mode. All of these modes exhibit

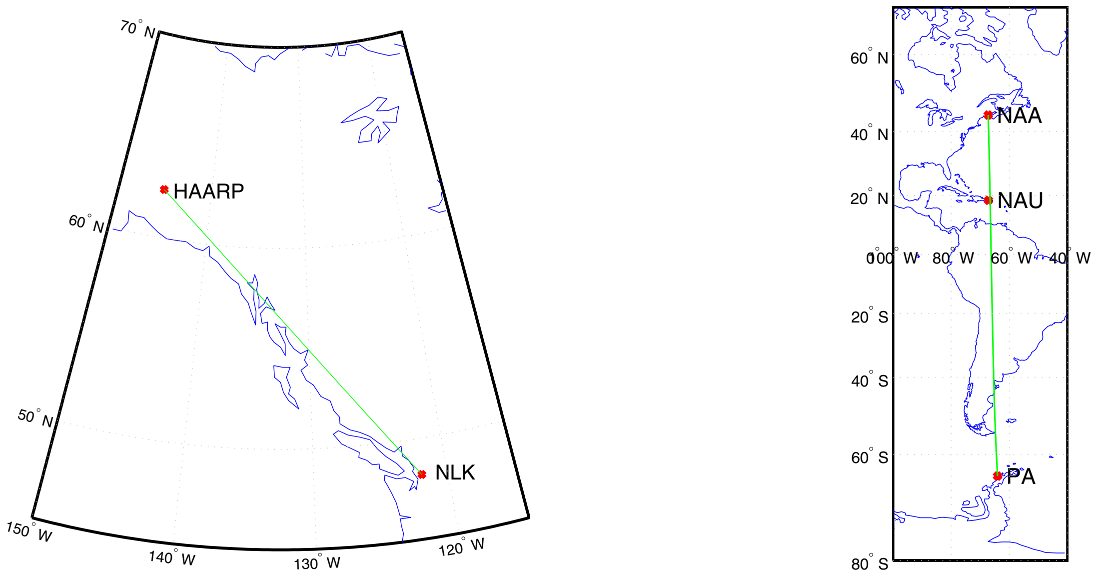

Figure 1: VLF transmitter and heating transmitter configurations for which the scattering was modelled. (Left) HF heating: NLK VLF transmitter, HAARP HF heater. (Right) VLF heating: NAA VLF transmitter, NAU VLF heater, PA is the VLF receiver at Palmer Station.

attenuation due to both absorption in the ionosphere and waveguide leakage of VLF waves into the ionosphere in the form of whistler waves. We calculate that the leakage may account for $\sim$%25 of the total attenuation.

Scattering in Born approximation. Although the disturbed ionosphere is not horizontally-stratified, it is still possible to use SFWM in Born approximation, using the technique outlined in [6]. The Born approximation consists of neglecting the scattered waves compared to the oncoming waves inside the scattering region. Then one can consider the additional currents flowing in the field of the oncoming wave due to the change of conductivity as the source current for scattered waves.

2 VLF scattering by an HF-heated region

We consider VLF waves emitted by NLK transmitter, which operates at frequency $f = 24.8$ kHz and power $P = 250$ kW. The ionosphere disturbance is created by the HAARP HF heater operating at $f_{\rm HF} =$ 5 MHz with ERP $= 1$ GW. It creates a disturbance of width $\sim$23 km [7], which is assumed to have Gaussian horizontal shape. The change in the electron temperature ΔT_e and the electron-neutral collision rate $\Delta\nu_e$ are found using kinetic approach [8], in steady state.

The scattered waves, shown as a perturbation ΔA of the VLF amplitude in the left panel of Figure 2, are emitted both into the EIW and into the ionosphere. The waves scattered into the waveguide can be detected as perturbations in VLF signal amplitude and phase by ground-based VLF receivers located in the "shadow" of the D-region disturbance, i.e., at positions such that the great-circle path from the source to the receiver goes through (or close to) the disturbance. The waves scattered upward into the ionosphere are shown in the lower panel of the Figure. Above the shown altitude of 137.5 km, the attenuation due to collisions is small, so the plotted result is indicative of what would be observed by a satellite. The radiation propagates in the form of whistlers in a relatively narrow (i.e., of the horizontal size of the disturbance) "column" in the direction of the whistler group velocity, i.e. between the vertical and the geomagnetic field. We see that the VLF enhancements inside the whistler "column" may significantly (in this case, by 20 dB) exceed the background which is due to waveguide leakage into the ionosphere. Moreover, there are also perturbations in the "shadow" region of the disturbance, due to the scattered waves entering the ionosphere after being

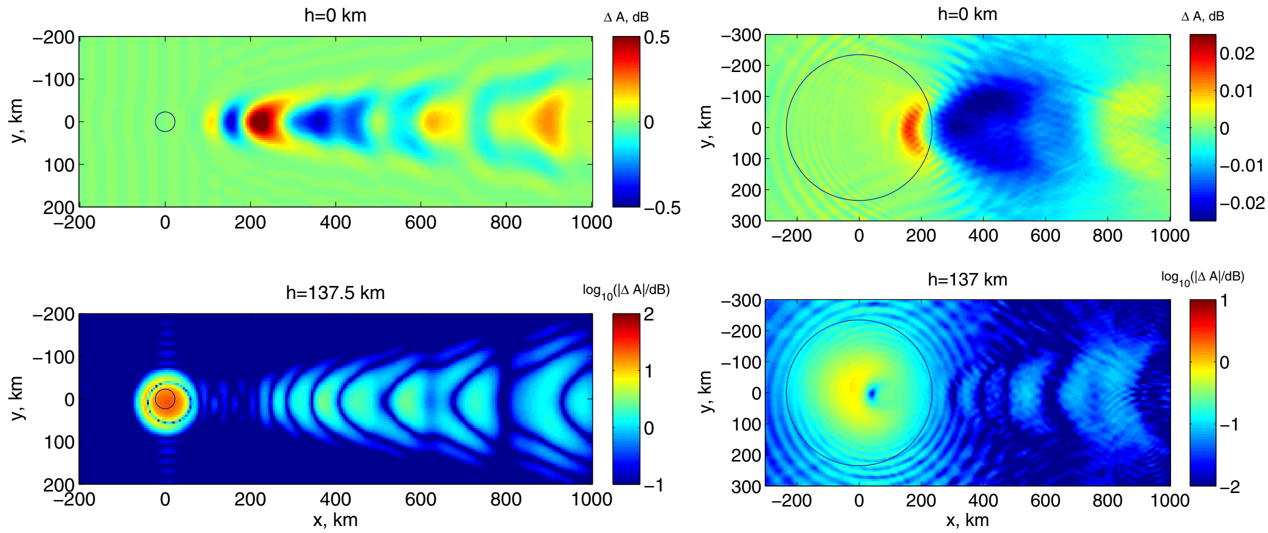

Figure 2: Scattered VLF wave (ΔA) on the ground and in space for QTM1 mode, in a horizontal plane. The ionospheric disturbance is denoted by a black circle. The VLF wave propagates from left to right ($x = R - R_0$, $x = 0$ corresponds to the center of the disturbance). Note that the lower panels (space) are on logarithmic scale, to show the large dynamic range of ΔA in the whistler "column" and in the "tail." (Left) HF heating case. (Right) VLF heating case.

first reflected from the ground. Although much smaller than the radiation in the whistler "column", when expressed in dB, these "shadow" region perturbations are of the same order as the amplitude perturbations seen by the ground-based VLF receivers (in this case, $\sim$0.5 dB), and also may be detectable by satellites.

3 VLF scattering by a VLF transmitter-heated region

We model the same configuration as in [4], i.e., VLF waves propagating from NAA transmitter (operating at frequency $f = 24$ kHz and power $P = 1000$ kW) and scattered by the ionospheric disturbance created above NAU VLF transmitter ($f = 40.75$ kHz, $P = 100$ kW). We calculate the changes in electron temperature ΔT_e and electron-neutral collision rate $\Delta\nu_e = \nu - \nu_{e0}$ in the following way. T_e is obtained from the temperature balance due to E-field heating and cooling due to collisions:

$$T_e = T_0 + \frac{2U}{3\delta\nu_e N_e k_B} \tag{1}$$

where $\delta\nu_e$ is the energy loss rate, with $\delta \approx 1.3 \times 10^{-3}$ being the fraction of electron energy lost in a collision with a molecule [4]; $U = \frac{1}{2}\mathfrak{Re}(\mathbf{J}^* \cdot \mathbf{E})$ is the absorbed VLF wave power, where the current $\mathbf{J} = \hat{\sigma}\mathbf{E}$, with anisotropic $\hat{\sigma}$. The electric field $\mathbf{E}$ is calculated in the vicinity of the transmitter using SFWM in which the transmitter is modelled as a ground-based vertical point dipole. In calculating $\mathbf{E}$, we neglected the effects of VLF heating on the propagation of the VLF waves from the same heater (i.e., used a linear approximation). The heated collision rate is $\nu_e = (T_e/T_0)\nu_{e0}$, where ν_{e0} is the background collision rate [4].

The results for VLF-heated scattering (presented in the right panel of Figure 2) demonstrate the same basic features as the HF-heated scattering, such as the "tail" (both on the ground and in space) and a relatively more intense "column" in space, which is, however, wider than in HF heating case, due to the wider VLF radiation pattern than the HF beam. The calculated VLF perturbation on the ground is of the order of $\pm$0.02 dB, which is somewhat lower than the experimental value of $\pm$0.03–0.12 dB [4]. Moreover, the maximum amplitude perturbation in the "column" is only of the order of 0.8 dB, giving a small contribution compared to the background waveguide leakage.

4 Discussion and Conclusions

We applied SFWM to calculate Earth-ionosphere waveguide modes and their scattering on D-region disturbances. We found that the scattered waves are emitted both into the Earth-ionosphere waveguide and into the ionosphere, and the whistler waves scattered into the ionosphere form an intense "column" and a weaker "tail" in the shadow of the scatterer. In the case of HF heating, the VLF enhancements inside the whistler "column" may significantly exceed the background leakage from the Earth-ionosphere waveguide. This suggests that the D-region disturbances may play in important role in contribution to the electromagnetic radiation environment in the ionosphere and magnetosphere. The difference in upward scattering from VLF-heated and HF-heated region may be attributed to (1) a wider VLF disturbance on which the scattering is not as efficient and (2) the fact that, as the model results indicate, most of the VLF heating occurred at lower altitudes, which lead to higher attenuation of the scattered radiation (than in HF case) before it reached the collisionless region of ionosphere.

In the future enhancements of this model, we will include corrections due to change in electron density N_e, which occur on longer timescales, and are caused by the change in the attachment coefficient. Beside this, in very strong VLF fields, a kinetic approach may be necessary [8]. Also, the presented theoretical results await experimental verification using satellite data.

5 Acknowledgments

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6 References

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