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HF modulated ionospheric currents

J. A. Payne,[1] U. S. Inan,[1] F. R. Foust,[1] T. W. Chevalier,[1] and T. F. Bell[1]

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[1] The HAARP HF facility is used to modulate the components of the auroral electrojet that flow in the D-region of the ionosphere, creating ELF/VLF radiation which is then measured at a receiver co-located with the HAARP HF antenna. An HF heating model is coupled to a full wave plasma interaction FDTD code to determine the ELF/VLF response of the ionospheric plasma to the modulated HF stimulation. The predicted FDTD fields on the ground are found to be in remarkable agreement with those measured at a receiver co-located with HAARP. The FDTD code also predicts an upwardly propagating whistler mode that is tightly bound to the magnetic field lines. **Citation:** Payne, J. A., U. S. Inan, F. R. Foust, T. W. Chevalier, and T. F. Bell (2007), HF modulated ionospheric currents, *Geophys. Res. Lett.*, *34*, L23101, doi:10.1029/2007GL031724.

1. Introduction

[2] ELF/VLF waves have been produced by modulated HF heating of the auroral electrojet since the 1970's [*Getmantsev et al.*, 1974; *Stubbe and Kopka*, 1977]. Many experiments have concluded that the ELF/VLF radiation produced results primarily from the modulation of the so-called Hall and Pedersen conductivities at ~60–100 km altitude [*Barr and Stubbe*, 1984]. However, the general treatment of these modulated conductivities at ELF/VLF frequencies ignores the complicated interaction between the conductivity changes and the formation of currents within the ionospheric plasma.

[3] The basis of the present work is data collected during an experimental campaign run in April 2003 using multiple time-synchronized recording stations to measure at different locations the ELF/VLF signals generated through HAARP HF modulation of the ionosphere. In this work, the collected data is compared against the predictions of a set of computer models that calculate the response of the ionospheric plasma to a modulated HF heater, and determine the ground based electromagnetic fields. Although the numerical simulation space is too restrictive to predict the fields at the eight stations that are located 70–150 km from the HF antenna, substantial amount of data collected at the receiver site co-located with HAARP shows excellent agreement with the results of numerical simulations.

[4] The results of our simulations are similar in some respects to those of *Keskinen and Rowland* [2006]. *Keskinen and Rowland* [2006] assumed a Gaussian distribution in space for their current source, whereas this paper quantitatively predicts the conductivity modulation that results from modulated HF heating. A self-consistent model of the modulated electrojet currents, such as that used in our paper is necessary for comparison of model predictions with observations.

2. Experiment Description

[5] During a two week campaign in April 2003, the HAARP beam modulated the ionosphere at various frequencies near 2 kHz while steering the beam in a predetermined angular pattern. The N/S and E/W magnetic field, and the vertical electric field were recorded at nine stations located within 150 km of HAARP. While this type of a heating experiment is similar to the experiment described by *Werner et al.* [1990] and *Werner* [1989], we additionally include a measurement of the vertical electric field. As a subset of the total collected data, we measured the amplitude and phase of the three components at the fundamental modulation frequency as a function of beam angle θ (off vertical) and ϕ (clockwise rotation from True East) at the HAARP receiver.

3. Modeling

[6] To predict the response of the plasma to the HF modulation, we use two separate models. The first model is an HF heating model that simulates the change in ionospheric conductivity due to the modulation of an HF heater. The HF Heating model takes as inputs the ambient electron density, the ambient N_2 and O_2 concentrations, and the neutral temperature T_n. We use a high density ionization profile first suggested by *Inan et al.* [1992] for the electron density (referenced as Profile III by *Inan et al.* [1992]), and the MSIS-E-90 model for the N_2, O_2, and T_n parameters. The collision rates are derived using the formulas presented by *Banks* [1966]. The output of the HF heating simulation is a 3-D map of the values of the Hall, Pedersen and Parallel components of the modulated ionospheric conductivity.

[7] In the second model, we take the 3-D map of the conductivity modulation generated by the HF heating model and input it into a wave-plasma interaction Finite Difference Time Domain (FDTD) code to determine how the plasma responds to the stimulation. The same election density profile used for the HF heating model is used in the FDTD simulation. The neutral constituents are not modeled in the FDTD code. The FDTD simulation models all of the field components and the currents that flow in a small region located around the heated spot. However, because of computational limitations, the simulation space is limited and does not include the recording sites other than the one co-located with HAARP.

[1]Space, Telecommunications, and Radioscience Laboratory, Stanford University, Stanford, California, USA.

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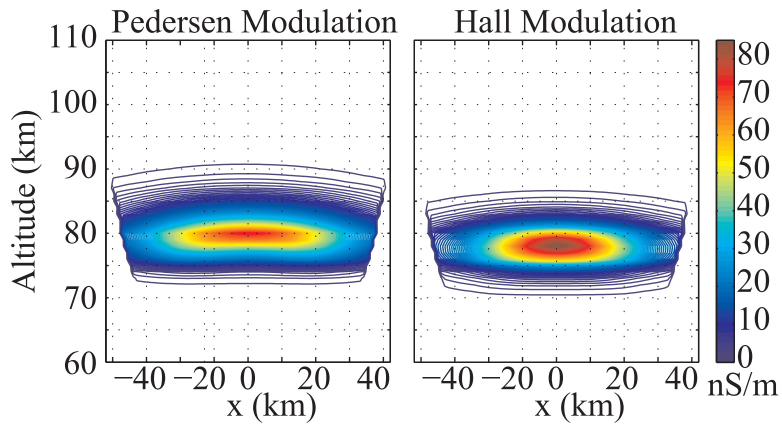

Figure 1. Modulated Hall and Pedersen conductivity amplitudes. The ambient electrojet electric field is assumed to point along the *x*-axis.

[8] Because the direction and strength of the electrojet is unknown, the FDTD field pattern must be oriented to the data. This orientation is done by comparing the predicted ground-based field patterns to the data collected at HAARP. As shown later, both the data and the model predictions indicate that the vertical electric field exhibits a distinct minimum in intensity along a particular ground-track. Using this minimum as an alignment marker, the model space can be rotated to accurately predict the data.

3.1. HF Heating Model

3.1.1. Model Description

[9] The method we use to calculate the variation in ionospheric temperature as a function of time is based on the equations presented by *Tomko* [1981] and *James* [1985]. The HF heating code used in this work is a streamlined version of the model presented by *Moore* [2007]. The main difference between our model and the model presented by *Moore* [2007] is the addition of presolver routines that greatly decrease computational time.

[10] The electron temperature as a function of time is converted to Pedersen and Hall conductivities [*Tomko*, 1981; *Papadopoulos et al.*, 1990]. The amplitude and phase of the first harmonic component of the conductivities is extracted as a function of position. We repeat this process using many rays which mimic the shape and power of the HF beam. We then interpolate the results onto a regular grid and use the conductivity values (all three components) as an input into the FDTD model. In the context of the FDTD model, and with a constant auroral electrojet field, the externally driven conductivities constitute three dimensional source currents at each of our grid points, which then drive the electromagnetic fields at other points in our numerical grid.

3.1.2. Model Results

[11] Figure 1 shows contour maps of the *x* slice of the Hall and Pedersen modulated conductivities. The color scale shows the amplitude of the conductivity modulation at the HF modulation frequency, in this case 1875 Hz. Nearly all of the modulation occurs between 75 and 85 km, with the peak modulation altitude being near 78 km.

3.2. FDTD Model

3.2.1. Model Description

[12] The FDTD code solves a rearrangement of the equations described by *Lee and Kalluri* [1999]. These equations are Ampere's Law, Faraday's Law, and the constitutive relation for a cold magnetoplasma The equations are solved on a 3-D staggered Lee and Kalluri mesh [*Lee and Kalluri*, 1999]. The source currents generated by the HF heating model are introduced into the FDTD model using a Gaussian envelope.

3.2.2. FDTD Results

[13] Because of the computational challenges in execution of an FDTD code with a large solution space, the San Diego Supercomputer Center's (SDSC) computing resources were utilized. Even with such a powerful tool, the dimensions of the solution space were too limited to directly compare with the recording sites located at distanced of 70–150 km from the HAARP facility. With this restriction in mind, a relatively conservative number of grid points were used in order to conserve a limited number of available supercomputer hours.

[14] The simulation presented in this work was performed using a 160 by 160 by 172 size grid where each element is a 1 km square box. A 30 cell Convolutional Curl Operator Perfectly Matched Layer (CCO-PML) composes the outermost cells on all faces of the solution space except the ground, which is assumed to be a perfect conductor [*Chevalier and Inan*, 2004]. The ambient electrojet electric field is assumed to be parallel to the ground, pointed along the *x*-axis, at 25 mV/m strength.

[15] Figure 2 (top left) shows that the plasma responds to the initial stimulation by developing a set of current sheets that are nearly perpendicular to the magnetic field. These current sheets keep the divergence of the current small, preventing large accumulation of charge as would be dictated by the continuity equation. The current sheets are the self-consistent currents that are required by the existence of a slowly propagating upwardly directed electromagnetic mode in a magnetoplasma.

[16] Figure 2 (bottom left) shows the horizontal electric fields that develop in the plasma in response to the HF-heating driven conductivity modulations. The amplitude

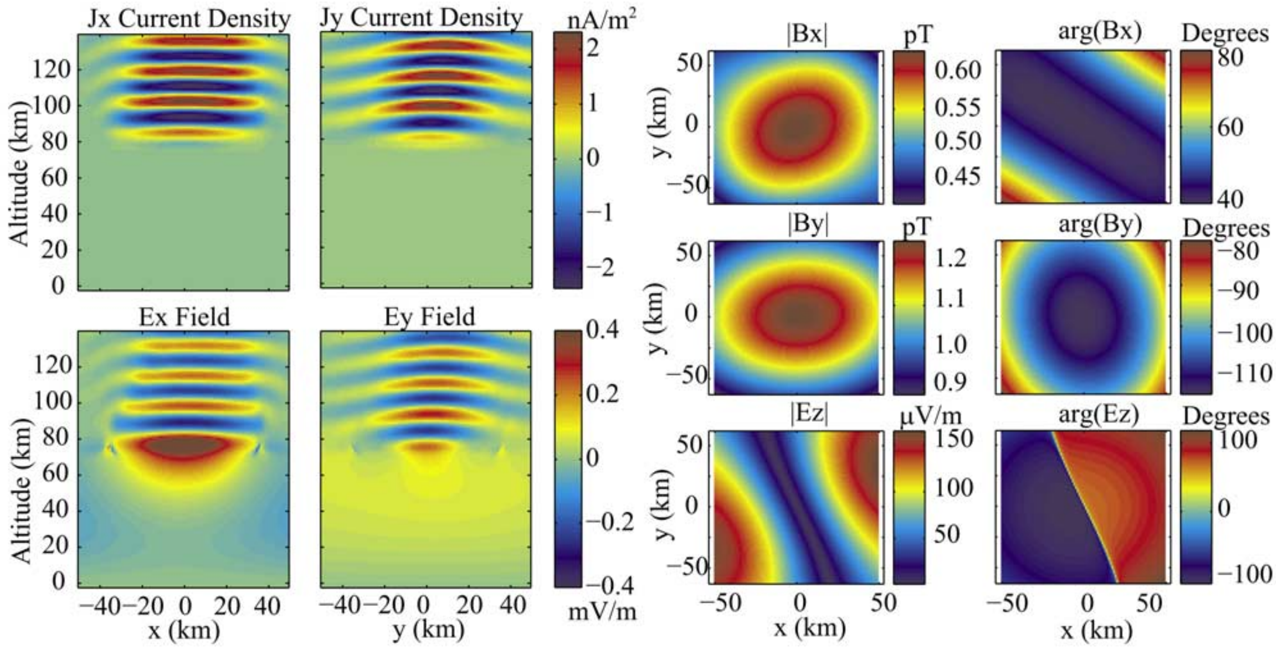

Figure 2. (left) A vertical slice through the FDTD solution illustrating the predicted current density and electric field patterns. (right) The predicted magnetic and electric fields on the ground beneath the heated region. The electric field is assumed to be 25 mV/m directed along the *x*-axis.

of the upwardly directed electromagnetic mode is much greater than the amplitude of the fields that propagate downward and which thus have the potential to couple into the Earth-ionosphere waveguide. The whistler mode clearly progresses upward, following the Earth's magnetic field without undergoing significant lateral spreading. The slight tilt in the *y* slice of both the electric field and the current density plots is due to the Earth's magnetic field which is oriented ∼16° from the vertical at the HAARP site.

[17] In Figure 3, the polarization of the electric field is plotted as the upwardly propagating whistler mode increases in altitude. Near the heated region, the electromagnetic mode is nearly linearly polarized. A few kilometers above the heated region, the wave is much more elliptically polarized. Finally, at 117 km, the wave has become right-hand circularly polarized (RHCP). A RHCP electromagnetic mode with self-supporting perpendicular current sheets traveling along a magnetic field is a whistler-mode wave propagating parallel to the ambient magnetic field [*Bittencourt*, 2003, pp. 439–442]. This determination is consistent with previous satellite measurements of radiation detected on satellites above a modulated ionosphere [*Bell et al.*, 2004; *Platino et al.*, 2004].

[18] Figure 2 (right) shows the amplitude and phase of the predicted B_x, B_y and E_z fields on the ground beneath the HF heated spot. The center of each subplot is the location of the HAARP HF antenna array. These three field components are shown because they are the components that were recorded at each of the receiver stations. The field patterns on the ground predicted by our FDTD simulation are very close to the patterns generated by assuming a simple model consisting of a small disk of radiating current at the altitude of maximum conductivity modulation.

[19] The most interesting feature of the ground based fields is the pattern presented by E_z. There is a clear minimum in this pattern that coincides with a sharp 180° change in the phase. By holding the elevation angle of the HF beam constant, and then varying the beam in azimuth, this pattern is mapped over a circular path.

4. Data at HAARP

[20] In Figure 4, we see a typical example of data collected at the receiver co-located with HAARP. The data was collected on April 9, 2003 between 0800–0820 UT when the HF heater was sinusoidally modulating the ionosphere at 1875 Hz with a 3.2 MHz HF full-power beam. The

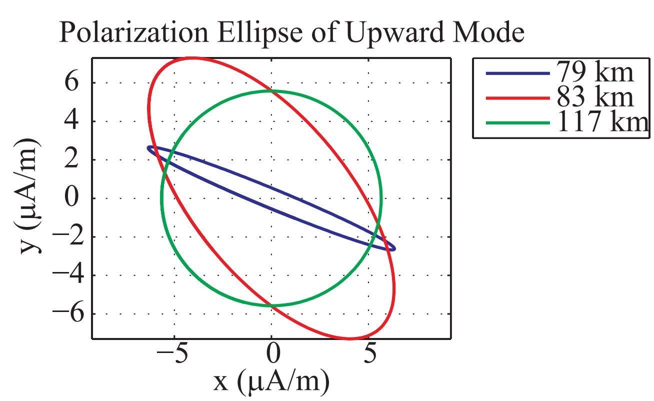

Figure 3. Polarization of upward traveling mode taken at three altitudes. In each case, the mode is right hand polarized.

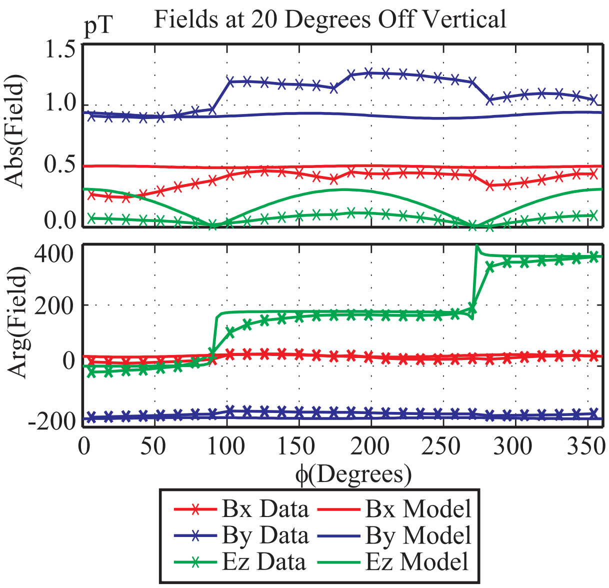

Figure 4. Data collected at the HAARP receiver. The data is plotted as a function of ϕ. The vertical electric field is divided by c to bring it into the same plot range as the magnetic field.

K_p index is between 5- and 4 throughout the transmission time. Each data point represents one second of data, integrated over this second to extract the average amplitude and phase at the modulation frequency of 1875 Hz. The display is limited to points where $\theta = 20°$.

[21] The general form the data takes is that the magnetic field from the N/S antenna remains roughly constant around 0.4 pT received field strength and 26° of phase. The E/W magnetic field antenna is also roughly constant, but is positioned at an average amplitude of 1.1 pT and −157 degrees of phase. The electric field shows two minima in amplitude, which coincide with a quick 180 degrees reversal in phase. The first minima occurs between 80–120° in all of the data examined.

[22] The second set of traces in Figure 4 show the predicted FDTD fields on the ground as the HF heated spot varies in azimuth. The FDTD predicted field patterns on the ground are rotated so that the minimum in the predicted E_z pattern matches the minimum in the E_z pattern shown in data. The best fit rotation in this example is 202°. The overall strength of the predicted field pattern is scaled by a single real valued number to take into consideration the unknown strength of the ambient electric field. In this case, the scale value used is 0.8. If the field pattern is assumed to vary linearly with electrojet strength, this scaling corresponds to an estimated ambient electric field of 20 mV/m.

[23] The match between the FDTD predictions and the data recorded at the HAARP receiver is quite striking, considering the variability of the ionosphere over relatively short time scales. The relative phase and amplitude of the fields provides an excellent match between the model and the data. The small difference in amplitude between simulation and data for E_z is most likely a result of the difficulty in calibrating the electric field antenna in the presence of its supporting aluminum structure.

5. Conclusions

[24] We have shown that an HF heating model and an FDTD code can be combined to accurately predict the ground field pattern below an HF modulated ionosphere, as evidenced by the good match between the predicted field pattern and the receiver located at HAARP. The same simulations also predict an upwardly propagating whistler mode electromagnetic wave, which is tightly aligned with and confined along the ambient magnetic field.

[25] The numerical methods outlined above illustrate a computational path for exploring modulated HF heating and its effects, both in the excitation of the plasma and in production of ground- and space-based electromagnetic waves. Future expansion of numerical space should allow the FDTD results to be expanded to include receivers located more than 50 km from the heated spot. Such an extension would allow Earth-ionosphere waveguide effects to be studied in conjunction with the modulated ionospheric heating.

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T. F. Bell, T. W. Chevalier, F. R. Foust, U. S. Inan, and J. A. Payne, Space, Telecommunications, and Radioscience Laboratory, Stanford University, Packard Building, Stanford, CA 94305, USA. (jopayne@gmail.com)