PROPAGATION OF LONG, HIGH-POWER MICROWAVE PULSES THROUGH THE AIR

Gizzing H. Khanaka and Jick H. Yee

March 1986

Lawrence
Livermore
National
Laboratory

Propagation of Long, High-Power
Microwave Pulses Through the Air

The propagation of high-power microwave pulses through the atmosphere has been a subject of investigation in the past few years. The primary objective of such work has been to assess the effect of microwave pulses on solid-state electronic systems, because a pulse of electromagnetic energy can induce destructive damages in such systems. Information on the energy and the peak power that are transmitted through the atmosphere are needed in evaluating the threat posed by microwave pulses on communication equipment, radar, computers, etc. A one-dimensional computer code has been developed to study the passage of a long, high-power microwave pulse at a constant altitude through the atmosphere. In this note, the electron conductivity and density, as well as plasma frequency, particularly during the passage of the microwave pulse through the atmosphere, are addressed.

In the computer model, electrons are treated as a fluid, and their effect on the passing microwave pulse is determined by means of the simultaneous solution of Maxwell's equations and the electron fluid equations. The model should give fairly accurate predictions, because it takes into account such variables as ambient electron density, beam intensity, ionization (avalanche) and attachment rates, and atmospheric pressure.

An electromagnetic pulse of specific frequency, shape, intensity, and length is assumed to exist at some desired altitude. Figure 1 shows the pulse type used in this study. This pulse is then assumed to propagate through the atmosphere at a constant altitude for a specified distance. The computer code is designed to focus on the pulse region and monitor the activities of both the electrons and the electromagnetic wave. In this code, all of the time intervals and distances are calculated relative to the front and of the electromagnetic pulse. The code produces plots of the electric field amplitude and the electron density, energy, conductivity, and velocity at specified time intervals. It also calculates the average and maximum electron conductivity, the peak electron density, and the peak plasma frequency at each time interval. Later, time history plots are made for these parameters.
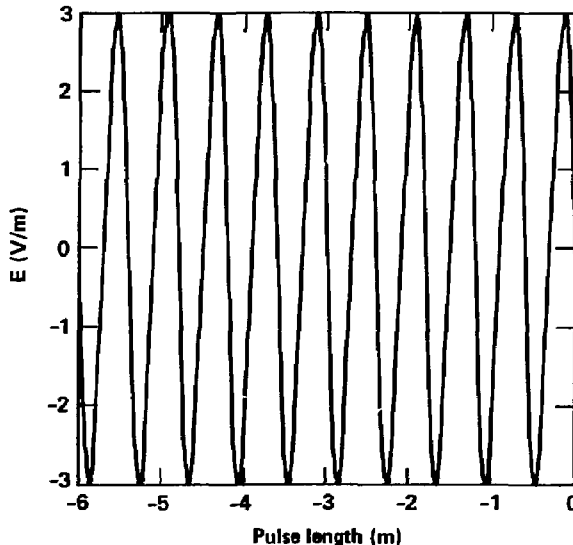

Figure 1. A sinusoidal pulse of $f = 0.5$ GHz , $T = 2$ ns, $L = 0.6$ m, pulse length $= 6$ m, pulse duration $= 20$ ns.

1

The Electron-Fluid Model

The electron-fluid model describes the passage of a plane microwave beam through the air by means of the following equations:

$$\partial E / \partial t = -(\partial H / \partial z + nev)/\varepsilon_0 \qquad (1)$$
$$\partial H / \partial t = -(\partial E / \partial z)/\mu_0 \qquad (2)$$
$$\partial n / \partial t = n(v_i - v_a) \qquad (3)$$
$$\partial v / \partial t = eE/m - v(v_m + v_i - v_a) \qquad (4)$$
$$\partial u / \partial t = -2Ev/3 - u(v_u + v_i - v_a) + u_0 v_u - 2E_c v_i/3 \quad , \qquad (5)$$

where E is the electric field (V/m) in the x direction, and H is the magnetic field (A/m) in the y direction. The wave propagates in the z direction, and e, m, n,v, and u are the electron charge (C), mass (kg), density (elec/m^3), velocity (m/s), and energy (eV), respectively. The parameters v_i, v_a, v_m, and v_u are the ionization (s^{-1}), attachment (s^{-1}), momentum transfer (s^{-1}), and energy loss rates (s^{-1}), respectively. E_c is the ionization energy of air molecules (eV), and u_0 is the initial energy of air molecules (eV). ε_0 and μ_0 are the free-space permittivity (F/m) and permeability (H/m), respectively. Finally, t is the time (s).

The electron conductivity and the plasma frequency are given by the following equations:

$$g = ne^2/mv_m \qquad (6)$$
$$w_p = (ne^2/m\varepsilon_0)^{1/2} \quad , \qquad (7)$$

where g is the electron conductivity (mho/m) and w_p is the plasma frequency (rad/s).

The electron conductivity is a function of electron density and energy (via the momentum transfer rate). At low altitudes, the conductivity is more affected by the density than by the energy, because the electrons collide frequently with the air molecules. Hence, their energy does not change rapidly enough to cause significant change in the momentum transfer rate. At high altitudes, where the air is less dense, the electrons can gain significant amounts of energy from the electric field before a collision. Hence, the momentum transfer rate is expected to affect the conductivity data. The plasma frequency is a function of the electron density only; hence, its behavior is affected by the electron density. Equations (1) through (5) have to be solved simultaneously in a two-dimensional space (z,t). It is clear that they form a set of coupled, nonlinear partial differential equations with no closed-form solution. In addition, the rates v_i,v_a, v_m, and v_u are functions of the electron energy and atmospheric pressure. The functional dependency of these rates on the electron energy is shown in Fig. 2. Thus, numerical methods are employed to obtain an approximate solution for this problem.

The Physics of Wave Propagation

The results of this study can be understood by means of the physics of the problem. The propagation of electromagnetic waves in matter, especially in air, is accompanied by many physical processes that adversely affect the transportation of electromagnetic waves. Air breakdown is considered to be one of the important processes, because it causes attenuation. Thus, determining the breakdown threshold as a function of frequency and intensity is essential whenever information on the transportation of electromagnetic waves is desired. Hence, it is expected that the front portion of a high-power microwave pulse can pass through the air, while the back portion (tail) erodes. Figure 3 shows the dependency of the transmitted portion of the pulse on the intensity, frequency, and length of that pulse.

This type of behavior can be explained by examining the interaction between the electrons and the electromagnetic wave. As the pulse starts to propagate, the electric field accelerates the ambient free electrons. If the field is intense enough, the electrons gain enough energy to ionize air molecules and liberate more electrons. These electrons in turn are accelerated by the field and can cause further ionization in the atmosphere. At atmospheric pressure, the time development of the electron density is described by Eq. (3); it is obvious that the electron ionization rate must exceed the electron attachment rate for air breakdown to occur. The threshold intensity for air breakdown is defined by the intensity at which
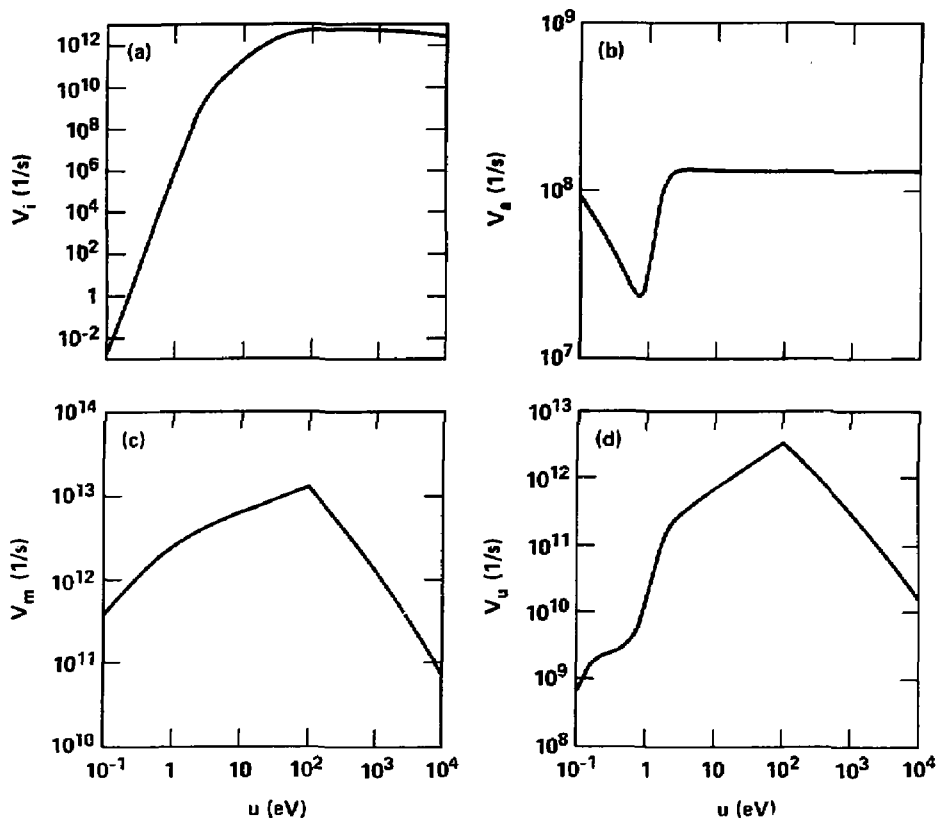
Figure 2. Ionization (v_i), attachment (v_a), momentum transfer (v_m), and energy loss (v_u) rates as a function of electron energy at sea level.

tail erosion is initiated. Figure 4 shows the time development of the electron density for a pulse intensity higher than the threshold intensity; the electron density in this case increased rapidly in a short time interval. For intensities above the threshold, the electron density usually reachs a high value (10^{14}—10^{19} elec/m^3) in nanoseconds. This study shows that tail erosion does not occur as long as the density is below 10^{14} elec/m^3. Once the tail of the pulse has eroded significantly, then the electron density starts to decrease. The manner and the speed by which the density increases and then decreases depends on the frequency and intensity of the pulse.

In summary, the front portion of an intense electromagnetic pulse creates an ionized atmosphere through which the tail has to pass. The creation of an ionized medium in the air has several interesting effects. Of particular interest here is the fact that the ionized air acts as an attenuator or a reflector for the incoming electromagnetic wave. Therefore, when the tail portion of the pulse passes through such an atmosphere, it is subject to attenuation and possibly reflection. Hence, it loses a significant amount of its energy to the electrons. The energy absorbed by these electrons is used in ionizing, exciting, and heating up the molecules.
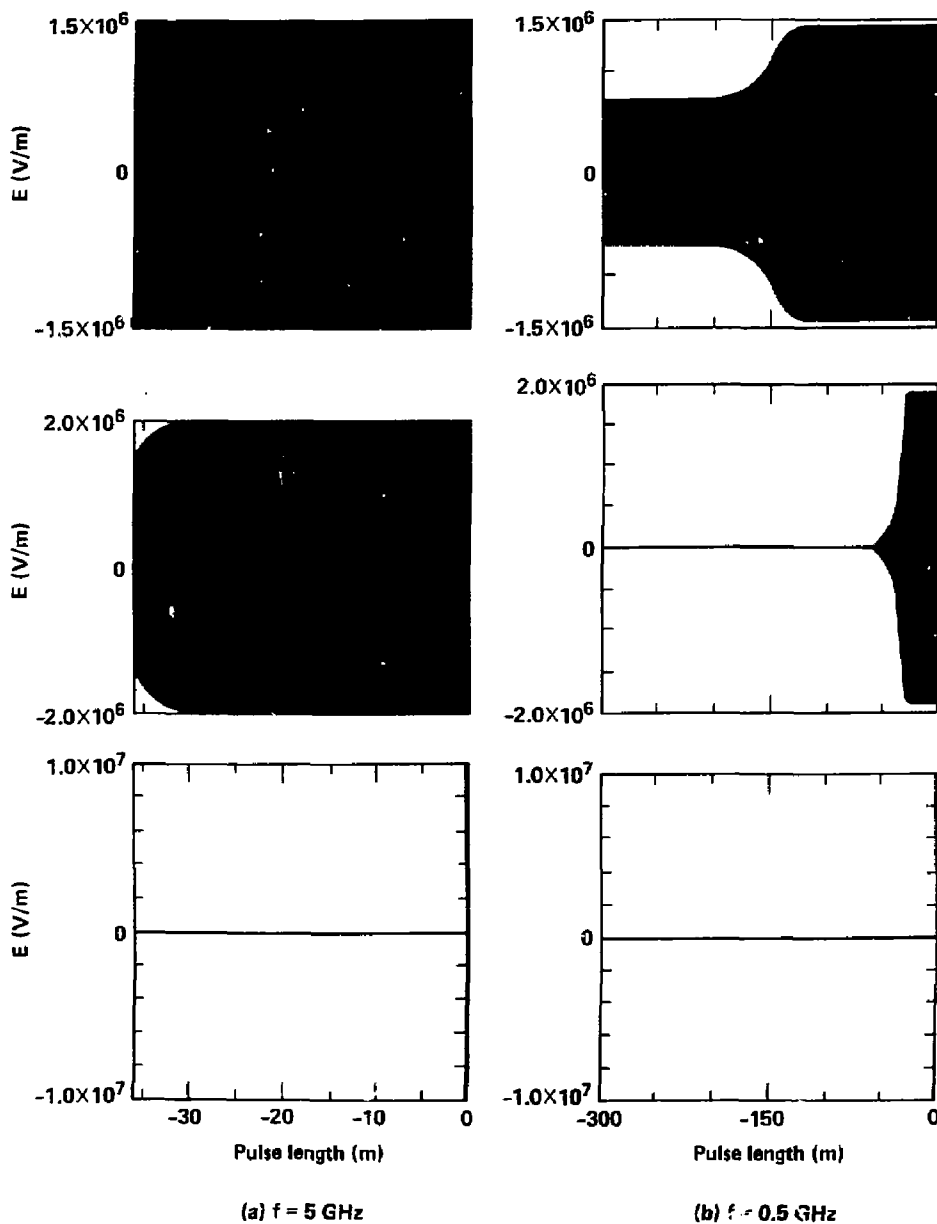
3

Figure 3. Plots of the electric field amplitude vs pulse length showing the dependency of the transmitted portion of a microwave pulse on intensity, frequency, and length of the pulse. These plots represent the electric field amplitudes at (a) t = 1 μs and (b) t = 1.5 μs.
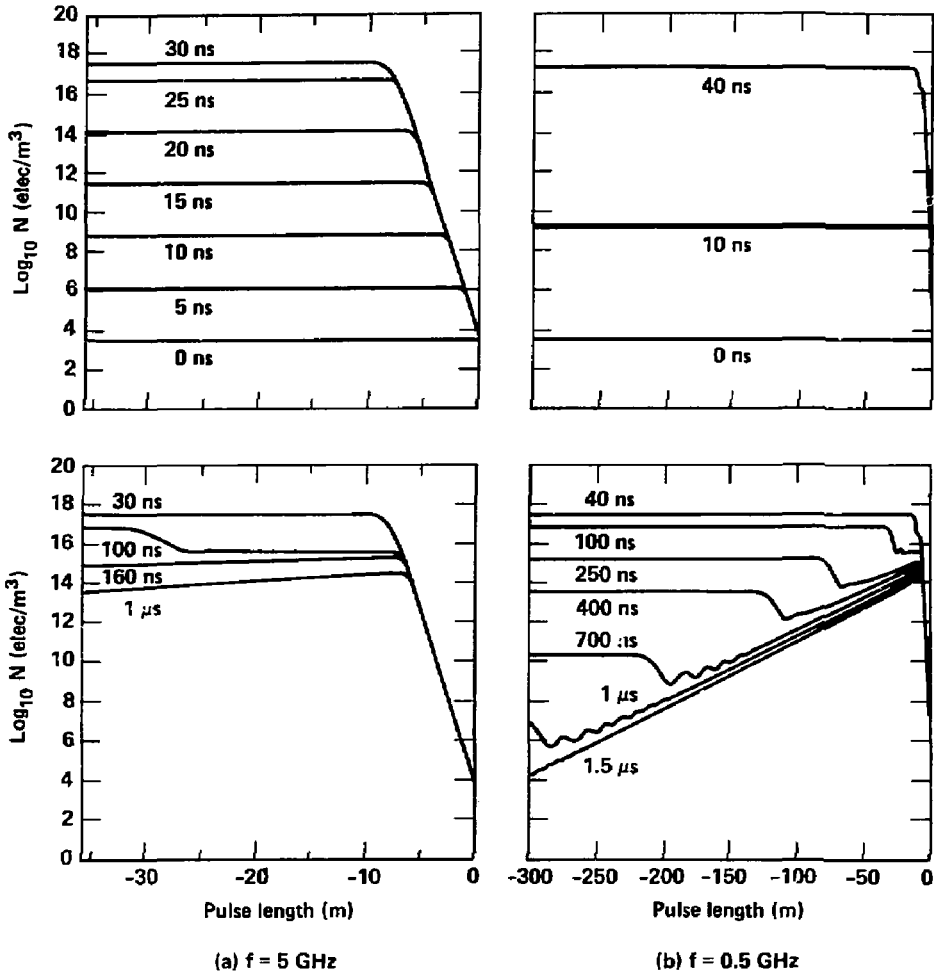
4

Figure 4. Plots showing the time development of the electron density for a field amplitude of 3 MV/m, where the electron density increases with time until it reaches a maximum value. It takes 30 ns for the 5-GHz pulse and 40 ns for the 0.5-GHz pulse to reach the maximum value. At this point, tail erosion is initiated; its effect on the electron density is seen in the lower graphs.

Electron Conductivity

The electron conductivity was studied for two pulses: a 5-GHz pulse of 120-ns duration (36 m long) and a 0.5-GHz pulse of 1-μs duration (300 m long). In both cases, the altitude was kept constant at 6.1 km (20,000 ft), and the electric field amplitude was varied from 1-10 MV/m (i.e., an intensity of 1.33×10^9 - 1.33×10^{11} W/m^2). The pulses were allowed to travel a distance longer than their lengths (300 m for the 5-GHz pulse and 450 m for the 0.5-GHz pulse).

5

This study shows that there is a specific air breakdown threshold associated with each pulse. The obtained threshold level is 1.4 MV/m for the 0.5-GHz pulse and 2.0 MV/m for the 5-GHz pulse. The electron conductivity is affected greatly by the term $(v_i - v_a)$ in Eq. (3). For pulse amplitudes below the threshold level, the term $(v_i - v_a)$ increases or decreases slowly with time; hence, the electron conductivity increases or decreases very moderately as in Fig. 5. When the intensity exceeds the threshold level, the electron conductivity increases by orders of magnitude over a short period of time, as shown in Fig. 6. This behavior in the electron conductivity is attributed to electron avalanche.
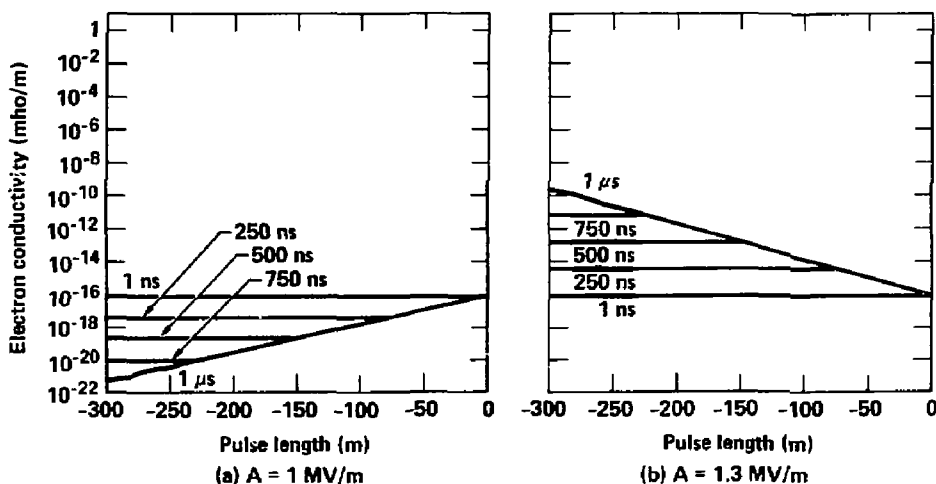
Figure 5. Plots demonstrating the time development of the electron conductivity for the 0.5-GHz pulse with field amplitudes below the avalanche ionization intensity.
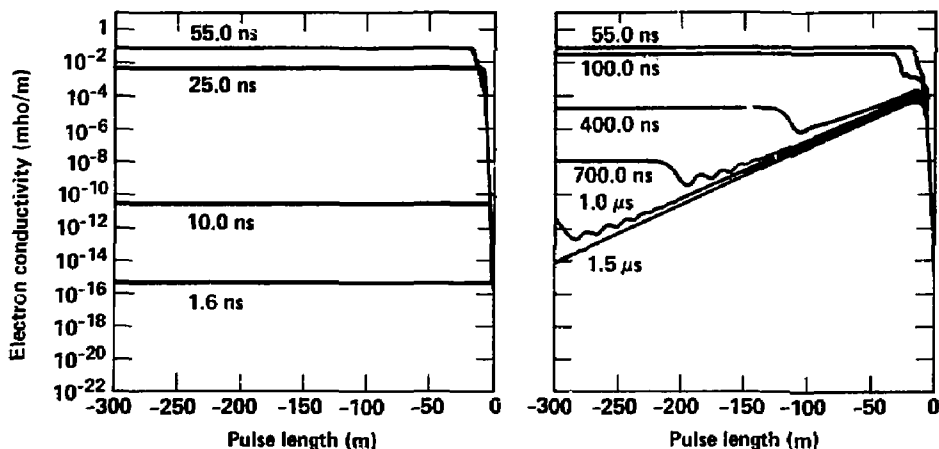
Figure 6. Conductivity values for pulse amplitude of 3 Mv/m, which is above the threshold level. The conductivity reaches its peak value in 55 ns. Then, it starts to decrease gradually.

At the end of each time interval, the average and maximum electron conductivity and the peak electron density were obtained. The peak plasma frequency was calculated by using the peak electron density in Eq. (7). All of these data points were used to produce Figs. 7-10. It is clear from these figures that the general behavior of these parameters is very similar for both pulses. The major difference is in their threshold level.
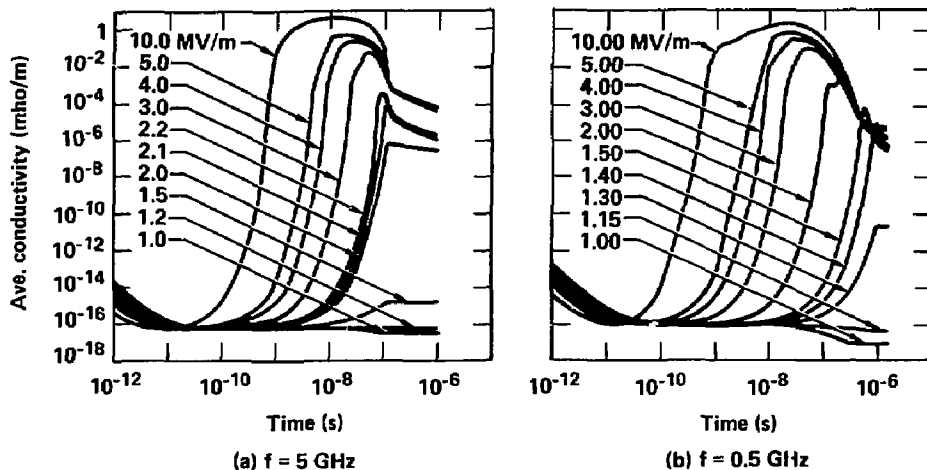

(a) f = 5 GHz

(b) f = 0.5 GHz

Figure 7. Plots of the average electron conductivity vs time for field amplitudes ranging from 1-10 MV/m.
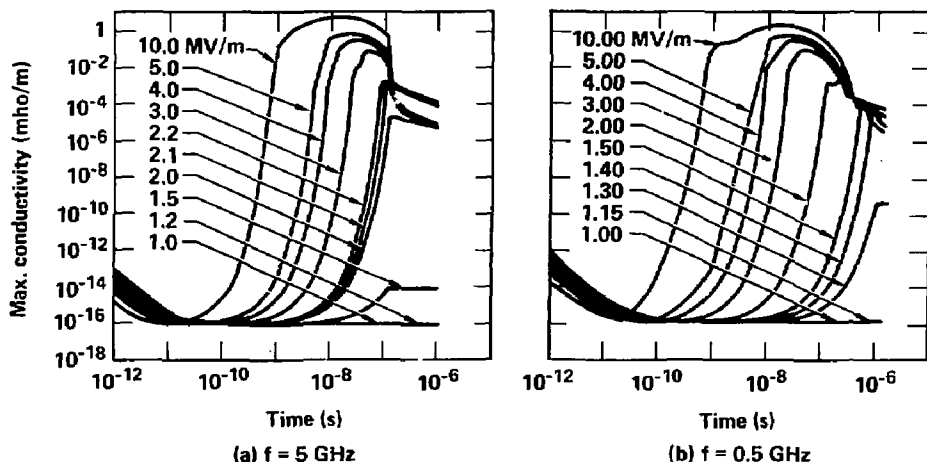
(a) f = 5 GHz

(b) f = 0.5 GHz

Figure 8. The maximum electron conductivity plotted as a function of time with field amplitudes of 1-10 MV/m for both pulses.
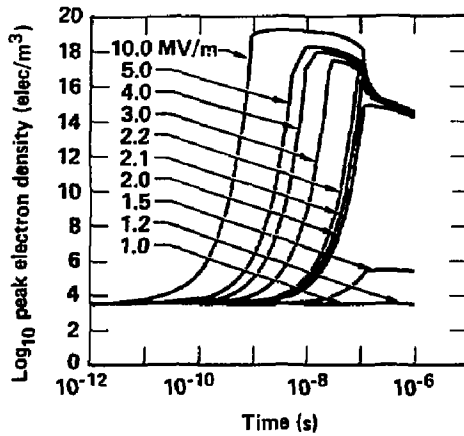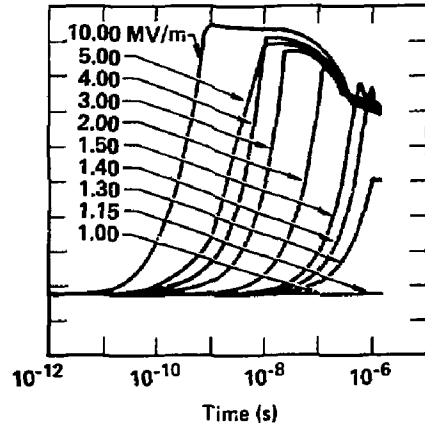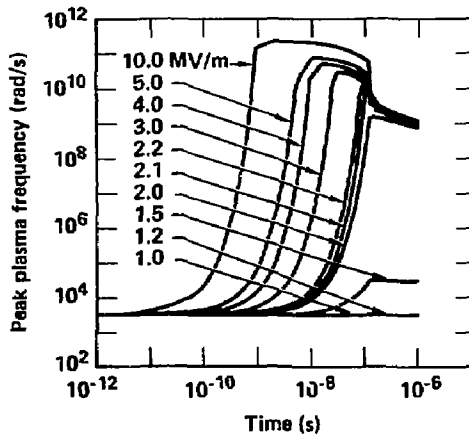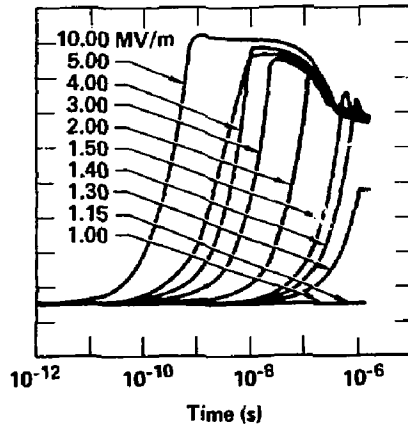
(a) f = 5 GHz (b) f = 0.5 GHz

Figure 9. Plots of the peak electron density as a function of time for both pulses. The electric field amplitude varies from 1-10 MV/m.

(a) f = 5 GHz (b) f = 0.5 GHz

Figure 10. Plots of the peak plasma frequency as a function of time for both pulses. The electric field amplitude varies from 1-10 MV/m.

Figure 10 shows the dependency of the peak plasma frequency on time for both cases. It shows that the plasma frequency exceeds 5 GHz when the field amplitude is equal to or greater than 4 MV/m. This indicates that the ionized atmosphere is acting as a reflector for the incoming microwave pulse. Similarly, the plasma frequency exceeds 0.5 GHz when the field amplitude is equal to or greater than 1.5 MV/m.

8

Summary

The passage of long, high-power microwave pulses in the atmosphere was studied using a one-dimensional computer code. The objective of this study was to obtain a time history of the electron conductivity and peak density, as well as the peak plasma density. The results are summarized as follows:

- The threshold level depends on pulse frequency and length.
- Electron avalanche occurs only when the pulse intensity exceeds the threshold level for air breakdown, and this results in tail erosion.
- For higher pulse intensities, it requires less time to initiate electron avalanche, which results in transmitting smaller portions of the pulse.
- The general characteristics of the electron density, conductivity, and plasma frequency are quite similar for both cases.
- As the pulse amplitude rises, the electron conductivity and density and the plasma frequency also rise.

9

Contents

MASTER

DISCLAIMER