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ScienceDirect

Advances in Space Research xxx (2017) xxx–xxx

ELSEVIER

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

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# Investigation of the radiation properties of magnetospheric ELF waves induced by modulated ionospheric heating

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Received 4 November 2016; received in revised form 29 December 2016; accepted 6 February 2017

## Abstract

Electromagnetic extremely low frequency (ELF) waves play an important role in modulating the Earth's radiation belt electron dynamics. High-frequency (HF) modulated heating of the ionosphere acts as a viable means to generate artificial ELF waves. The artificial ELF waves can reside in two different plasma regions in geo-space by propagating in the ionosphere and penetrating into the magnetosphere. As a consequence, the entire trajectory of ELF wave propagation should be considered to carefully analyze the wave radiation properties resulting from modulated ionospheric heating. We adopt a model of full wave solution to evaluate the Poynting vector of the ELF radiation field in the ionosphere, which can reflect the propagation characteristics of the radiated ELF waves along the background magnetic field and provide the initial condition of waves for ray tracing in the magnetosphere. The results indicate that the induced ELF wave energy forms a collimated beam and the center of the ELF radiation shifts obviously with respect to the ambient magnetic field with the radiation power inversely proportional to the wave frequency. The intensity of ELF wave radiation also shows a weak correlation with the size of the radiation source or its geographical location. Furthermore, the combination of ELF propagation in the ionosphere and magnetosphere is proposed on basis of the characteristics of the ELF radiation field from the upper ionospheric boundary and ray tracing simulations are implemented to reasonably calculate magnetospheric ray paths of ELF waves induced by modulated ionospheric heating.

*Keywords:* Modulated ionospheric heating; ELF waves; Full-wave method; Radiation properties

## 1. Introduction

ELF/VLF waves exist widely in the Geo-space environment. Many studies have shown that these waves can play an important role in modulating the Earth's radiation belt electron distribution (e.g., Wang et al., 2012a, 2012b; Harid et al., 2014; Soria-Santacruz et al., 2014; Li et al., 2014; Ni et al., 2014; Horne, 2015). In addition to the natural emission of ELF/VLF waves in the magnetosphere, these waves can also be generated by modulated ionospheric heating to penetrate through the ionosphere into the magnetosphere (Leyser and Wong, 2009; Gołkowski et al., 2010, 2011; Jin et al., 2012; Moore et al., 2013), thereby affecting the magnetospheric radiation environment. However, a number of studies pointed out that the radiation efficiency of ELF/VLF waves by modulated ionospheric heating is highly variable and complex. Jin et al. (2009) studied the correlation between the radiating source of the D region ionosphere and ELF amplitude on basis of the ground observation of electrojet current strength to find that the

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http://dx.doi.org/10.1016/j.asr.2017.02.009
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Please cite this article in press as: Wang, F., et al. Investigation of the radiation properties of magnetospheric ELF waves induced by modulated ionospheric heating. Adv. Space Res. (2017), http://dx.doi.org/10.1016/j.asr.2017.02.009

electrojet strength and ELF amplitude are poorly or negatively correlated. Numerical models of ELF/VLF propagation in the Earth-ionosphere waveguide were also developed using the full-wave finite element approach (e.g., Lehtinen and Inan, 2008, 2009). The full-wave model not only provides stability against the numerical 'swamping' caused by the evanescent wave, but also has high computational efficiency and has recently become available and experimentally verified to within a few decibels via comparison to more extensive satellite data (Graf et al., 2013). Cohen et al. (2011, 2012a, 2012c) and Cohen and Gołkowski (2013) applied this model to study the effect of HF wave frequency and beam shape on the amplitude of generated ELF/VLF waves. His results indicated good consistency with the observations, based on which the effect of ELF/VLF waves injected into the magnetosphere via the High Frequency Active Auroral Research Program (HAARP) facilities was also predicted for given beam parameters. Gołkowski et al. (2013) performed the full-wave simulation to study the modulation of auroral electrojet currents using the dual modulated HF beam and subsequently proposed a potential D-region ionospheric diagnostic. It is worthwhile to point out that all the above researches mainly focused on the radiating source strength and ELF/VLF amplitude corresponding to various modulated heating modes and parameters, but the propagation properties of these artificial ELF/VLF waves injected into the magnetosphere are much less investigated. Thus, it is critical to take into account the propagation of generated ELF/VLF waves in the ionosphere and magnetosphere as a whole and to quantify the complete injection process in order to fully understand the effect of ionospheric ELF/VLF radiation.

In this study we develop a full-wave model with the numerical stability on basis of recursive calculations of reflection coefficients and characteristic modes without swamping in a horizontally stratified medium (Nygren, 1982). The radiation field strength is evaluated through a parametric analysis for different parameters. Furthermore, in order to obtain the trajectories of these waves injected into the magnetosphere, we calculate the ray path from the general ray tracing equation for which the initial conditions are obtained by the output of full-wave model. By doing so, we intend to acquire a comprehensive understanding of the relatively complete system for reflecting ELF/VLF injection process from ionosphere to magnetosphere, using these simulations together for this aim.

## 2. Model description

### 2.1. Full-wave model

The Full-wave Method is to seek a solution for plane waves in horizontal stratified medium directly from Maxwell's Curl equations:

$$\begin{cases} \vec{k} \times \mathbf{E} = \omega\mu_0 \mathbf{H} \\ \vec{k} \times \mathbf{H} = -\omega\hat{\varepsilon}\mathbf{E} \end{cases}, \tag{1}$$

where $k$ is wave vector, $\omega$ is wave frequency, $\mu_0$ is permeability, $\hat{\varepsilon} = \varepsilon_0(I + \hat{\chi})$ is dielectric tensor, and $\hat{\chi}$ is electric susceptibility tensor. According to Eq. (1), we can get values for $\mathbf{E} = (E_\perp, E_z)$ and $\mathbf{H} = (H_\perp, H_z)$ with a series of $k$ vector if background medium parameters are given. There are 5 major ion composition $O^+$, $H^+$, $He^+$, $O_2^+$, $NO^+$ in the ionosphere taken into account in this model so that $\hat{\chi} = \sum_\alpha \hat{\chi}_\alpha$, the expression for each component is given by

$$\hat{\chi}_\alpha = -\frac{X_\alpha}{U_\alpha(U_\alpha^2 - Y_\alpha^2)} \times \begin{pmatrix} U_\alpha^2 - l_x^2 Y_\alpha^2 & i l_z Y_\alpha U_\alpha - l_x l_y Y_\alpha^2 & -i l_y Y_\alpha U_\alpha - l_x l_z Y_\alpha^2 \\ -i l_z Y_\alpha U_\alpha - l_x l_y Y_\alpha^2 & U_\alpha^2 - l_y^2 Y_\alpha^2 & i l_x Y_\alpha U_\alpha - l_z l_y Y_\alpha^2 \\ i l_y Y_\alpha U_\alpha - l_x l_z Y_\alpha^2 & -i l_x Y_\alpha U_\alpha - l_z l_y Y_\alpha^2 & U_\alpha^2 - l_z^2 Y_\alpha^2 \end{pmatrix}, \tag{2}$$

where $X_\alpha = \omega_{\alpha p}^2/\omega^2$, $Y_\alpha = \omega_{\alpha H}/\omega$, $U_\alpha = 1 + iZ$, $Z = v_\alpha/\omega$. The ionospheric electron-neutral and ion-neutral collision frequency used in this work is analytical approximation of experimental data and is given by Wait and Spies (1964) and Morfitt and Shellman (1976):

$$v_e = 1.816 \times 10^{11} \exp(-0.15z)\ \mathrm{s}^{-1}, \tag{3}$$

$$v_i = 4.54 \times 10^9 \exp(-0.15z)\ \mathrm{s}^{-1}, \tag{4}$$

where $z$ is the altitude measured in kilometers. The electron density profile is obtained by the IRI model. The magnetic field is calculated using the IGRF model.

A Cartesian coordinate system is chosen with $x$, $y$ in the horizontal plane and $z$ vertical upward. A uniformly spaced rectangular grid is used in the $k_x$ and $k_y$ direction and dielectric tensor $\hat{\varepsilon}$ in each layer can be obtained in the vertical $z$-direction. According to Snell's law, the horizontal component $E_\perp = (E_x, E_y)$ and $H_\perp = (H_x, H_y)$ is conserved during propagation through all layers. Eliminating the $Z$ components from Eq. (1), we can obtain the following elegant form:

$$\frac{\partial f}{\partial z} = i k_0 \hat{T} \cdot f, \tag{5}$$

where $f = (E_\perp, Z_0 H_\perp)^T$, $Z_0$ is wave impedance, $\hat{T}$ is $4 \times 4$ matrix:

$$\hat{T} = \begin{pmatrix} -\frac{k_x \varepsilon_{31}}{k_0 \varepsilon_{33}} & -\frac{k_x \varepsilon_{32}}{k_0 \varepsilon_{33}} & \frac{k_x k_y}{k_0^2 \varepsilon_{33}} & 1 - \frac{k_x^2}{k_0^2 \varepsilon_{33}} \\ -\frac{k_y \varepsilon_{31}}{k_0 \varepsilon_{33}} & -\frac{k_y \varepsilon_{32}}{k_0 \varepsilon_{33}} & -1 + \frac{k_y^2}{k_0^2 \varepsilon_{33}} & -\frac{k_x k_y}{k_0^2 \varepsilon_{33}} \\ -\varepsilon_{21} + \frac{\varepsilon_{23}\varepsilon_{31}}{\varepsilon_{33}} - \frac{k_x k_y}{k_0^2} & -\varepsilon_{22} + \frac{\varepsilon_{23}\varepsilon_{32}}{\varepsilon_{33}} + \frac{k_x^2}{k_0^2} & -\frac{k_y \varepsilon_{23}}{k_0 \varepsilon_{33}} & \frac{k_x \varepsilon_{23}}{k_0 \varepsilon_{33}} \\ \varepsilon_{11} - \frac{\varepsilon_{13}\varepsilon_{31}}{\varepsilon_{33}} - \frac{k_y^2}{k_0^2} & \varepsilon_{12} - \frac{\varepsilon_{13}\varepsilon_{32}}{\varepsilon_{33}} + \frac{k_x k_y}{k_0^2} & \frac{k_y \varepsilon_{13}}{k_0 \varepsilon_{33}} & -\frac{k_x \varepsilon_{13}}{k_0 \varepsilon_{33}} \end{pmatrix}, \tag{6}$$

The electromagnetic field $E_\perp$ and $H_\perp$ can be obtained by solving Eq. (5), and then the component in the $Z$ direction can be obtained according to Eq. (1):

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