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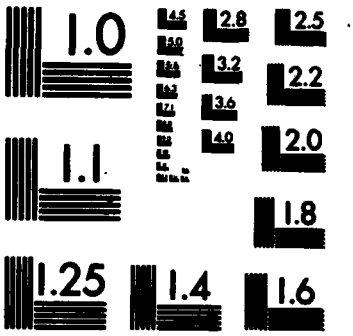

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ARTIFICIAL IONOSPHERIC DISTURBANCES CAUSED BY POWERFUL RADIO WAVES

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ABSTRACT

Artificial ionospheric disturbances evidenced as fluctuations in plasma density and geomagnetic field can be caused by powerful radio waves with a broad frequency band ranging from a few KHz to several GHz. The filamentation instability of radio waves can produce both large-scale plasma density fluctuations and large-scale geomagnetic field fluctuations simultaneously. The excitation of this instability is examined in the VLF wave injection experiments, the envisioned MF ionospheric heating experiments, the HF ionospheric heating experiments and the conceptualized Solar Power Satellite project. Significant geomagnetic field fluctuations with magnitudes even comparable to those observed in magnetospheric (sub)storms can be excited in all of the cases investigated. Particle precipitation and airglow enhancement are expected to be the concomitant ionospheric effects associated with the wave-induced geomagnetic field fluctuations.

I. INTRODUCTION

Manifest ionospheric disturbances may be produced by powerful radio waves such as fluctuations in ionospheric density, plasma temperature, and the earth's magnetic field (see e.g., Fejer, 1979; Stubbe et al., 1982). Among them, we single out for discussion the excitation of ionospheric density irregularities and the geomagnetic field fluctuations. The interesting finding in our theoretical analyses is that the geomagnetic field fluctuations may be excited simultaneously with large-scale field-aligned ionospheric irregularities by radio heater waves. The frequencies of radio heater waves may be as low as in the VLF band and as high as in the SHF band.

Unexpectedly large perturbations in the earth's magnetic field (~10.8γ) were observed in the Tromsø HF ionospheric heating experiments (Stubbe and Kopka, 1981; Kuo and Lee, 1983). Transmitters operated at frequencies close to but less than the local electron gyrofrequency are expected to cause both plasma density fluctuations and geomagnetic field fluctuations in the ionosphere if MF signals are transmitted or in the magnetosphere if VLF signals are injected, instead (Lee and Kuo, 1984). Microwave transmissions at the conceptualized power density (230 W/m^2) from the Solar Power Satellite (SPS) are also expected to perturb the earth's magnetic field significantly in the ionosphere along the beam path. Our studies, therefore, add an additional effect to those that should be assessed as the possible environmental impact of the SPS program.

The formulation of the theory is first presented in Section I. In the subsequent four sections (i.e., Sections III-VI), we discuss the excitation of the instability in the VLF wave injection experiments, the envisioned MF ionospheric heating experiments, the Tromsø HF ionospheric heating experiments, and the conceptualized Solar Power Satellite program, respectively. The conclusions are finally drawn in Section VII with a brief discussion.

II. THEORY

For simplicity, radio waves are assumed to be circularly polarized propagating along the earth's magnetic field. This is a reasonable assumption for the VLF wave injection experiments and the Tromsø HF ionospheric heating experiments. As for the microwave propagation, the geomagnetic field imposes a relatively immaterial effect. If the positive z axis of a rectangular coordinate system represents the wave propagation direction and is taken to be parallel to the geomagnetic field, the monochromatic radio wave with frequency, ω_o, and wave vector, k_o, can be represented by $\underset{\sim}{E}_o(\underset{\sim}{r},t) = \mathcal{E}_o(\hat{x} \pm i\hat{y}) \exp[i(k_o z - \omega_o t)] + C.C.$ where the wave field amplitude, $\mathcal{E}_o$, is assumed to be a constant;

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the ± signs designate the right-hand and the left-hand circular polarizations, respectively.

Since the wave field interacts with the charged-particles, the plasmas experience a radiation pressure force (i.e., the nonlinear Lorentz force) and a thermal pressure force. The latter force results from the collisional dissipation of wave energy in plasmas. If the wave field is intense enough, a sideband mode ($\underset{\sim}{\varepsilon}_1$) can be excited together with zero-frequency modes via the filamentation instability, this is similar to the self-focusing instability of a radio wave beam. This high-frequency sideband is a quasi-mode, satisfying the Fourier transform wave equation

$$[k_o^2 + k^2 - \frac{\omega_o^2}{c^2}) \underset{\approx}{1} - k_o^2 \hat{z}\hat{z} - k^2 \hat{x}\hat{x} + ik_o \frac{\partial}{\partial x} (\hat{x}\hat{z} + \hat{z}\hat{x})] \cdot \underset{\sim}{\varepsilon}_1 = i \frac{4\pi\omega_o}{c^2} (\underset{\sim}{J}_\ell + \underset{\sim}{J}_n) \qquad (1)$$

where $\underset{\sim}{\varepsilon}_1 = (\underset{\sim}{\varepsilon}_{1\perp} \cos kx + \hat{z}\, \varepsilon_{1z} \sin kx) \exp(\gamma t)$ is the wave field perturbation with the growth rate, γ, and the filamentation wave vector, $\underset{\sim}{k} = \hat{x}k$; $\underset{\sim}{J}_\ell$ and $\underset{\sim}{J}_n$ represent the induced linear and nonlinear electric current densities. While $\underset{\sim}{J}_\ell$ given by $-en_o\underset{\sim}{V}_1$ results from the linear response of electrons to the sideband field ($\underset{\sim}{\varepsilon}_1$), $\underset{\sim}{J}_n$ includes two parts, $-en_o\underset{\sim}{V}_M$ and $-e\delta n\underset{\sim}{V}_o$, that are nonlinear beating currents caused by the nonlinear coupling between the purely growing mode (δn and $\delta\underset{\sim}{B}$) and the incident wave field ($\underset{\sim}{\varepsilon}_o$). The electron velocity perturbations denoted by $\underset{\sim}{V}_o$, $\underset{\sim}{V}_1$, and $\underset{\sim}{V}_M$, have the following expressions:

$$\underset{\sim}{V}_j = -i\frac{e}{m} \frac{\omega_o}{(\omega_o^2 - \Omega_e^2)} [\underset{\sim}{\varepsilon}_{j\perp} + \hat{z}\,(1 - \frac{\Omega_e^2}{\omega^2}) \cdot \underset{\sim}{\varepsilon}_{jz} + i \frac{\Omega_e}{\omega_o} \hat{z}x\, \underset{\sim}{\varepsilon}_j]$$

where $j = o, 1$ represents the response of electrons to the incident wave field ($\underset{\sim}{\varepsilon}_o$) and the sideband field ($\underset{\sim}{\varepsilon}_1$) respectively;

$\underset{\sim}{V}_M = -i\frac{e}{mc} \frac{\omega_o}{(\omega_o^2 - \Omega_e^2)} [\underset{\sim}{V}_o \times \hat{z} + i \frac{\Omega_e}{\omega_o} \underset{\sim}{V}_o]\delta B$ is the electron velocity perturbation induced by the $\underset{\sim}{V}_o \times \delta\underset{\sim}{B}$ Lorentz force, where M, Ω_e, e, and c have their conventional meanings as the electron mass, the electron gyrofrequency, the electric charge, and the speed of light in vacuum, respectively. Because of the large inertia, the corresponding ion responses have been ignored.

The purely growing mode has the general form of $\delta\tilde{P} = \delta\tilde{P}(\cos kx)\exp(\gamma t)$, that is associated with the excitation of both the plasma density fluctuations (i.e., $\delta\tilde{P} = \delta\tilde{n}$) and the geomagnetic field fluctuations (i.e., $\delta\tilde{P} = \hat{z}\,\delta\tilde{B}$). It is the wave-induced quasi-DC current that gives rise to the magnetostatic fluctuations. This can be seen in the Maxwell equation

$$(k^2 + \frac{1}{c^2} \frac{\partial^2}{\partial t^2}) \delta\underset{\sim}{A} = \frac{4\pi}{c} e N_o (\delta\underset{\sim}{V}_i - \delta\underset{\sim}{V}_e)_y = \frac{4\pi}{c} \delta\underset{\sim}{J}_y \qquad (2)$$

where $\delta\underset{\sim}{A}$ is the vector potential defined by $\nabla\times\delta\underset{\sim}{A} = \delta\underset{\sim}{B}$ and the Coulomb gauge $\nabla\cdot\delta\underset{\sim}{A} = o$ has been chosen in (2). The wave-induced quasi-DC current, $\delta\underset{\sim}{J}_y = en(\delta\underset{\sim}{V}_i - \delta\underset{\sim}{V}_e)_y$, and a relation between δn and δB can be derived from Equation (2), the continuity equation and the momentum equation for both electrons and ions. They are

$$\delta J_y = \frac{en_o}{\Omega_i} \{\frac{F_{ex}}{M} + \frac{\partial}{\partial x} (\frac{\delta T_e}{M}) - [\frac{\gamma(\gamma + \nu_{in})}{k} + kc_s^2](\frac{\delta n}{n_o})\} \qquad (3)$$

$$\text{and } \frac{\delta n}{n_o} = [1 + (1 + \frac{\nu_e}{\gamma}) (\frac{k^2c^2 + \gamma^2}{\omega_{pe}^2})] (\frac{\delta B}{B_o}) \qquad (4)$$

where M, Ω_i, ω_{pe}, c_s, ν_e, and ν_{in} are, respectively, the ion mass, the ion gyrofrequency, the electron plasma frequency, the ion acoustic velocity, the electron-ion collision frequency, and the ion-neutral collision frequency; δT_e is the electron temperature perturbation caused by the collisional dissipation of the radio pump and the excited sideband; and F_{ex} is the x component of the nonlinear Lorentz force

$$\underset{\sim}{F}_e = m\nabla(\underset{\sim}{V}_o^* \cdot \underset{\sim}{V}_1 + \underset{\sim}{V}_o \cdot \underset{\sim}{V}_1^*) + i\frac{\Omega_e}{\omega_o} m \{-ik_o(V_{1z}^*\underset{\sim}{V}_o + V_{1z}\underset{\sim}{V}_o^*) \times \hat{z} + \underset{\sim}{V}_o^* \times [\nabla \times (\underset{\sim}{V}_1 \times \hat{z})] - \underset{\sim}{V}_o \times [\nabla \times (\underset{\sim}{V}_1^* \times \hat{z})]\}$$

It is seen from (3) that the wave-induced quasi-DC current is primarily caused by the F x B drift motion of electrons under the influence of the thermal pressure force, $n_o(\partial/\partial x)\delta T_e$, and the nonlinear Lorentz force, $n_o F_{ex}$. The electron temperature perturbation (δT_e) obtained from the

electron energy equation is found to be

$$\delta T_e = \frac{2}{3} \frac{Q_e + \gamma T_o \delta n}{n_o \bar{\gamma}} \tag{5}$$

where $Q_e = 2\nu_e n_o m (\underset{\sim}{V}_o^* \cdot \underset{\sim}{V}_1 + \underset{\sim}{V}_o \cdot \underset{\sim}{V}_1^*)$ is the wave energy dissipation rate in the electron gas due to the differential Ohmic loss of the incident wave and the excited sidebands, and $\bar{\gamma} = \gamma + 2\nu_e(m/M) + \nu_e k^2 V_t^2/\Omega_e^2$, where V_t is the electron thermal velocity.

Equation (4) shows that the simultaneously excited δn and δB are proportional to each other. In all cases under study, $\nu_e >> \gamma$ and $k^2c^2 >> \gamma^2$. Therefore, Equation (4) can be reduced to

$$\frac{\delta n}{n_o} = [1 + (\frac{\nu_e}{\gamma}) (\frac{k^2c^2}{\omega_{pe}^2})] (\frac{\delta B}{B_o}) \tag{4'}$$

indicating that if $(\nu_e/\gamma)(k^2c^2/\omega_{pe}^2)$ is much greater than unity, the magnetostatic fluctuations $(\delta B/B_o)$ is much less than the plasma density fluctuations $(\delta n/n_o)$. It is thus expected that significant magnetic field fluctuations are associated with the excitation of large-scale (i.e., small k) modes.

The coupled mode equation for the purely growing mode that can be obtained from (2) and (3) with the aid of (5) has the expression of

$$\{(\gamma^2 + k^2c^2) [1 + \frac{m}{M} (1 + \frac{\nu_e}{\gamma}) f + \omega_{pe}^2 f\} \delta B = \frac{8\pi e c k}{3 m \Omega_e \bar{\gamma}} \frac{\partial}{\partial x} Q_e \tag{6}$$

where $f = (\gamma \bar{\nu}_{in} + k^2 c_s^2 + 2\gamma k^2 V_s^2/3\bar{\gamma})$; $\bar{\nu}_{in} = \gamma + \nu_{in}$; ω_{pi} and V_s are the ion plasma frequency and the ion plasma frequency and the ion thermal velocity. It should be mentioned that the nonlinear Lorentz force term $(\underset{\sim}{F}_e)$ has been neglected in (6) because it is negligibly small compared to the differential Ohmic heating force term (Q_e). Substituting (4') into (6) and eliminating δn from (1) and (6) yields the dispersion relation

$$k^2c^2(\gamma + \frac{m}{M} \bar{\nu}_e f) + \gamma \omega_{pi}^2 f$$

$$= 2 (\frac{\omega}{\Omega_e}) (\frac{\omega_{pe}}{\omega_o \mp \Omega_e})^4 (\frac{e\epsilon_o}{mc})^2 [(\frac{\omega_o}{\Omega_e} \mp 1) \bar{\nu}_e \frac{k^2c^2}{\omega_{pe}^2} + \gamma \frac{\omega_o}{\Omega_e}] [$$

$$\frac{4}{3} (\frac{\nu_e}{\bar{\gamma}}) \frac{(4 - q_\pm - P_\pm q_\pm)}{(1 + P_\pm - P_\pm q_\pm)}] \tag{7}$$

where $\bar{\nu}_e = \gamma + \nu_e$; $P_\pm = \frac{\omega_o (\omega_o^2 - \omega_{pe}^2 \mp \omega_o \Omega_e)}{(\omega_o \mp \Omega_e)(\omega_o^2 - \omega_{pe}^2 - k^2c^2)}$ (8a)

and $q_\pm = \pm \frac{k^2c^2(\omega_o^2 - \Omega_e^2)}{\omega_o \Omega_e \omega_{pe}^2}$; (8b)

$P_+(P_-)$ and $q_+(q_-)$ correspond to the right - (left -) hand circularly polarized wave. The threshold field (ϵ_{th}) of the instability is determined from (7) by taking $\gamma = 0$, namely,

$$|\frac{e\epsilon_{th}}{mc}|^2 = 0.75 \frac{(\omega_o \mp \Omega_e)^3}{\omega_o \omega_{pe}^2} \frac{k^2V_t^2 (2\frac{m}{M} + \frac{k^2V_t^2}{\Omega^2}) (1 + P_\pm - P_\pm q_\pm)}{(4 - q_\pm - P_\pm q_\pm)} \tag{9}$$

These characteristics of the instability are discussed separately for different wave frequency regimes of the incident radio waves as follows.

III. VLF WAVE INJECTION EXPERIMENTS

The VLF signals transmitted from the Siple circular polarization (i.e., whistler modes) on

their paths through the neutral atmosphere and into the ionosphere (Kintner et al., 1983). The whistler waves are assumed to satisfy the cold plasma dispersion relation

$$1 - \frac{\omega_{pe}^2}{\omega_o(\omega_o - |\Omega_e|)} = \frac{k_o^2 c^2}{\omega_o^2}$$

in the wave propagation regime: $|\Omega_i| << \omega_o < |\Omega_e|$. Since the positive z axis represents the wave propagation direction and has been taken to be parallel to the geomagnetic field, $\Omega_e > (<) 0$ for the right- (left-) hand circularly polarized wave and thus

$P_+ = P = \omega_o (\omega_o^2 - \omega_{pe}^2 - \omega_o|\Omega_e|) / (\omega_o - |\Omega_e|) (\omega_o^2 - \omega_{pe}^2 - k^2c^2)$ and $q_+ = q = k^2c^2 (\omega_o^2 - \Omega_e^2) / \omega_o|\Omega_e|\omega_{pe}^2$ for a whistler mode.

In the upper atmosphere, the electron plasma frequency is much greater than the electron cyclotron frequency, viz., $\omega_{pe}^2 >> \Omega_e^2 > \omega_o^2$. Therefore, $P \approx - \omega_o\omega_{pe}^2 / (|\Omega_e| - \Omega_o) (\omega_{pe}^2 + k^2c^2) < 0$ and $q = - k^2c^2 (\Omega_e^2 - \omega_o^2)/\omega_o|\Omega_e|\omega_{pe}^2 < 0$. The positive RHS of (8) thus requires the factor, $(1 + P - q)$, to be negative, namely,

$$1 - \frac{\omega_o\omega_{pe}}{(|\Omega_e| - \omega_o)(\omega_{pe}^2 + k^2c^2)} - \frac{k^2c^2(|\Omega_e| + \omega_o)}{(\omega_{pe}^2 + k^2c^2)|\Omega_e|} < 0. \qquad (10)$$

For the excitation of large-scale modes (i.e., $\omega_{pe}^2 >> k^2c^2$), the above inequality leads to $\omega_o > |\Omega_e|/2$. In other words, the filamentation instability of whistler waves that generate both plasma density fluctuations and geomagnetic field fluctuations can only be excited within the narrow frequency range:

$$|\Omega_e| > \omega_o > |\Omega_e|/2 \qquad (11)$$

Since $|\Omega_e| \sim 1.4$ MHz in the ionosphere (e.g., the F region) and $|\Omega_e| \sim 13.65$ MHz in the magnetosphere at L = 4.0, the condition for the instability shown in (11) leads to the following conclusions. The frequencies of VLF signals that are injected in the active VLF wave experiments typically range from a few KHz to a few tens of KHz (<30 KHz). These signals are not expected to cause ionospheric disturbances via the filamentation instability. But those with frequencies larger than 6.83 KHz but less than 13.65 KHz can excite the instability in the magnetosphere at L = 4.0. It is predicted from (11) that ionospheric distrubances caused by the filamentation instability of whistler waves are possible if the wave frequencies are less than $|\Omega_e| \sim 1.4$ MHz but greater than $|\Omega_e|/2 \sim 0.7$ MHz, namely, whistler waves in the MF band can cause large-scale ionospheric density irregularities and geomagnetic field fluctuations in the ionosphere. Quantitative analyses of these two cases are illustrated as follows.

The relevant magnetospheric parameters used in this work include $|\Omega_e|/2\pi = 13.65$ KHz (i.e., $B_o \sim 500$ γ), $\omega_{pe}/2\pi = 179$ KHz, $T_o = 0.4$ ev, and $M(H^+)/m = 1840$. If the VLF wave frequency is 10.9 KHz, i.e., $\omega_o/|\Omega_e| = 0.8$, the threshold field ($\varepsilon_{th}$) calculated from (9) are e.g., 12 μV/m and 2 μV/m for the excitation of modes with scale lengths of 10 Km and 100 Km, respectively. These threshold fields can be exceeded by the injected VLF waves from the Siple station even in the "non-ducted" whistler propagation mode. The growth rates of the instability expressed in terms of the threshold field is obtained from (7) as

$$k^2c^2(\gamma + \frac{m}{M}\bar{\nu}_e f) + \gamma\omega_{pi}^2 f$$
$$= k^2V_t^2(2\frac{m}{M} + k^2\frac{V_t^2}{\Omega_e^2})\frac{2}{|\Omega_e|}\frac{\omega_{pe}^2}{(\omega_o - |\Omega_e|)}|\frac{\varepsilon_o}{\varepsilon_{th}}|^2[\frac{(\omega_o - |\Omega_e|)}{|\Omega_e|}\frac{\nu_e}{\omega_{pe}^2}k^2c^2 + \gamma\frac{\omega_o}{|\Omega_e|}]\frac{\nu_e}{\bar{\gamma}}.$$

This equation can be easily solved for γ under the following assumptions: $\nu_e >> \gamma$, $k^2c_s^2 >> \gamma\bar{\nu}_{in}$, and $m/M >> k^2V_t^2/\Omega_e^2$ that can be confirmed. For large-scale modes, $\omega_{pe}^2 >> k^2c^2$ (i.e., $\lambda >> 1.7$ Km), the growth rate is found to have the following simple expression $\gamma \sim (2\nu_e kV_s/|\Omega_e|)(\varepsilon_o/\varepsilon_{th})$. This growth rate turns out to be independent of the scale lengths because as shown in (9), $\varepsilon_{th} \propto k$. Although the threshold of the instability can be exceeded by the "non-ducted" whistler mode in the

magnetosphere at L = 4.0, the growth rate is rather small ($\sim 10^{-5}$ Hz) if $\epsilon_o/\epsilon_{th} \sim 0(1)$ because of the small electron-ion collision frequency ($\sim$0.1 Hz). However, the ϵ_o/ϵ_{th} of the "ducted" whistler mode may be increased by two to three orders of magnitude though only 20% of the injected VLF waves are found to propagate in the "ducted" whistler mode (Carpenter and Miller, 1976). The growth rate of ducted whistler waves can be as high as (10^{-3} - 10^{-2}) Hz, namely, the instability can be excited by the ducted mode within a few minutes.

For modes with scale lengths >10 Km, $(\delta n/n_o) \simeq (\delta B/B_o)$ from (4'). Presumably, a few percents of magnetospheric density fluctuations are able to be generated. Then, a few percents of geomagnetic field fluctions in the magnetosphere at L = 4.0 is of the order of 10 γ(c.f. the background magnetic field $\sim$ 500 γ), that may significantly affect the orbits of charged particles. The scintillations of the Siple signals received at Roberval, Canada (Inan et al., 1977), may be attributable to the excitation of large-scale plasma density fluctuations in the magnetosphere by the injected VLF waves via the filamentation instability.

IV. ENVISIONED MF IONOSPHERIC HEATING EXPERIMENTS

The ionospheric heating facilities located at, for example, Arecibo (Puerto Rico), Boulder (Colorado), and Tromsø (Norway) are currently operated at lowest frequencies on the order of 3 MHz. The transmission of signals at frequencies close to the electron gyrofrequency ($\lesssim$ 1.4 MHz) would require a major antenna and transmitter change. In our "envisioned" MF ionospheric heating experiments, we adopt the typical ionospheric parameters: $|\Omega_e|/2\pi$ = 1.4 MHz (i.e., $B_o = 5 \times 10^4$ γ), $\omega_{pe}/2\pi$ = 6 MHz, and $M(0+)/m = 16 \times 1840$. The threshold fields of the instability excited by the incident MF wave at 1.12 MHz (i.e., $\omega_o/|\Omega_e| = 0.8$) are found from (9) to be 6 mV/m and 0.4 mV/m for the excitation of modes with scale lengths of 100 m and 1 Km, respectively. If we assume that ϵ_o = 0.3 V/m, the growth rate of the instability for large-scale modes (i.e., $\omega_{pe}^2 >> k^2c^2$ or $\lambda >> 50$ m) is about 1 Hz. Under the illumination of powerful MF radio waves, large-scale ionospheric disturbances can be produced in seconds.

It is obtained from (4') that $(\delta n/n_o) \simeq 2.3\ (\delta B/B_o)$ (e.g., λ = 1 Km) for modes with $\lambda >> 50$ m. The excitation of a few percents of ionospheric density fluctuations are accompanied by the concomitant excitation of geomagnetic field fluctuations of the order of 500 γ, that is comparable to the perturbation in a severe magnetospheric (sub)storm.

V. HF IONOSPHERIC HEATING EXPERIMENTS

The HF radio waves transmitted in ionospheric heating (or modification) experiments have frequencies greater than the electron gyrofrequency ($\omega_o^2 >> \Omega_e^2$) but less than FOF2 in the ionosphere. Ordinary (O) or extraordinary (X) modes have been employed. At the Tromsø facilities, these modes can be represented by two circularly polarized waves propagating along the geomagnatic field. Since the wave propagation direction is antiparallel to the geomagnetic field, the X and O modes correspond to a left-hand and a right-hand circularly polarized wave, respectively, and satisfy the dispersion relations:

$$1 - \frac{\omega_{pe}^2}{\omega_o(\omega_o \mp |\Omega_e|)} = \frac{k_o^2 c^2}{\omega_o^2} \qquad (12)$$

where the $\mp$ signs denote the left-and right-hand circularly polarized waves, respectively.

Near the reflection heights of these pump waves (i.e., $k_o \to 0$), it is from (12) that $\omega_{pe}^2 \simeq \omega_o(\omega_o \mp |\Omega_e|)$. In this case, $P_\pm$ given by (8a) approximately vanish and $q_\pm \simeq \mp k^2c^2(\omega_o \pm |\Omega_e|)/\omega_o^2|\Omega_e|$ from (8b). Expression (9) then reduces to

$$\left|\frac{e\epsilon_{th}}{mc}\right|^2 = 0.75\ \frac{(\omega_o \mp |\Omega_e|)^2}{\omega_o^2\ (4 - q_\pm)}\ k^2V_t^2\ \left(2\ \frac{m}{M} + \frac{k^2V_t^2}{\Omega_e^2}\right) \qquad (13)$$

where q_+ (q_-) is for the right- (left-) hand circularly polarized wave. While the factor, $(4-q_+)$, is positive, a positive $(4 - q_-)$ requires that $q_- < 4$, viz., $\lambda > (\pi C/\omega_o)\ [(\omega_o + |\Omega_e|)/|\Omega_e|]^{\frac{1}{2}}$ (14) that can thus ensure the positive RHS of (13). If we take $|\Omega_e|/2\pi$ = 1.4 MHz, $V_t = 1.3 \times 10^5$ m/sec, $M(0^+)/m = 16 \times 1840$, $\omega_o/2\pi$ = 4.04 MHz, the scale lengths of the modes that are excited by the X mode cannot be less than 70 meters according to (14). By contrast no minimum scale length is found in the case of O mode heating.

The threshold fields of kilometer-scale instability excited by either X or O mode are a few mV/m calculated from (13) that are quite small compared with the incident power densities (~1 V/m) of the Tromsø signals. Although the growth rate of the instability is generally a function of scale lengths, it has an asymptotic value found to be

$$\sim 2.5 \times 10^{10} \frac{\nu_e \omega_o^2 |\epsilon_o|^2}{\Omega_e^2(\omega_o - |\Omega_e|)} \sim 3.4 \times 10 \text{ Hz for x - mode heating}$$

$$\sim 3.0 \times 10^{-2} \text{ Hz for O - mode heating}$$

when the scale lengths exceed a few hundreds of meters. It thus takes a few minutes for the instability to be excited in agreement with the observations that HF wave-induced geomagnetic field fluctuations needs a few minutes for development (Stubbe and Kopka, 1981). Substituting ν_e = 500 Hz, $\gamma = 3.4 \times 10^{-2}$Hz, λ = 1 Km, $\omega_{pe}/2\pi$ = 3.4 MHz and $B_o = 5 \times 10^4$ γ into (4'), we have $\delta B = 4.4 \times 10^2 \left(\frac{\delta n}{n_o}\right) = (4.4 - 44)\ \gamma$ for $\left(\frac{\delta n}{n_o}\right) = (1 - 10)\%$ also in agreement with the Stubbe and Kopka's experiments.

VI. CONCEPTUALIZED SOLAR POWER SATELLITE (SPS) PROJECT

The conversion of solar energy into microwaves is the basic idea behind the conceptualized Solar Power Satellite (SPS) project. The microwave energy would be transmitted from the satellite to the surface of the earth at a frequency of 2.45 GHz, that is much greater than the electron gyrofrequency ($|\Omega_e|$). The cross section of the microwave beam has been estimated to have a linear dimension of 10 Km in the ionosphere, and the incident power density at the center of the beam would be as high as 230 W/m^2 (i.e., the wave field intensity is about 640 V/m).

The formulation outlined above for the excitation of both plasma density fluctuations and geomagnetic field fluctuations can be also applied to the case of SPS project after some modifications. First of all, the microwave beam does not necessarily propagate along the geomagnetic field. Therfore, the positive z axis taken as the wave propagation direction is generally not in the direction of the geomagnetic field in this case. The polarization of the microwave is assumed to be within a meridian plane (i.e., the assumption of an ordinary mode) for efficiently exciting the field-aligned modes. Hence, the geomagnetic field perturbations (δB) are still in the direction of the background earth's magnetic field.

Since $\omega_o >> |\Omega_e|$, we then have $P_\pm \approx 1$ from (8a) and $q_\pm \to \infty$ from (8b) by taking $|\Omega_e| \to 0$ (i.e., equivalent to an unmagnetized plasma case). The threshold field given by (9) then reduces to

$$\left|\frac{e\epsilon_{th}}{mc}\right|^2 = 0.38 \frac{\omega_o^2}{\omega_{pe}^2} k^2 V_t^2 \left(2\frac{m}{M} + k^2 \frac{V_t^2}{\Omega_e^2}\right). \qquad (15)$$

Using $\omega_o/2\pi$ = 2.45 GHz, $\omega_{pe}/2\pi$ = 6 MHz, $V_t = 1.3 \times 10^5$ m/sec, $|\Omega_e|/2\pi$ = 1.4 MHz, and m/M(O+)=3.4x10^{-5} in (15), we obtain $\epsilon_{th} = 2.89 \times 10^3/\lambda$. For instance, 2.89 V/m (2.89 V/m) for the excitation of the modes with a scale length of 100 m (1 Km). The growth rate derived from (7) has the approximate form

$$\gamma \sim 2\nu_e \left(\frac{m}{M} \frac{c_s \omega_o}{C\Omega_i} \frac{\epsilon_o}{\epsilon_{th}}\right)^2 \qquad (16)$$

In spite that the power density of the microwave beam is not uniform, we assume a constant value of 20 W/m^2 (~60 V/m), that is about one tenth of the maximum intensity at the beam center, for the calculation of the growth rate. Then, if ν_e is taken to be 500 Hz, $\gamma \sim 5$ Hz for the excitation of one kilometer scale modes, namely, it takes a few seconds for the filamentation instability of microwaves to be excited.

The percentage of the geomagnetic field fluctuations is estimated from (4') as $\left(\frac{\delta B}{B_o}\right) \approx 0.4 \left(\frac{\delta n}{n_o}\right)$, that has a comparable magnitude to that of ionospheric density fluctuations. For the 1% of $\left(\frac{\delta n}{n_o}\right)$, the geomagnetic field fluctuations (δB) can be as large as 200 γ. Such large geomagnetic field fluctuations are expected to significantly perturb the orbits of charged particles and, consequently, to cause particle precipitation and airglow effects. These ionospheric effects introduced by the powerful microwave beams should be taken into account in the evaluation of environmental impacts of the conceptualized Solar Power Satellite program.

VII. CONCLUSION AND DISCUSSION

Ionospheric and magnetospheric disturbances evidenced as fluctuations in plasma density and geomagnetic field can be generated by powerful radio waves with frequencies as low as a few KHz and as high as several GHz. Depending on the incident power density of radio waves, ionospheric (or magnetospheric) plasma density fluctuations and geomagnetic field fluctuations can be excited simultaneously by the filamentation instability of radio waves within a few seconds or minutes. This instability typically has kilometric scale lengths in the ionosphere and tens of kilometric scale lengths in the magnetosphere.

Radio waves with frequencies less than the electron gyrofrequency may propagate in a whistler mode. The excitation of the filamentation instability is only possible for those with frequencies greater than half the local electron gyrofrequency. This criterion for the instability leads to the conclusions that the injected VLF signals can produce magnetospheric rather than ionospheric disturbances. It is, however, predicted that ionospheric disturbances can be induced by MF signals whose frequencies are less than 1.4 MHz but larger than 0.7 MHz.

In the HF ionospheric heating experiments ($\omega_0^2 >> \Omega_e^2$), both the ordinary and the extraordinary modes have been used. The scale lengths of the instability are found to have a cut-off in the case of extraordinary wave heating. The microwave beams that are transmitted from the conceptualized Solar Power Satellite to the surface of the earth are also expected to cause large ionospheric disturbances in their ordinary mode propagation. The geomagnetic field fluctuations caused by the filamentation instability of radio waves are very significant in all of the cases discussed in this paper. Their magnitudes may even become comparable to those seen in the magnetospheric (sub)storms.

It is interesting to note from (9) that the threshold field of the instability is inversely proportional to the electron plasma frequency. Therefore, ionospheric disturbances excited by radio waves should be most noticeable in the F region. Finally, it should be pointed out that the nonlinearity for the mode coupling is dominantly provided by the thermal pressure force due to the collisional dissipation of the pump wave field and the excited high-frequency sideband field in the electron gas. To emphasize this outstanding feature, the instability may be adequately termed the thermal filamentation instability of radio waves.

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Artificial ionospheric disturbances evidenced as fluctuations in plasma density and geomagnetic field can be caused by powerful radio waves with a broad frequency band ranging from a few KHz to several GHz. The filamentation instability of radio waves can produce both large-scale plasma density fluctuations and large-scale geomagnetic field fluctuations simultaneously. The excitation of this instability is examined in the VLF wave injection experiments, the envisioned MF ionospheric heating experiments, the HF ionospheric heating experiments and the conceptualized Solar Power Satellite project. Significant geomagnetic field fluctuations with magnitudes even comparable to those observed in magnetospheric (sub)storms can be excited in all of the cases investigated. Particle precipitation and airglow enhancement are expected to be the concomitant ionospheric effects associated with the wave-induced geomagnetic field fluctuations.

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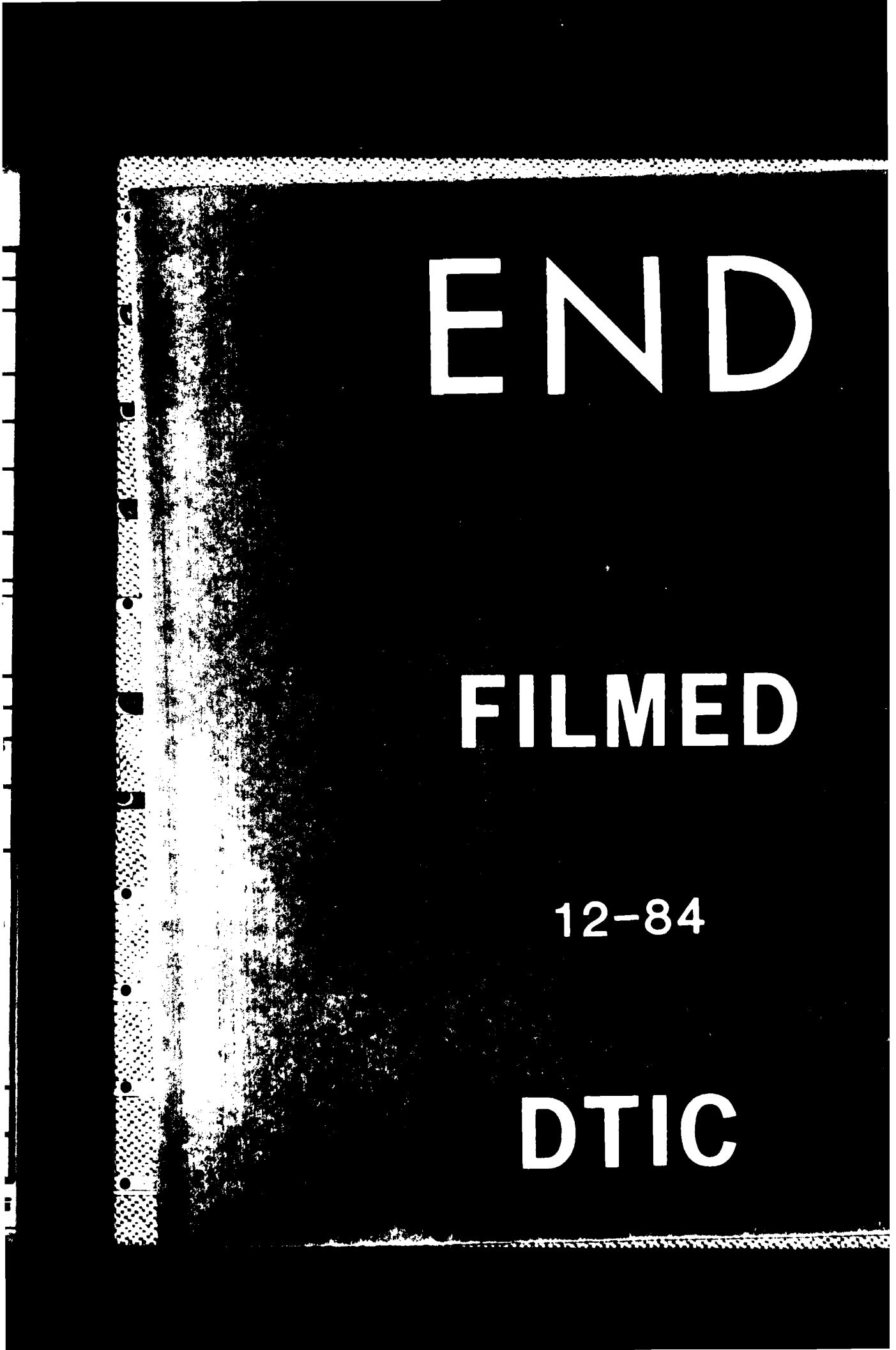
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