The magnetic response of the ionosphere to pulsed HF heating

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[1] It shown theoretically and confirmed for the first time experimentally that the magnetic response of the lower auroral ionosphere to pulsed ionospheric HF heating depends critically on the parameter T/T_h, where T is the pulse duration and T_h is the time required for the electron temperature to reach its steady state value. Theoretical analysis shows that the strength and pulse shape of the near-zone magnetic field on the ground depends not only on the traditional quasi-static near-field term, but also on a term which depends on the derivative of the current (i.e., the impulse response of the ionosphere). Results from newly-conducted experiments using the HAARP transmitter in Gakona, Alaska are presented that verify our model, and it is shown that for $T \leq T_h$ the magnetic flux on the ground due to the impulse response is 10–15 dB larger than the flux due to the quasi-static term. **Citation:** Papadopoulos, K., T. Wallace, G. M. Milikh, W. Peter, and M. McCarrick (2005), The magnetic response of the ionosphere to pulsed HF heating, *Geophys. Res. Lett.*, *32*, L13101, doi:10.1029/2005GL023185.

1. Introduction

[2] The generation of ELF/VLF waves by modulated HF heating has been the subject of many experimental and theoretical studies [*Tripathi et al.*, 1982; *Belyaev et al.*, 1987; *Barr and Stubbe*, 1993; *Papadopoulos et al.*, 2003; *Rietveld et al.*, 1989]. Despite several years of experimental and theoretical papers [*Rietveld and Stubbe*, 1987; *McCarrick et al.*, 1990; *Ferraro et al.*, 1989; *Papadopoulos et al.*, 1989; *Rowland*, 1999; *Zhou et al.*, 1996], critical issues concerning the efficiency of HF to ELF/VLF conversion and its dependence on ELF/VLF frequency remain unresolved. A key input in understanding the physics underlying the efficiency of ELF/VLF generation is the magnetic response of the ionosphere to short heating pulses. In this paper we demonstrate theoretically and experimentally that the temporal magnetic response of the ionosphere to pulsed HF heating is composed of the superposition of three sequential components. The first one is due to the time derivative of the induced current that, under most experimental conditions, is equivalent to the time derivative of the electron temperature. It has the form of a magnetic impulse and goes to zero on a time of the order of the temperature saturation time T_h. This is followed by an essentially square magnetic pulse, with amplitude much smaller than the initial impulse. This is proportional to the induced current and continuous for the duration T of the HF pulse. The final component is due to the reflection of the two components mentioned above from the ground and the bottom of the ionosphere. It includes a delay time corresponding to the round trip T_r of the pulse between the ground and the ionosphere and has amplitude approximately 0.2 of the initial pulse that corresponds to the reflection coefficient. Following heater turn-off the magnetic waveform is composed only of the impulse with a duration of the order of the cooling time T_c followed by its reflected component. It is shown that the efficiency of HF to ELF/VLF as a function of the ELF/VLF frequency can be accounted by superposing periodic pulses with the above described temporal structure.

[3] We should mention that in a previous experiment *Rietveld et al.* [1987] examined the magnetic response of the ionosphere to short pulse heating. The objective of their work was the determination of the characteristic times for conductivity changes in the D-region caused by HF heating, as well as measurement of the ELF/VLF reflection height. While the approximate values of these constants scale with the ones we found, they failed to note the important three-component waveform structure mentioned above, the asymmetry of the response between pulse-on and pulse-off and its implications to the ELF/VLF generation efficiency. In fact the motivation for our experiment was that important features of our theoretically predicted waveforms were at variance with the ones reported by *Rietveld et al.* [1987]. In this letter we present a theoretical/computational model of the expected waveforms along with their physical basis. This is followed by presentation of new results from pulsed heating experiments and a discussion of their implications to the HF to ELF/VLF conversion efficiency.

2. Magnetic Response for Long Heating Pulses

[4] The overall model for the theoretical investigation is based on three components. The first component models the absorption of the HF in the ionosphere, the accompanying heating of the ambient electron gas, the modification of the collision frequency and the modification of the conductivity tensor of the ionosphere. The inputs to the HT code are the heater power, ERP, frequency, pulse length and a model of the ambient ionosphere. The latter has been taken to be one of the standard models introduced by *Barr and Stubbe* [1984]. The important part of the output is the spatio-temporal profile of the current density in the modified region. This is computed by assuming an electric field profile in the modified region. Since the objective of the study is on waveforms rather than amplitudes, we assumed a constant electric field with a value of 1 mV/m.

[5] The second component of our model takes the spatio-temporal profile of the current density and computes the

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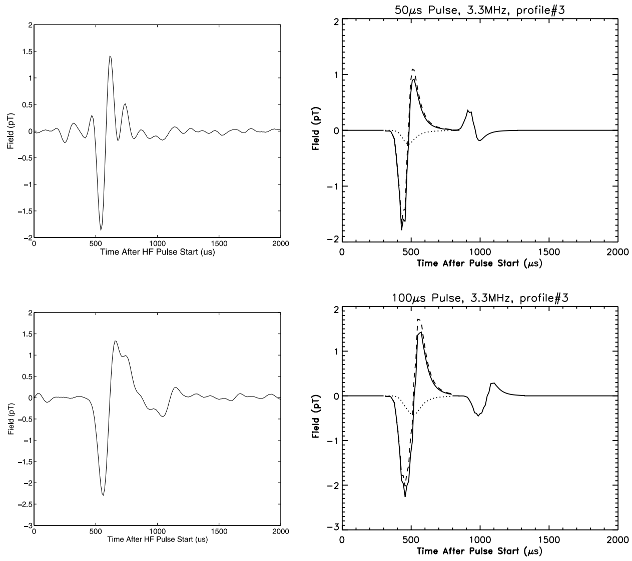

Figure 1. Comparison of experimental (left column) and theoretical (right column) waveforms for pulse lengths 0.05 msec (top) and 0.1 msec (bottom). Here the solid traces show the total magnetic field, dotted traces show the field due to the pulsed current, and dashed traces show the field due to the derivative of the current.

vector potential $\vec{A}$ in the near zone by first finding the three-dimensional Green's function of the equation

$$\nabla^2\vec{A} - \mu\overleftrightarrow{\sigma}(z)\cdot\frac{\partial\vec{A}}{\partial t} - \frac{1}{c^2}\frac{\partial^2\vec{A}}{\partial t^2} = -\mu\vec{J}(z,t) \qquad (1)$$

[6] In equation (1) $\overleftrightarrow{\sigma}(z)$ is the conductivity tensor [*Sorokin and Yaschenko*, 1992] in a coordinate system with the z-axis along the ambient magnetic field B_0. The major difference between our model and those discussed previously [*Barr and Stubbe*, 1984; *Rietveld et al.*, 1989; *Pashin and Lyatsky*, 1997] is that it retains the temporal variation of the current during the pulse and it uses the three-dimensional Green's function to compute the fields on the ground, rather than the plane wave formulas. Furthermore, the ionospheric absorption is computed by using kinetically derived coefficients. An important feature of equation (1) can be seen by using a one layer approximation with scalar conductivity σ and finding the three-dimensional Green's function due to an impulsive current density source of unit strength at r_0 at a time t_0. It is given by (*Morse and Feshbach* [1953])

$$G_3(R,\tau) = \frac{c}{R}\exp\left(-\frac{\mu\sigma c^2\tau}{2}\right)\left[\delta(c\tau - R) + \frac{\mu\sigma c R}{2\sqrt{R^2 - c^2\tau^2}} \times u(c\tau - R)J_1\left(\frac{\mu\sigma c}{2}\sqrt{R^2 - c^2\tau^2}\right)\right] \qquad (2)$$

where we have defined $R = |\vec{r} - \vec{r_0}|$ to be the distance to the measurement location on the ground, and $\tau = t - t_0$. In equation (2) $u(z)$ is the step function, J_1 is the ordinary Bessel function of the first kind, and the other symbols have their usual meaning. Without going much further in the mathematical analysis we can see that since the magnetic (electric) field associated with the vector potential involves the spatial (temporal) derivative with respect to R the associated Green's function, in addition to the terms proportional to the current $\vec{J}(z, t)$, involve a term proportional to the derivative of the current $\partial\vec{J}(z, t)/\partial t$ due to the derivative of the δ-function [i.e., $\delta'(ct - R)$]. To our knowledge the presence of these two terms has not been noted in previous analysis [*Papadopoulos et al.*, 1990; *Tomko et al.*, 1980; *Barr and Stubbe*, 1984; *Rietveld et al.*, 1989; *Pashin and Lyatsky*, 1997].

[7] We should remark that the dominant effect of the modulation occurs at altitudes lower than 78 km. As a result (i) current modulation is not affected by electrojet instabilities that occur at altitudes above 95 km, and (ii) the substitution of the tensor conductivity $\overleftrightarrow{\sigma}(z)$ in equation (1) by the scalar σ results only in a small rotation of the downward propagating whistler before it reaches the collision-dominated region (∼72 km).

[8] The third and final component computes the contribution to the measured field from ground and ionospheric reflection. Due to the difficulty of analytically determining the time-domain reflection coefficients of single-cycle pulses from a magnetoplasma we used empirical coefficients consistent with *Rietveld et al.* [1987] and our experiment. The delay time was taken as 0.5 msecs which corresponds to a 70 km reflection height. The reflection coefficient was assumed to be 0.2.

[9] These predictions were tested in a set of experiments using the HAARP heater in Gakona, Alaska, in a number of campaigns between September 2000 and July 2004. The data presented below were obtained during the period of July 14–31, 2004. During this campaign the heater operated at 3.3 MHz, X- mode with power 960 kW and ERP 73 dBW. Since near field effects are primarily of interest, the ELF/VLF data were recorded at a diagnostic trailer site located 12 km away from the heater. The magnetic fields were measured with EMI BF-6 sensors oriented along the magnetic NS and EW directions. The sensor output was digitized at 24-bit resolution with 96 kHz sampling frequency, giving temporal resolution of 10 μsec. Figures 1 and 2 show the NS component of the magnetic field, measured on the ground.

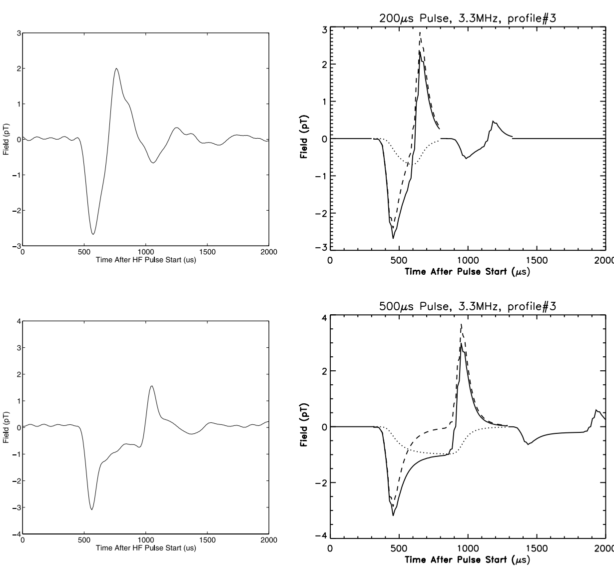

Figure 2. Same as Figure 1, except for pulse lengths 0.2 msec (top) and 0.5 msec (bottom).

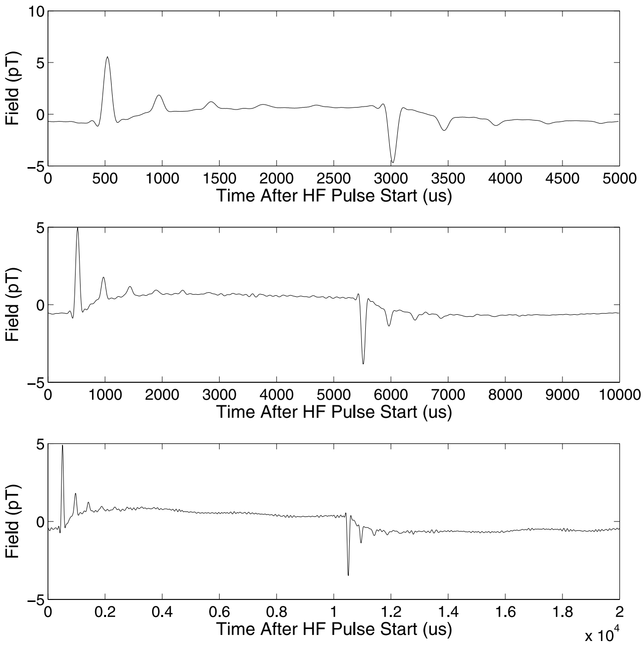

Figure 3. Magnetic response for pulse lengths 2.5, 5, and 10 msec. Note that the dominant flux corresponds to a square pulse due to J. The contributions of the time derivative term and the reflections are very small.

[10] Figures 1 and 2 show both the measured (left column) and predicted magnetic field on the ground (right column) for an X-mode heating pulse with an HF frequency of 3.3 MHz, a power of 960 kW, and an ERP of 73 dBW for Hall conductivity modification. The pulse lengths shown in Figures 1 and 2 are T = 0.05, 0.1, 0.2 and 0.5 msec. The nighttime disturbed ionosphere [*Barr and Stubbe*, 1984, profile #3] was used in the computations. For these parameters the numerical code indicates that the heating reaches steady state at approximately 0.125 msecs., while it cools on an approximate millisecond timescale. In Figures 1 and 2 the overall predicted magnetic field is shown by the solid traces, the component due to $\partial J/\partial t$ by the dashed traces, and the component due to J by the dotted traces. The most important feature is that the amplitude of the $\partial J/\partial t$ term is more than a factor of 3–4 larger than the second term. Furthermore the magnetic flux due to the first term will be dominant for pulse lengths 6–8 times longer than the width of the first term. In comparing Figures 1 and 2 with *Rietveld et al.* [1987, Figures 1 and 2] we see that the response proportional to the current (dotted traces) is completely absent. From their paper it is difficult to determine whether it was due to lack of resolution and/or high noise.

[11] All of the features shown in left-hand columns of Figures 1 and 2 are quite apparent in the right-hand columns, and are significantly different than those previously presented in the literature. We should mention that the above magnetic structure was observed under widely different experimental conditions.

3. Magnetic Waveform vs. Pulse Length

[12] The magnetic field waveform as a function of the pulse length was studied experimentally and compared with theoretical predictions. Figures 1 and 2 show the measured and theoretical waveforms for pulse lengths shorter than 1 ms, while Figure 3 shows the measured waveforms for pulse lengths larger than 1 ms. A number of important conclusions can be drawn from Figures 1–3:

[13] 1. The maximum amplitude grows monotonically with time and saturates asymptotically for pulse lengths close to $T_h \approx 0.25$ msec. This of course is due to the fact that the temperature as well as the level of conductivity modulation is smaller than at saturation.

[14] 2. The magnetic component driven by the current is negligible for pulses shorter than 0.25 msecs, and starts contributing for pulses longer than 0.5 msecs.

[15] 3. The ratio of the maximum amplitude of the two contributions is approximately $B_1/B_2 \approx 3-4$.

[16] 4. The contributions to the magnetic flux of these two components become approximately equal for pulse lengths T $\approx (B_1/B_2)^2 T_h/2 \approx 1.5$ msec.

[17] 5. For pulse lengths much longer than 1 msec the response is essentially that of a square pulse with the addition of a large initial impulse and impulses with diminishing amplitude at multiples of 0.5 msec.

4. Implications of Results for Near-Zone HF to ELF/VLF Conversion Efficiency

[18] The above results can be applied directly to resolve many puzzling features associated with the HF to ELF/VLF near-zone conversion efficiency and level of harmonics shown by *Rietveld et al.* [1989, Figure 8]. Consider generation of ELF/VLF waves by square pulses with pulse length T and duty cycle 50%. Such a process will generate a frequency of $f = 1/2T$. Following the previous results and the heating parameters discussed above that are very similar to the ones used in Tromso, we have:

[19] 1. For $T > 1$ msec or equivalently for $f < 500$ Hz, square pulse heating will deliver a square waveform with amplitude approximately 0.20–0.25 of the maximum of the impulse. As a result the near zone field will be independent of frequency and its power 12–14 dB lower than the peak power. Rich frequency structure is also expected and seen in this frequency range, composed of a broadband component due to the initial impulse and a set of periodic components due to the reflections, in addition to the ones associated with square pulse shape.

[20] 2. As the ELF/VLF frequency increases the contribution from the initial impulse response increases the average power by approximately $(B_1/B_2)^2(T_h/T)/2 \sim f$. This continues till $f \approx 1/2T_h \approx 2$ kHz at which point the contribution of the component due to J becomes negligible and the amplitude of the impulse response reaches maximum due to temperature and conductivity saturation. While harmonic structure is expected between 0.5–1.0 kHZ, at frequencies $f \geq$ kHz where the impulse response dominates, the harmonics are expected to be small, consistent with observations.

[21] 3. For pulse lengths T between 0.01–0.25 msecs corresponding to frequencies between 2.0–5.0 kHz the value of the field changes slowly with pulse length giving an essentially flat response with frequency. At this frequency range the conversion efficiency maximizes.

[22] 4. For the 2–6 kHz range, as noted by *Rietveld et al.* [1987], the component due to ionospheric reflection adds

positively to the next pulse for frequencies that are multiples of $1/T_r \approx 2$ kHz and negatively for frequencies in-between, thus creating the observed max-min structure. The role of the reflection is maximal at the first multiple, which depending on the ionospheric density profile, could be between 2 and 4 kHz. Very weak harmonics are expected or seen in this range.

[23] 5. For pulse lengths $T \ll T_h$ the temperature, conductivity and the value of B_1 at the end of the pulse varies linearly with T (Figure 1), and the conversion efficiency varies as $1/f$ consistent with *Rietveld et al.* [1989, Figure 8].

[24] An important result of our study, besides presenting the correct Green's function magnetic response of the ionosphere to pulsed heating and explaining the conversion efficiency puzzles associated with *Rietveld et al.* [1989, Figure 8], is the recognition that the efficiency maximizes for $f \approx 1/2T_h$. When the HAARP facility is completed as planned in 2007, its output power capability will have increased from 0.96 MW to 3.6 MW which, along with full frequency coverage and higher ERP, would permit us to use optimal frequency and ERP combinations as well as array scanning to improve the generation efficiency of ELF/VLF in the frequency range below 1 kHz and above 10 kHz. The results of an ongoing study will be published elsewhere.

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