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VLF-HF HEATING OF THE LOWER IONOSPHERE AND ELF WAVE GENERATION

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Abstract. For incident wave power densities of $10^{-6}-10^{-2}$ W/m^2 (at 30 km altitude), VLF heating of the D-region ($<$ 90 km) is found to be 2-10 times more effective (depending on power) than HF heating, resulting in comparable perturbations of subionospheric VLF probe waves in spite of up to 10^3 times larger power density utilized in HF heating and at least as efficient in ELF wave generation. In view of generally larger (100×100 km) areas of the ionosphere illuminated by VLF transmitters, ELF wave generation by modulated VLF heating is estimated to produce ELF power levels of $\sim$100 mW, comparable with or larger than those produced in typical HF heating experiments. ELF wave generation in a typical midlatitude ambient ionosphere occurs primarily via the modulation of Pedersen current whereas in a typical auroral ionosphere Hall current is dominant for pump wave frequencies up to $\sim$6 MHz. For 10-30 MHz and power densities $> 10^{-4}$ W/m^2, Pedersen current modulation is again dominant, potentially providing up to 2-15 times higher ELF dipole moment than those found in recent experiments using 3-5 MHz heaters.

1. Introduction

The possibility of ionospheric heating by VLF radio waves from ground-based transmitters was discussed by *Galejs* [1972*a*] and the generation of ULF waves by modulated VLF heating was demonstrated in an early experiment [*Kopytenko et al.*, 1977].

Recent observation of ionospheric heating by VLF waves during a controlled wave-injection experiment with a 100 kW, 28.5 kHz transmitter [*Inan*, 1990] has raised the question of the relative efficiency of heating by VLF versus the traditional HF waves used in past experiments [*Barr and Stubbe*, 1991 and references therein]. The experimental detection of VLF heating has been via its effect on a subionospheric probe VLF signal [*Inan*, 1990], with the observed signal perturbation being comparable to HF heating effects [*Barr et al.*, 1985] measured by VLF probe waves in spite of $\sim 10^3$ times higher wave power densities for HF [*Dowden and Adams*, 1991].

In this paper, we present a comparative analysis of ionospheric heating and ELF wave generation by VLF to HF waves based on a general formulation of the radiowave absorption and a standard formulation of the transfer of the absorbed wave energy to the electrons [*Maslin*, 1974]. The efficiency of VLF versus HF heating for ELF generation via modulation of ambient ionospheric currents induced by a ground-based 'heater' is investigated using a simple model [*Papadopoulos et al.*, 1990] of the total current moment due to the heating.

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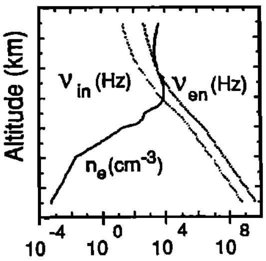
2. Heating of electrons and conductivity modulation

For heater wave power densities P_d at 30 km altitude (reference level) $< 10^{-2}$ W/m^2, the enhancement of the effective electron collision frequency ν_{en} is low enough so that $\nu_{en} \sim v^2$ where v is the electron thermal velocity, and the electron distribution function can be assumed to remain a Maxwellian [*Inan et al.*, 1991; *Papadopoulos et al.*, 1990]. The modified $\nu_{en} = (\nu_0/2) + [(\nu_0/2)^2 + 2\nu_0 U/3Gn_e k_B T_n]^{\frac{1}{2}}$, where ν_0 is the ambient ν_{en}, U is the absorbed wave power, $G \simeq 1.3 \times 10^{-3}$ is the fraction of electron energy lost per collision, n_e is electron density, k_B is Boltzman's constant, and T_n is ambient temperature of electrons [*Maslin*, 1974].

The International Reference Ionosphere [*Rawer et al.*, 1978] and the MSIS neutral atmosphere model [*Hedin*, 1987] are adopted in the 80 to 150 km altitude range. Typical exponential nighttime profiles are assumed for n_e and ν_0 for altitudes <80 km. The magnetic dip angle and the electron gyrofrequency are respectively assumed to be 75° and 1.15 MHz (constant with height), with the wave propagating vertically upward. The scale height for n_e and ν_0 were taken to be H_n = 2.86 km for 60-80 km and H_n = 8.21 km for < 60 km [*Galejs*, 1972*b*, p.28-30] and H_ν = 6.66 km for < 80 km [*Wait and Spies*, 1964]. The ambient temperature of the electrons varies from 200° to 700° K depending on altitude [*Galejs*, 1972*b*]. The model profiles used in the calculations are shown for reference in Figure 1 and correspond to a typical midlatitude nighttime ionosphere.

The self absorption of the upward propagating radio wave [*Gurevich*, 1978] is accounted for by using the absorbed wave power $U(h)$ at each altitude in the calculation of the refractive index μ at the next altitude, using altitude increments of 0.2 km. $U(h)$ is calculated using the WKB approximation [*Maslin*, 1974] and μ is calculated using general magnetoionic theory including electrons and ions. The wave polarization is



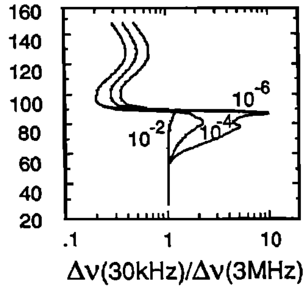


Fig. 1. (Left.) Ambient midlatitude ionospheric profiles for the electron density (n_e), the electron-neutral (ν_{en}) and ion-neutral (ν_{in}) collision frequencies.

Fig. 2. (Right.) Ratio of collision frequency changes at VLF and HF, i.e., $\Delta\nu_{en}$(30 kHz)/ $\Delta\nu_{en}$(3 MHz) for 10^{-6}, 10^{-4}, and 10^{-2} W/m^2 heater power densities.

assumed to be linear, with the wave field components being horizontal, i.e., perpendicular to the direction of propagation (upward). The evolution of μ and the absorbed wave power between each altitude increment is determined separately for the two circularly polarized components (i.e., o-mode and x-mode) that constitute the linearly polarized wave, with the total heating being a superposition of that due to each component.

The reflection of the upgoing heater wave is not accounted for in our formulation. We estimate that the reflection will only result in a 1-4 km change in the altitude of maximum heating and 10-30 % overestimate of the magnitude of heating by VLF and MF (< 800 kHz) heaters. In view of the uncertainties already involved in the ambient ionospheric models, the main conclusions of the paper would not be affected.

We assume that the ELF power generated (P_{ELF}) [*Papadopoulos et al.*, 1990] is given by

$$P_{ELF} \sim [L^2(E \int_0^{h_{max}} \Delta\sigma(h)dh)]^2 \equiv (L^2\Sigma)^2 \equiv M^2 \qquad (1)$$

where $\Delta\sigma(h)$ is the change in the conductivity tensor, L is the transverse dimension of the heated region, h_{max}=150 km, and the ambient d.c. electric field was assumed constant ($E \sim 20$ mV/m) so that P_{ELF} is dependent only on $\Delta\sigma(h)$.

3. VLF (30 kHz) versus HF (3 MHz) Heating and Subionospheric VLF Probing

Figure 2 shows the ratio of computed $\Delta\nu_{e_n}$ for 30 kHz and 3 MHz for $P_d = 10^{-6}$, 10^{-4}, and 10^{-2} W/m^2. We find that (*i*) VLF heating dominates over HF up to ~90 km altitude and (*ii*) maximum VLF heating occurs near the nighttime reflection height of subionospheric VLF probe signals (~85 km) [*Wait and Spies*, 1964] suggesting that VLF probe signals could be highly sensitive indicators of such heating.

We compare the influence of VLF and HF heater waves on VLF subionospheric probe waves in the context of two examples: 1) HF heater wave at 2.8-MHz, 1 to 5 mW/m^2 power density and a 12.1-kHz probe wave (*Barr et al.* [1985] experiment), with $n_e(h)$ similar to profile 1 from *Barr and Stubbe* [1984*b*]; 2) VLF heater wave at 28.5-kHz, 5-10 μW/m^2 power density, and a 24.0-kHz probe wave (*Inan* [1990] experiment), with an $n_e(h)$ appropriate for midlatitudes (Figure 1). The comparison of these two experiments was also the subject of the *Dowden and Adams* [1991] paper.

The first order effect of the ionospheric heating on VLF probe waves is a change in effective reflection height as defined in *Inan* [1990] or in the height-integrated (up to the reflection height) absorption. We find that despite the ~1000 times higher P_d of the HF heater, the VLF heater produces approximately the same incremental absorption (0.4-2 dB) and comparable changes in reflection height (0.8-1.4 km for VLF and 2.8-3.5 km for HF) of the VLF probe wave. For some parameter regimes (ionospheric model, P_d) the VLF heater produces even stronger amplitude disturbances than the HF one. The higher sensitivity of the VLF probe signal to VLF rather than HF heating is primarily due to the fact that the HF heater wave deposits a smaller percent of its power in the lower ionosphere whereas the VLF heater induced disturbance is maximized near the subionospheric VLF reflection height.

While it is clear that the effect of the modified ionospheric spot on a propagating subionospheric VLF probe wave will in general depend on the waveguide mode structure and great circle path length [*Poulsen et al.*, 1990], the simple estimate above clearly demonstrates that a VLF probe wave is substantially more sensitive to ionospheric heating at VLF than at HF. In this connection, we also note that 3-dimensional multiple waveguide mode modeling of subionospheric VLF propagation in the presence of VLF-heater produced disturbances as applied to the *Inan* [1990] experiment revealed amplitude changes comparable to those measured, as discussed in a separate paper [*Inan et al.*, 1992].

4. Frequency and Power Dependence of ELF Generation

Figures 3 *a*,*b* show the dependence of M on the heater wave frequency for P_d at 30 km altitude of 10^{-6} to 10^{-2} W/m^2 for both Pedersen (darker curves) and Hall (lighter curves) current modulations. Results for 10^{-6}-10^{-4} W/m^2 are similar, being relatively flat from 1 kHz to 2 MHz and exhibiting a mild local maximum at a frequency f_{max} somewhat above the gyrofrequency (1.15 MHz). Results for 10^{-3} and 10^{-2} W/m^2 show a stronger maximum at $f_{max} \simeq 4$ and 7 MHz respectively, and a comparable value for low VLF frequencies.

For the midlatitude ambient profiles adopted here (Figure

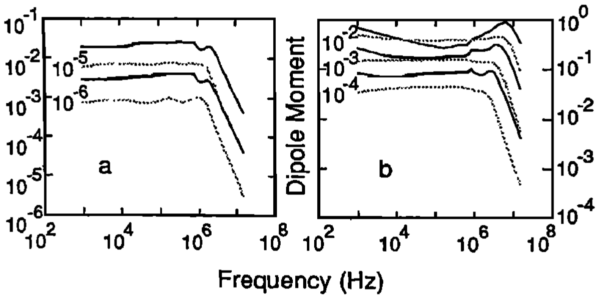


Fig. 3. (*a*). Normalized dipole moment M (A-km/km^2) of generated ELF currents as a function of heater wave frequency for wave power densities of 10^{-6} and 10^{-5} W/m^2 at 30 km altitude. (*b*). Normalized dipole moment M (A-km/km^2) of generated ELF currents as a function of heater wave frequency for wave power densities of 10^{-4}, 10^{-3}, and 10^{-2} W/m^2 at 30 km altitude.

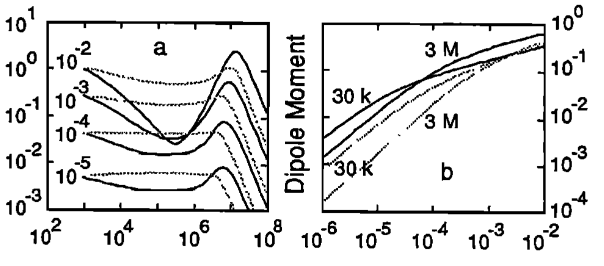


Fig. 4. (*a*). Normalized dipole moment M (A-km/km^2) of generated ELF currents as a function of heater wave frequency for wave power densities of 10^{-5}, 10^{-4}, 10^{-3}, and 10^{-2} W/m^2 at 30 km altitude. (Auroral ionospheric model.) (*b*). Normalized dipole moment M (A-km/km^2) of generated ELF currents as a function of heater wave power density at 30 km altitude for heater wave frequencies of 30 kHz and 3 MHz. (Midlatitude ionospheric model).

1) Pedersen current modulation produces in general higher M than Hall current modulation, in contrast to the results of *Barr and Stubbe* [1984*b*] at auroral latitudes (i.e., a denser ambient D-region) who found the Hall current to be dominant for ELF generation by ~3 MHz waves and for $P_d \sim 10^{-2}$ W/m^2. The determination of the dominant modulated current direction is important since this effects the radiation pattern of the ionospheric antenna and hence the polarization of the wave fields as might be observed in ground-based experiments.

To compare the role of Hall versus Pedersen currents in ELF generation, we note that RF heating (increased ν_{en}) results respectively in a reduction and enhancement of the Pedersen conductivity at altitudes where $\nu_{en} > \omega_H$ (ω_H being the electron gyrofrequency) and $\nu_{en} < \omega_H$ which leads to a partial self cancellation of the height integrated ELF Pedersen currents [*Barr and Stubbe*, 1984*b*]. However, the absolute value of the local ELF Pedersen currents is higher than the ELF Hall currents in both limiting cases of $\nu_{en} \ll \omega_H$ and $\nu_{en} \gg \omega_H$. Thus it is to be expected that the Pedersen current be dominant over the Hall current in ELF generation for some ranges of heater wave frequency and P_d.

To confirm that this effect is not a peculiarity of the chosen ionospheric model and to make a direct comparison with *Barr and Stubbe* [1984*b*], we performed calculations of generated ELF dipole moments for an auroral ionospheric nighttime model similar to that marked as 1 in *Barr and Stubbe* [1984*b*]. The results are presented in Figure 4*a* and agree well with their results for the 2.76 MHz heater employed in the Tromsø experiments, for which the modulation of the Hall current is the dominant source of ELF. However, a more interesting general conclusion is apparent from Figure 4*a*. The Pedersen current modulation rapidly becomes dominant with increasing frequency beyond a threshold that depends on P_d. For $P_d \sim 10^{-2}$ W/m^2, (appropriate for the Tromsø 'super heater' facility [*Barr and Stubbe*, 1991]), an 11 MHz heater wave would be ~100 % more efficient than a 5.4 MHz heater in terms of stimulated ELF current dipole moment, or in accordance with (1), ~300 % more efficient in terms of the total radiated ELF power. For the daytime ionospheric models of *Barr and Stubbe* [1984*b*] which have several times higher plasma density, the P_{ELF} for an optimal heater wave frequency ~25 MHz is predicted to be a factor of 30 larger than that produced at the 5.4 MHz frequency used in the *Barr and Stubbe* [1991] experiment.

The dependence of M on P_d for typical VLF (30 kHz) and HF (3 MHz) heater waves are compared in Figure 4*b* and shows increasing M with P_d, as recently observed [*Barr and Stubbe*, 1991]. This agreement with data suggests that even for $P_d > 10$ mW/m^2 in the D-region, our assumptions of $\nu_{en} \sim v^2$ and $\nu_{en} = (\nu_0/2) + [(\nu_0/2)^2 + 2\nu_0 U/3Gn_e k_B T_n]^{\frac{1}{2}}$ (i.e., *Maslin* [1974] formulation) are appropriate.

5. Summary and Discussion

On the basis of the results presented above we conclude that:

- VLF waves are at least as efficient as HF waves in heating lower ionospheric electrons, although the altitude of maximum heating depends sensitively on heater frequency for lower P_d ($\leq 10^{-5}$W/m^2 at 30 km). For such relatively low P_d, heating at VLF (e.g., 30 kHz) leads to ~10 times larger temperature changes at altitudes < 90 km than can be produced at HF (e.g., 3 MHz), thus accounting for the relatively easy detection of ionospheric effects of VLF heating using subionospheric VLF probing [*Inan*, 1990]. Quantitative estimates of VLF probe wave amplitude changes in response to ionospheric heating show similar amplitude changes for typical reported parameters of VLF and HF heating experiments in spite of ~10^3 times higher heater wave power density for HF.
- VLF heating is at least as efficient as HF heating in terms of generated ELF power per unit wave power density incident on the lower ionosphere.
- Modulation of the Pedersen conductivity is the dominant means of ELF generation for a midlatitude ambient ionosphere (Figures 1). For typical auroral ambient ionospheres [*Barr and Stubbe*, 1984*b*] the Hall current is dominant for heater frequencies up to ~ 5 MHz, including those frequencies and power levels used in previous HF experiments at Tromsø [*Barr and Stubbe*, 1991, and references therein]. However, our results indicate that up to 4-30 times higher ELF power than for the case of 4 MHz heater would result from ELF Pedersen current modulation for higher frequency (10-30 MHz) heater waves, suggesting that future HF heater facilities be designed to be capable of operation at 10-30 MHz.

In assessing the practical use of VLF versus HF heating for ELF generation, we need to also consider the size of the heated spot in the ionosphere. Operational VLF communications transmitters generally use vertical monopole antennas [*Watt*, 1967] which radiate most of their power into the earth-ionosphere waveguide. The effective size of the heated spot in this case may be ~100 ×100 km. From Figure 4*b* we conclude that $\Sigma \sim (P_{RF}/L^2)^\alpha$, where P_{RF} is the transmitter radiated power and $\alpha < 1$, similar to the dependence found by *Barr and Stubbe* [1991]. Using this dependence and (1) we have [*Papadoupoulos et al.*, 1990]:

$$P_{ELF} \sim P_{RF}^{2\alpha} \times L^{4(1-\alpha)} \tag{2}$$

Since, M is almost independent of frequency at midlatitudes (see Figure 3) and a VLF transmitter illuminates a larger area of the ionosphere, (2) shows that a VLF heater would generate more ELF power per unit of radiated power than an HF heater. In previous work concerning HF heating, P_{ELF} for 200-500 Hz was found to be 10-100 mW for a normalized dipole moment $M = 5 \times 10^4$ A-m [*Barr and Stubbe*, 1984*a*]. An approximate evaluation of P_{ELF} can be made assuming similar proportionality between M and P_{ELF}. For example, for the nighttime subauroral ionosphere with a 20 mV/m ambient electric field perpendicular to the magnetic field lines and for a VLF transmitter that illuminates a 100 × 100 km region of the ionosphere at 70 km altitude with ~10 μW/m^2, the ELF (~ 300 Hz) power generated is found to be ~ 100 mW.

In terms of common configurations of VLF transmitters and HF heating facilities, it is also important to note that in the case of the former the heater waves are necessarily linearly polarized, whereas for HF all of the available radiated power can be placed in one of the two circular polarizations. Since the wave polarization primarily affects the altitude of maximum heating [*Inan*, 1990], and since we have assumed linear polarization in all our VLF versus HF comparisons, the relative efficiency of heating at any given altitude (i.e.,

$\Delta\nu(VLF)/\Delta\nu(HF)$) can potentially be different by a factor of not more than two from the estimates given here. For example, calculations indicate that for linearly polarized VLF and circularly polarized HF heater waves with the same power density, the maximums of $\Delta\nu(VLF)/\Delta\nu(HF)$ ratio are <35% lower than those presented in Figure 2.

The generated ELF radiation estimates are based on an integral of $\Delta\sigma(h)$ over altitude, and should thus be relatively less sensitive to the polarization of the heater wave. However, due to the self absorption effect, the evolution of the wave with height is dependent on P_d and separate calculations of ELF generated by purely o-mode (or x-mode) HF waves would need to be done for accurate estimates.

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