D71 N82 22747

MICROWAVE HEATING OF THE LOWER IONOSPHERE

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The SPS microwave power beam is sufficiently intense to cause large changes in the properties of the lower ionosphere by ohmic heating of the plasma. Although the fraction of power that is absorbed from the beam is very small, it is comparable to the solar heating rate of the neutral gas. Power is absorbed from the beam at a rate that is proportional to the product of the electron density n_e and the electron-neutral collision rate ν, and the ratio of the intensity S to the square of the microwave frequency f. The peak absorption occurs at an altitude where n_e is a maximum. During the day, this is between 75 to 105 km, depending on the time-of-day, season, and solar activity. The maximum ohmic loss rate Q_{max} is approximately

$$Q_{max} \simeq 4 \times 10^{-7} \ (\nu n_e / 3.9 \times 10^9 \ s^{-1} \ cm^{-3})$$
$$\times \ (S/23 \ mW \ cm^{-2})(f/2450 \ MHz)^{-2} \ ergs/s - cm^{-3}$$

using representative values for ν and n_e at 100 km. For comparison, the neutral heating rate is about 9.8 X 10^{-7} ergs/s-cm^{-3}.[1] Since the microwave absorption is almost one-half of the solar heating, major changes can be expected in the properties of the D and E-layers of the ionosphere.

This paper addresses the development of a predictive model of the underdense interaction of an electromagnetic beam and the lower ionosphere. The interaction is considered to be underdense if the electromagnetic frequency exceeds the maximum plasma frequency throughout the ionospheric region of interest. A self-consistent fluid theory formulation of underdense heating, incorporating the latest information on electron cooling and electron-temperature-dependent reaction rates, has been used to estimate the expected changes in the lower ionosphere due to the SPS beam. A computer code has been developed to integrate the coupled equations for power density, electron temperature, and electron density as a function of altitude and time for both time-varying and steady heating fluxes. The principal electron cooling mechanisms are: (1) rotational excitation of N_2 and O_2; (2) vibrational excitation of N_2 and O_2, and (3) excitation of ^3P fine structure ground state levels of O. At the base of the D-region, namely at altitudes of 50-75 km, the density will decrease[2] due to an increase in the electron-temperature-dependent attachment rate to molecular oxygen. Above 85 km, the density will increase as a result of sustained heating due to a reduction in the recombination rate of O_2^+ and NO^+.

The absorption coefficient and the corresponding ohmic loss are both inversely proportional to the square of an effective frequency f_e defined by

$$f_e = f[(1 \pm f_B/f \cos\theta)^2 + (\nu/2\pi f)^2]^{1/2} \qquad (1)$$

in terms of the gyrofrequency f_B, θ the angle between the propagation direction and the magnetic field, and ν an effective Appleton-Hartree collision frequency. It can be seen from (1) that unless $(f_B/f)\cdot\cos\theta \ll 1$ and $(\nu/2\pi f) \ll 1$, ohmic loss and absorption will not scale simply as $1/f^2$. In general, the scaling from SPS to HF frequencies is quite complicated and nonlinear since an increase in temperature changes ν and thus f_e. The scaling is further complicated by the fact that the absorption coefficient is directly proportional to

n_e and thus depends on the ambient D and E layer electron density distributions.

The fluid theory results can be used to predict the effects of the SPS beam on the ionosphere and to judge to what extent the Platteville and Arecibo experiments simulate SPS conditions. The predicted changes in electron temperature and density for the SPS peak reference flux of $23 mW/cm^2$ are shown in Fig. 1 and compared with the estimated changes for the Platteville facility operating at 5 MHz X-mode with an effective radiated power of 102MW. It can be seen that Platteville is capable of simulating or exceeding the effects of the SPS beam over a 30 km altitude range, centered near 70 km. A detailed examination of the frequency scaling implied in Eq. (1), the absorption, and the reduction in flux due to spherical spreading shows why Platteville cannot simulate the effects of SPS heating over a larger altitude range. The effective frequency increases below 65 km due to electron-neutral collisions thus reducing the flux below SPS equivalent levels and the combination of nonlinear absorption and spreading loss limit the flux above 95 km. Nevertheless, Platteville will simulate SPS conditions throughout a major portion of the D-layer. In this portion of the lower ionosphere, the electron density will be decreased, rather substantially, after several seconds of heating due to an increase in the electron-temperature-dependent three-body molecular oxygen attachment rate.

The electron temperature generally reaches steady-state in less than one second but the density increases build up on a much longer time scale. The changes shown in Fig. 1b are after 10 minutes of heating. It is unlikely that sustained heating will take place on a longer time scale since the neutral winds convect the plasma across the beam at speeds of 10-30m/s.

The fluid theory estimates of the expected electron temperature increase assume that the energy distribution is Maxwellian. This is questionable since the degree of ionization in the D and E regions is too low for electron-electron collisions to thermalize the population. Following the approach of Engelhart and Phelps[3], we have also developed a kinetic theory estimate by numerically solving the Boltzmann equation appropriate to ac heating of slightly ionized air. The integro-differential Boltzmann equation is solved parametrically in E/N and ω/N, where N is the total neutral density, $\omega/2\pi$ is the heating wave frequency and E is the rms electric field. If ω is much greater than the electron collision and gyro frequencies, then the energy gain per electron and the form of the distribution function depend on the effective electric field E/ω and the neutral composition but not the total density

The results of the kinetic theory computations are shown in Figs. 2a and 2b. For a flux of $23 mW/cm^2$, the temperature increase is between a factor of two to three times ambient. The relative importance of the various electron cooling mechanisms is shown in Fig. 2b. At 115 km, the standard concentration of atomic oxygen is about 1.5 times that of molecular oxygen and as a result, a significant fraction of the energy is dissipated in $O(^3P)$ fine structure excitation.

The agreement between fluid and kinetic theory is quite good for a microwave flux of 23mW/cm^2. With a power flux of 46mW/cm^2, fluid theory predictions significantly overestimate the electron temperature increase by as much as 120°K.

A comparison of the fluid theory predictions and the Arecibo 430 MHz incoherent scatter radar experiments (Fig. 3) validate the E-layer electron temperature predictions. The difference between theory and experiment at 95 km (and below, not shown) is thought to be due to the interpretation of the incoherent backscatter measurements of electron temperature (cf. presentation by L. M. Duncan,[4] and F. T. Djuth[5] in these proceedings).

The following conclusions can be drawn from the theoretical results: (1) kinetic and fluid theory estimates for SPS flux levels agree and predict a factor of 2-3 increase in electron temperature; (2) the E-layer predictions are validated by the 430 MHz Arecibo radar heating experiments and recent HF Arecibo measurements also validate the D-layer results; (3) Platteville, operating at 5 MHz X-mode simulates or exceeds SPS effects over most of the D-layer; (4) electron density decreases of up to 50 percent can be expected below 80 km and increases of up to 20% can be expected in the E-layer.

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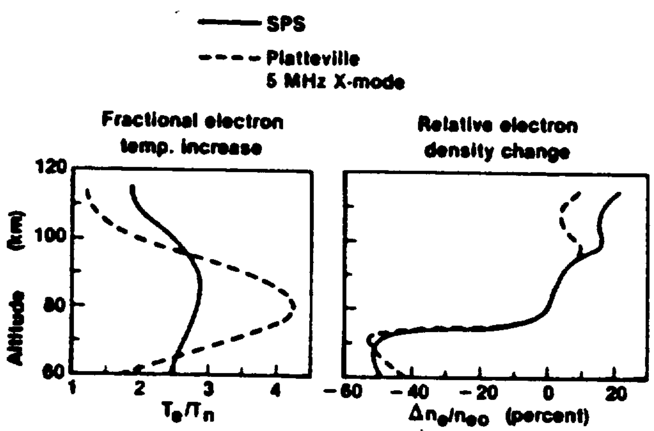

Fig. 1a Fig. 1b

Daytime D&E Layer Modification

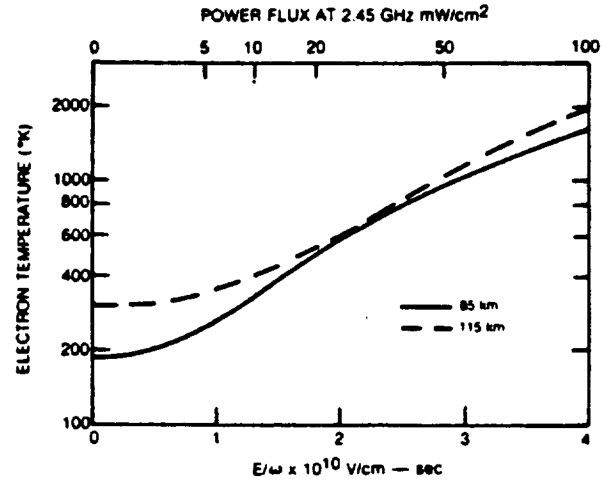

Fig. 2a Electron Temperature as a Function of Effective Field and Power Flux

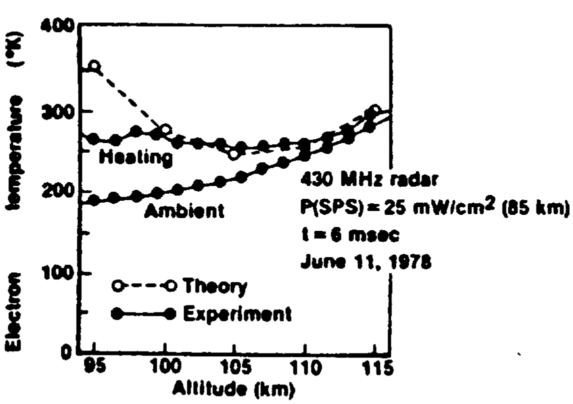

Fig. 3 Arecibo Electron Heating Observations

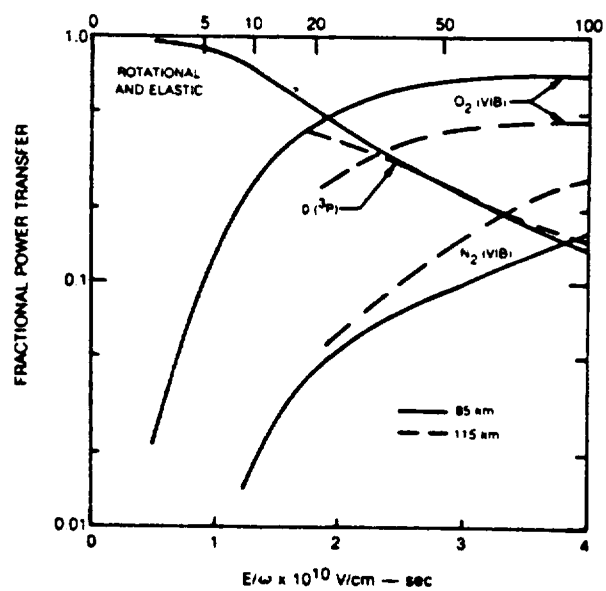

Fig. 2b Electron Cooling Mechanisms