Interaction Notes

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Time-Domain Computer Models of Thin-Wire Antennas and Scatterers*

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The transient responses of various thin-wire antennas and scatterers have been studied through the numerical solution of a time-dependent electric field integral equation. The solution is set up as an initial value problem and proceeds via time stepping. This is a generally more efficient approach for determining the transient response of wire objects than frequency domain solutions which are Fourier transformed to obtain transient characteristics. The time-domain solutions have been verified by comparisons with other solutions for structures such as the linear dipole, circular ring, conical spiral, and V-dipole. In addition to providing wide-band frequency domain information via Fourier transformation, the time-domain solutions permit the temporal development of the currents and charges to be followed, which permits ready demonstration of reflections from junctions or ends of wires, the effects of loading, phase dispersion of the current waves as they travel along the structure, and structure resonances.

The characteristics of several structures is considered with the aim of providing insight into their EMP response characteristics. Attention is devoted to methods of data presentation which efficiently utilize the large amount of information which the time domain solution yields and to exploiting this data for problems of practical interest. These studies show, for example, that a current saturation occurs when a long wire (in free space) is illuminated by a short pulse plane wave. Insight gathered from the time-domain solution of this problem has lead to a simple method of estimating the maximum current on the wire.

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INTRODUCTION

Transient responses of electromagnetic bodies may be obtained through transformation of frequency domain characteristics or through solution of time dependent equations directly in the time domain. Until recently, however, few time domain calculations have been performed for determining the electromagnetic characteristics of thin wire structures. In 1968, Bennett and Weeks[1] presented time-domain solutions for several electromagnetic objects employing a time dependent integral equation based on the magnetic field. About the same time, Sayre and Harrington[2] applied the thin wire approximation to a coupled set of equations based on the magnetic vector and electric scalar potentials and obtained results for the linear dipole and circular ring. Recently, Miller, et al.[3] and Poggio et al.[4] applied the thin wire approximation to a time-dependent version of the frequency domain Pocklington electric field integral equation. While some aspects of their analysis is similar to the previously listed efforts, they included in addition a 9-point Lagrangian interpolation scheme which permitted efficient treatment of more complicated wire structures as demonstrated by the analysis of the zig-zag antenna in (4).

In this paper, the techniques of (3) and (4) have been used to analyze several wire structures with the aim of providing insight into the EMP response of these structures. For this application, it has been found convenient to present the data as a movie, so that the temporal behavior of the currents may be followed in proper spatial perspective. The presentation of this paper was concluded with a viewing of this movie, here select frames are presented for illustrative purposes.

APPROACH

The theory and the numerical approach used were presented in (3, 4, and 5). A users manual, program listing, and sample output is given in (6). This program is based on a moment method solution of the time dependent electric field integral equation

$$\hat{s}\cdot\overline{E}_{inc}(\overline{r},t) = \frac{\mu_o}{4\pi}\int_{C(\overline{r})} \frac{\hat{s}\cdot\hat{s}'}{R}\frac{\partial}{\partial t'} I(s',t')$$

$$+ C\,\frac{\hat{s}\cdot\overline{R}}{R^2}\,\frac{\partial}{\partial s'} I(s',t')$$

$$- C^2\,\frac{\hat{s}\cdot\overline{R}}{R^3}\,q(s',t')\;\;ds' \qquad (1)$$

where $\overline{E}_{inc}(\overline{r},t)$ is the incident field at observation point $\overline{r}$ at time t, $\hat{s}$ and $\hat{s}'$ are unit vectors parallel to $C(\overline{r})$ at $\overline{r}$ and $\overline{r}'$, c is the velocity of light, μ_0 the permeability of free space, $I(s',t')$ and $q(s',t')$ are the current and charge at source point s', retarded time $t' = (t - R/C)$ where $R = |\overline{r}-\overline{r}'|$, and $C(\overline{r})$is the structure contour. The moment method solution proceeds by approximating the object by a set of straight wire segments and using a subsectional bases function expression in space and time in the form of a 9-point Lagrangian interpolation scheme to describe the current on each segment. The integral equation is reduced to a matrix form

$$\underline{E}_{sca} + \underline{E}_{inc} = \underline{\underline{Z}}\ \underline{I}$$

where E_{inc} is the value of $\overline{E}_{inc}(\overline{r}_0,t_0)\cdot\hat{s}_0$ at time t_0 and for $\overline{r}_0$ a wire radius away from $C(\overline{r})$ at the observation point, and where E_{sca} is the electric field tangent to the wire segment at $\overline{r} = \overline{r}_0$ and $t = t_0$, due to earlier charges and currents.

The solution is obtained by finding $\underline{Y} = \underline{Z}^{-1}$ once (since $\underline{Z}$ is independent of time) and then calculating $\underline{I}$ by solving (2) sequentially at each time step. As a consequence of this time stepping proceedure, the computation time is controlled mainly by the number of time steps desired in the solution for a given number of segments. Once the currents are obtained, other aspects of the electromagnetic behaviour of the structure may be found. For antennas, the source current can be transformed to the frequency domain providing input admittance. The radiated far fields may be computed, thus providing either antenna gain or radar cross-section. Near fields may also be computed for use in coupling and interaction studies.

For wide-band calculations, this time-domain method has several advantages over more commonly used frequency-domain solutions. In general, the time-domain method is much more efficient than frequency-domain methods for obtaining the transient behaviour for a given excitation. Further, non-linear loading is more tractable in this time-domain formulation which permits evaluation of the transient behaviour of devices such as a spark gap attached to an antenna. Finally, the dynamic electromagnetic behaviour of the structure is generated directly in the time domain which permits the natural development of the response to be followed and allows ready identification of peak currents and structure resonances.

NUMERICAL RESULTS

Analysis of straight wire structures using this time-comain approach indicates that peak currents induced on these structures are controlled by the width of the incident pulse with respect to the structure length as well as the magnitude, direction of arrival, and polarization of the incident pulse. The examples given here illustrate this phenomenon and also give insight into the natural behaviour of the structures.

The current at the center of a 1 meter long straight wire illuminated by a gaussian pulse is shown in Figure 1. In this case, the incident plane wave impinges at a 45 degree angle to the wire. The electric field strength is of the form $e(t) = \exp(-a^2t^2)$ where $a = 3.63 \times 10^9$. For this value of a, the width of the pulse between 10% levels is 25% of the wire length. The current resonates at the fundamental resonance of the straight wire with a decreasing proportion of higher frequency components at late times. The development of the current is followed in Figure 2. The shaded area indicates the region in space where the incident wave is above its half power levels, the straight line indicates the location of the wire, and the current is plotted from this line. As the incident wave progresses along the wire, the current continues to rise. This rise terminates when the current is reflected from the end of the wire, a behaviour typical of structures that are comparible to or shorter than the width of the incident pulse, whether the pulse is gaussian as in this example, or an EMP wave.

The relationship between pulse width and structure size is investigated in Figures 3 and 4. In this case, the width of the gaussian pulse is 8% of the wire length. Figure 3 shows the initial pulse of current at the center of the structure. The calculation ends before the current wave reappears at the center of the wire. Notice that the current saturates for this example. The peak current is not influenced by the length of the structure, as was found in the first example. For structures that are much longer than the width of the incident pulse, the peak current is not a function of the length of the wire. This phenomenon can be explained by noticing that the leading edge of the current pulse is in phase with the incident field. Along the wire, the incident field appears to travel at a velocity greater than the speed of light. The current wave travels at about the speed of light, resulting in a widening between the leading and trailing edges of the current pulse. After the incident field has passed a given part of the current wave, the current stops increasing, thus limiting the peak current irrespective of the exact length of the wire. After the pulse has passed the entire wire, the current wave is left to resonate back and forth on the wire. This portion of the response is similar to the late-time behaviour of the first example and is omitted here.

Figure 5 shows the current at the center of the long wire used in the previous example, but for broadside incidence. The peak current in this case is 20.6 ma, and for the previous example 27.2 ma. Approximate solutions indicate that the peak current varies as $1/\cos\theta$ on long lines where θ is the angle the front of the incident plane wave makes with the wire ($\theta = 0$ for broadside). The actual ratio of the two currents measured above is 1.32, where the $1/\cos\theta$ approximation gives 1.4. The development of the current is followed in Figure 6. As in the previous example, the peak current is reached before the current is limited by reflections from the end of the wire.

The response of a monopole above a perfect ground plane illuminated by an EMP wave is shown in Figure 7. This monopole approximates a tower with a radius of 0.06 m and a height of 31.25 m. The EMP wave is a 4 term exponential with a rise time of 20 nsec, zero crossing at 1.5 μsec and with a peak field strength of 5×10^4 v/m. For this example, the wave impinges on the monopole 45° from broadside. The width of the pulse is 14 times the length of the monopole. Consequently, the current rise is terminated by reflections. This is evident in the sequence shown in Figure 8. The current along the monopole is plotted horizontally away from the monopole and is shown as a solid line. The dotted line is the magnitude of the incident field parallel to the monopole. As the incident field progresses, the current peak along the monopole increases almost linearly until the time of reflection from the ground. After the reflected waves have traveled back to the top of the monopole, the incident field has little influence on the nature of the current. The major part of the current wave then resonates at the fundamental harmonic of the monopole.

SUMMARY

Numerical results obtained in the time domain have been presented for several straight wire scatterers. The foundation of these results is a time-dependent electric field integral equation. Although the results presented here are for straight wires, the computer program is adapted to handle more complicated geometries. Structures such as circular loop, zig-zag, conical spiral, and V-dipole antennas as well as cylindrical models of aircraft have been analyzed using the program.

For the straight wire structures, it appears that the peak current is approximately

$$I_{peak} = k \int_0^T e(t)dt$$

where e(t) describes the incident field parallel to the wire, and k is a function of the wire radius as well as the angle of arrival and frequency spectrum of e(t). The value of T is chosen as $\frac{L}{2C}$ for wires that are shorter than the width of the incident field, and as ∞ for cases where the wire is much longer than the width of the pulse. In either case, the late time behaviour was found to be governed by the fundamental harmonic of the structure.

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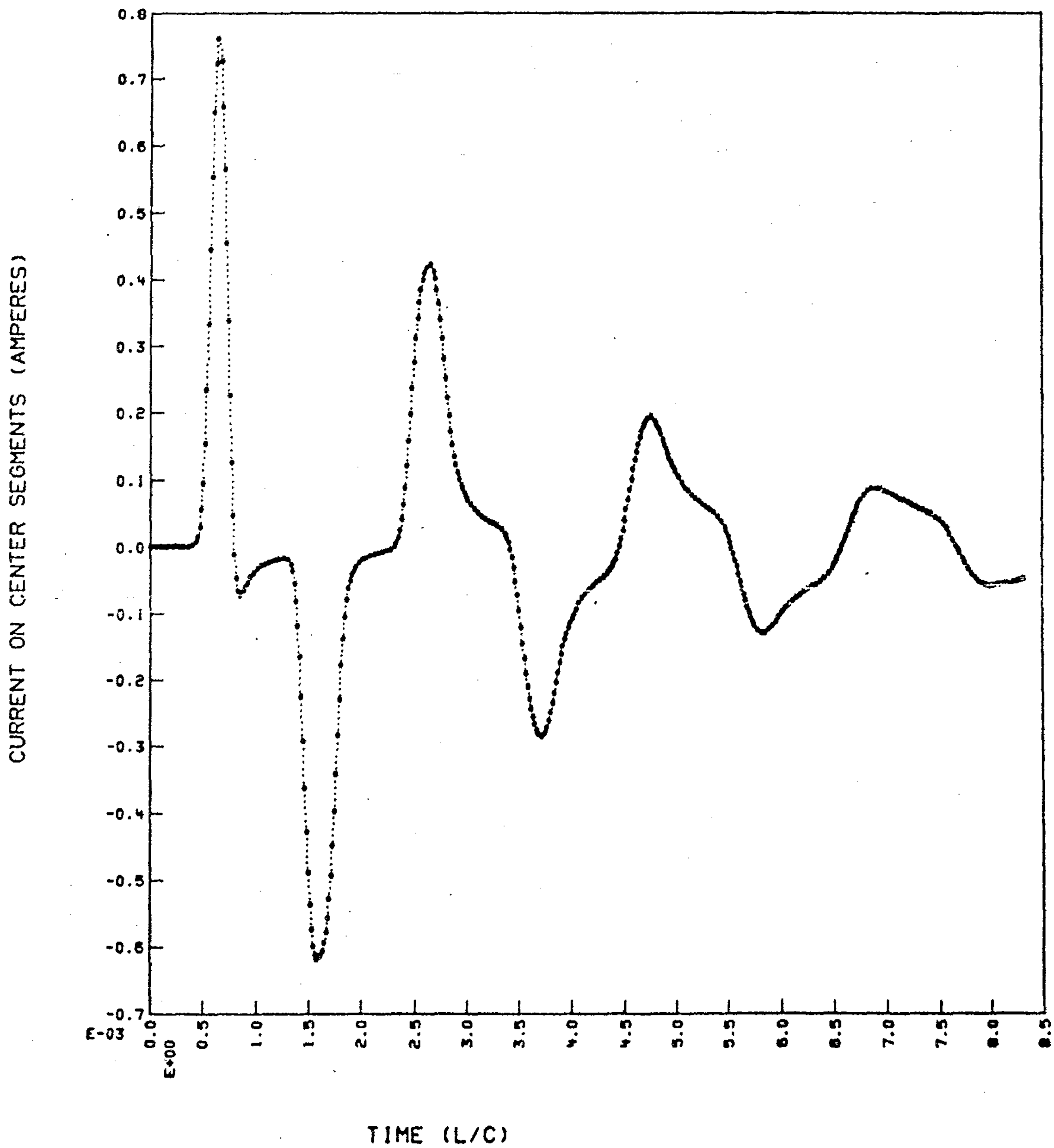

FIGURE 1. Current at the center of a 1 m straight wire

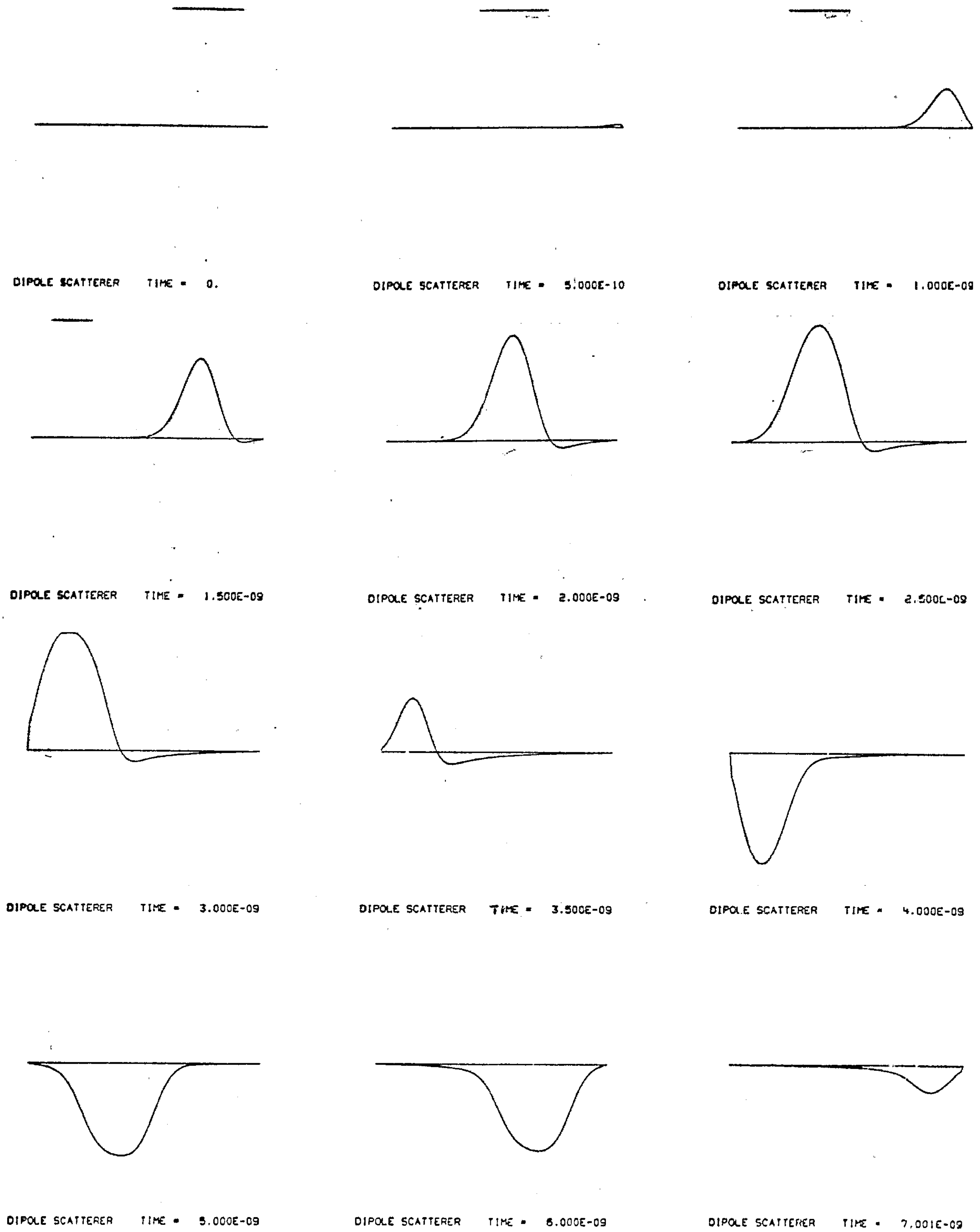

FIGURE 2. Development of current on a 1 m straight wire.

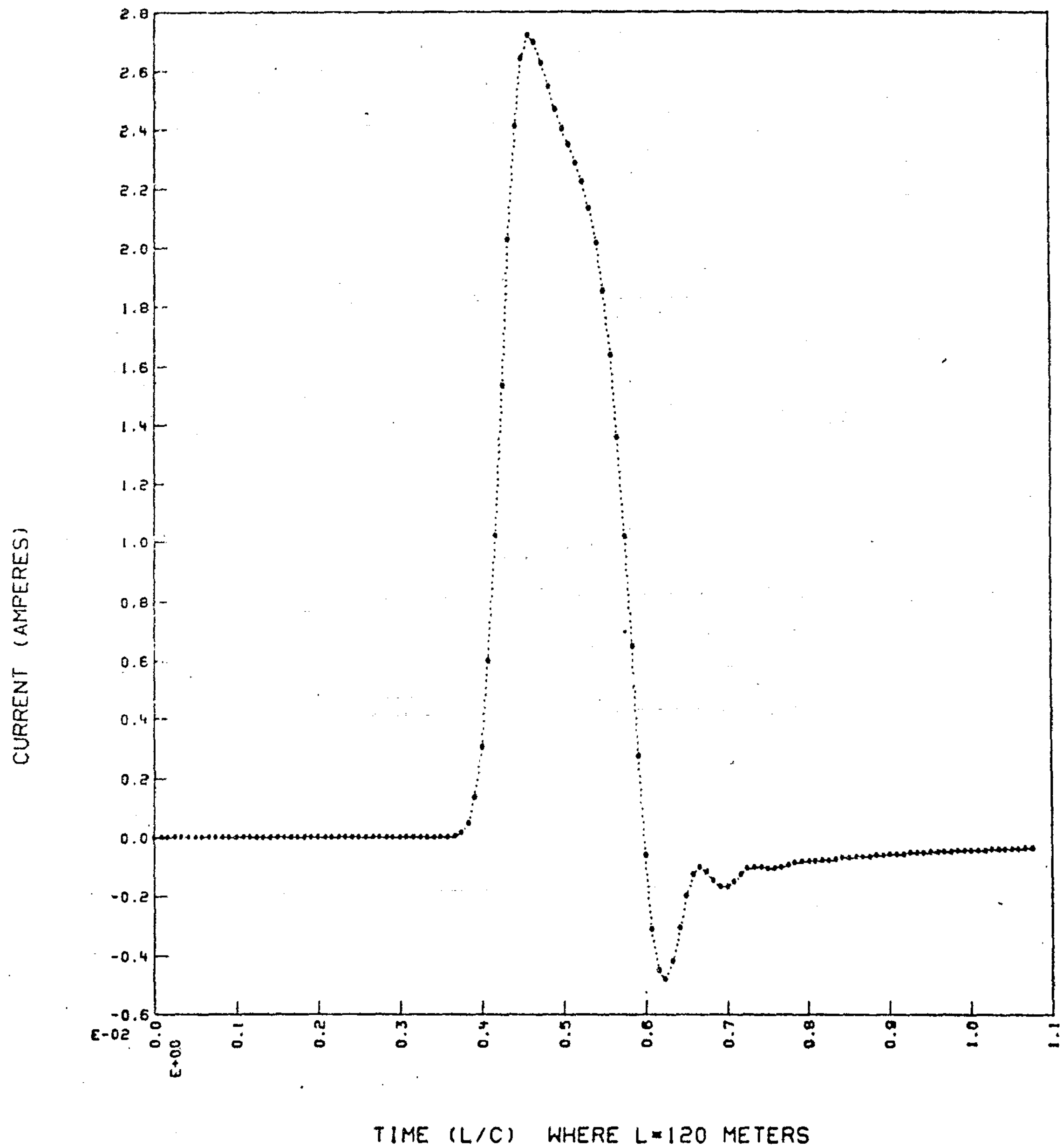

FIGURE 3. Current at the center of a 120 m straight wire.

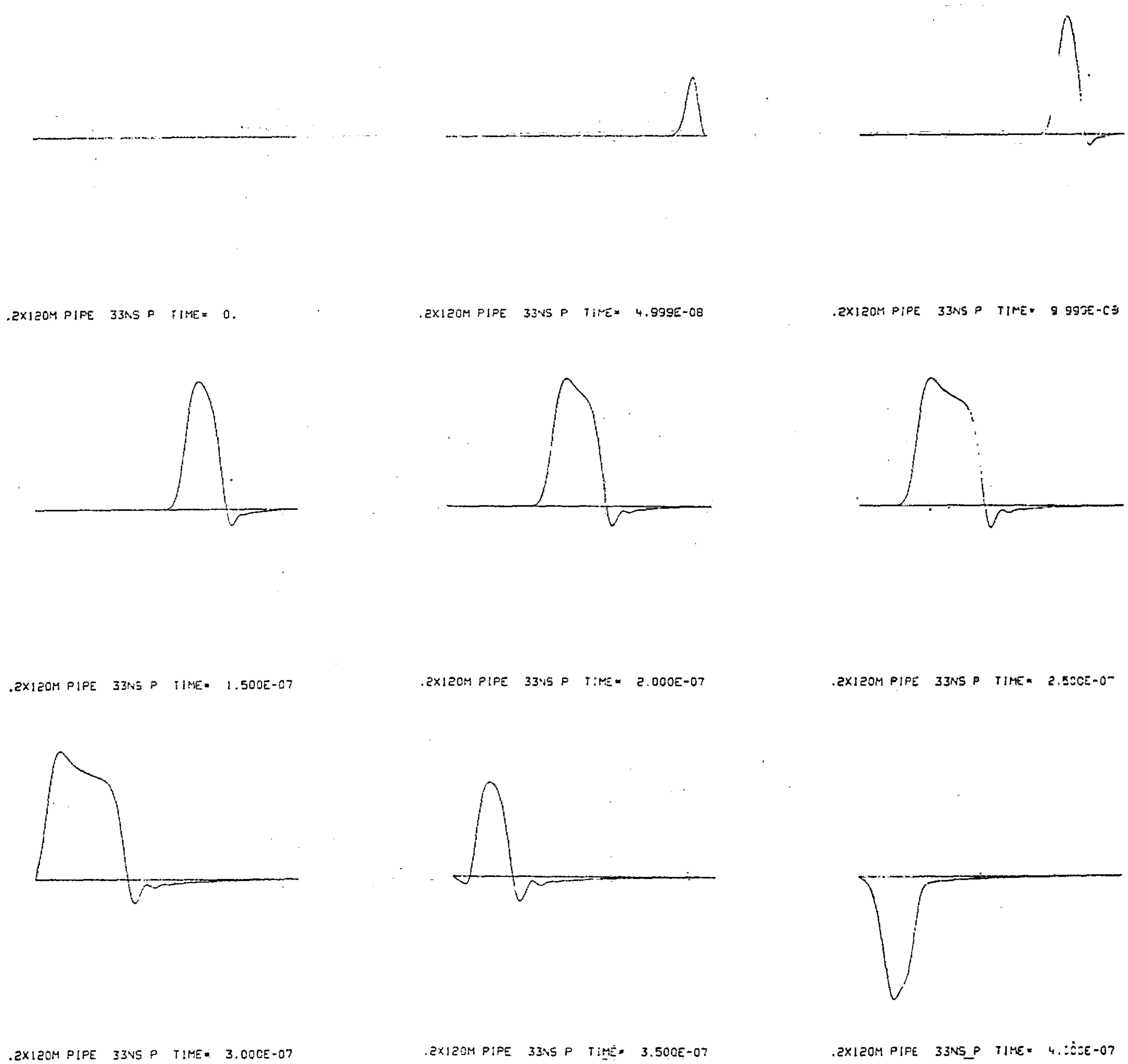

FIGURE 4. Development of current on a 120 m straight wire.

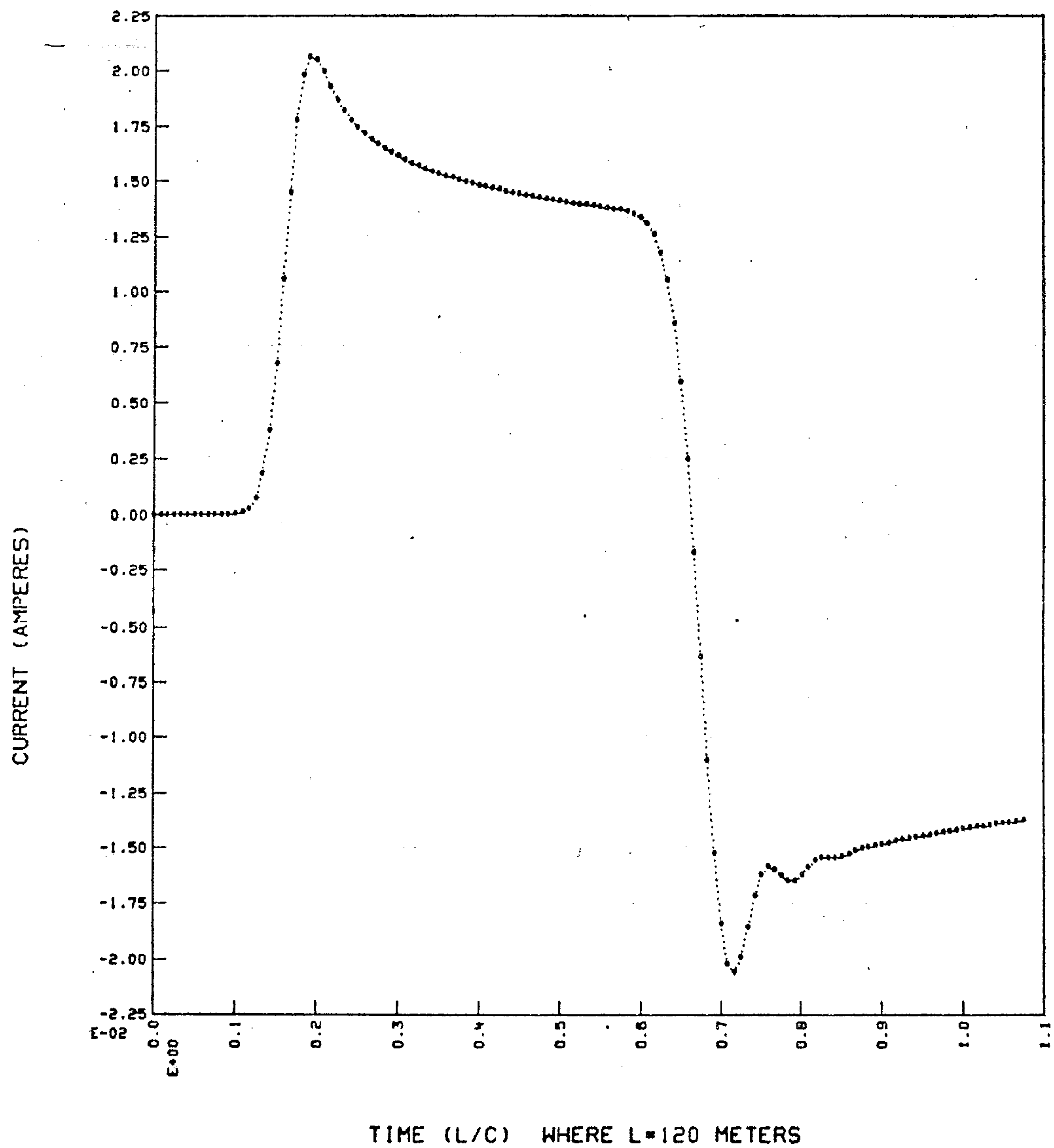

FIGURE 5. Current at the center of a 120 m straight wire for broadside incidence.

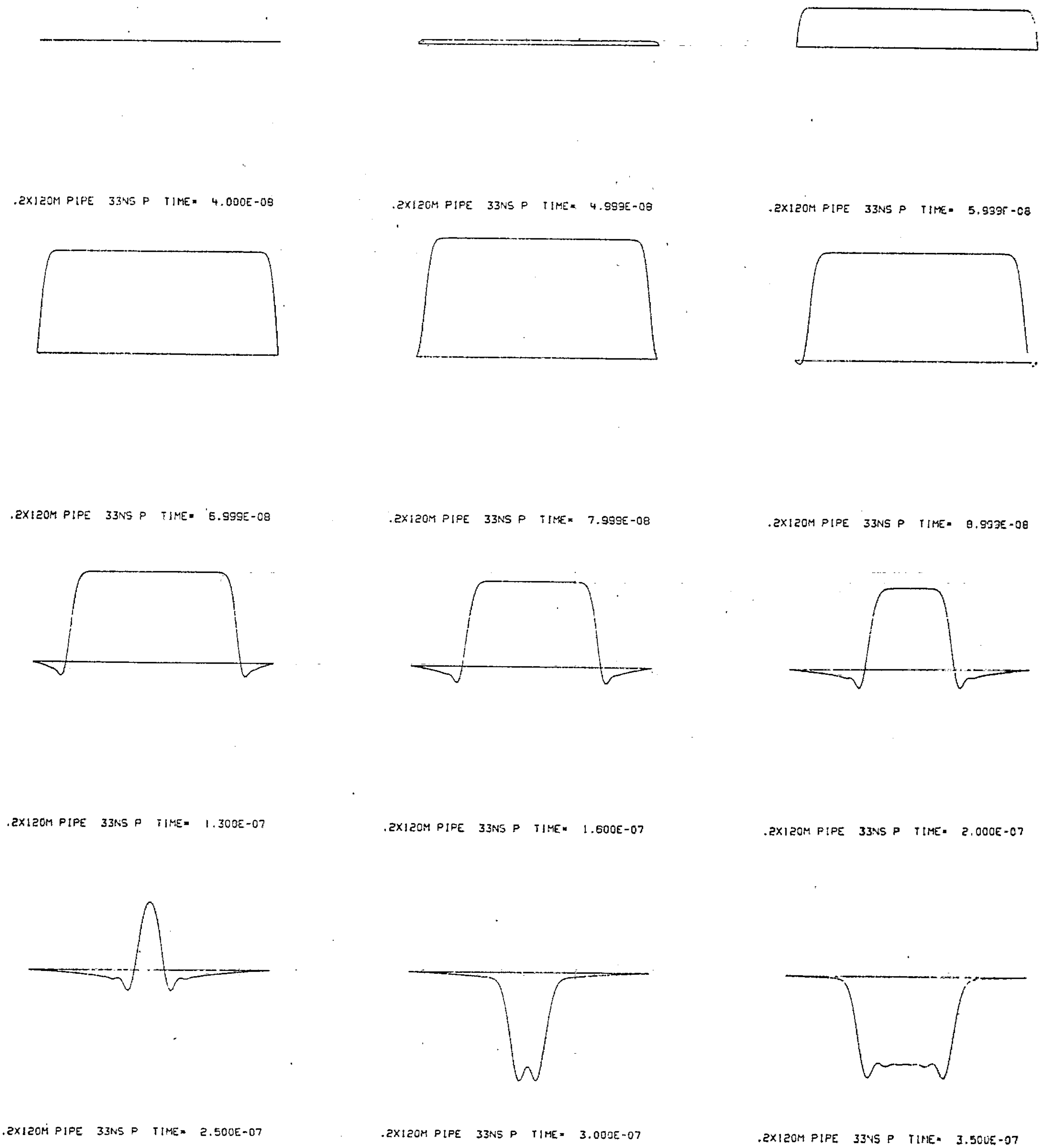

FIGURE 6. Development of the current on a 120 m straight wire for broadside incidence.

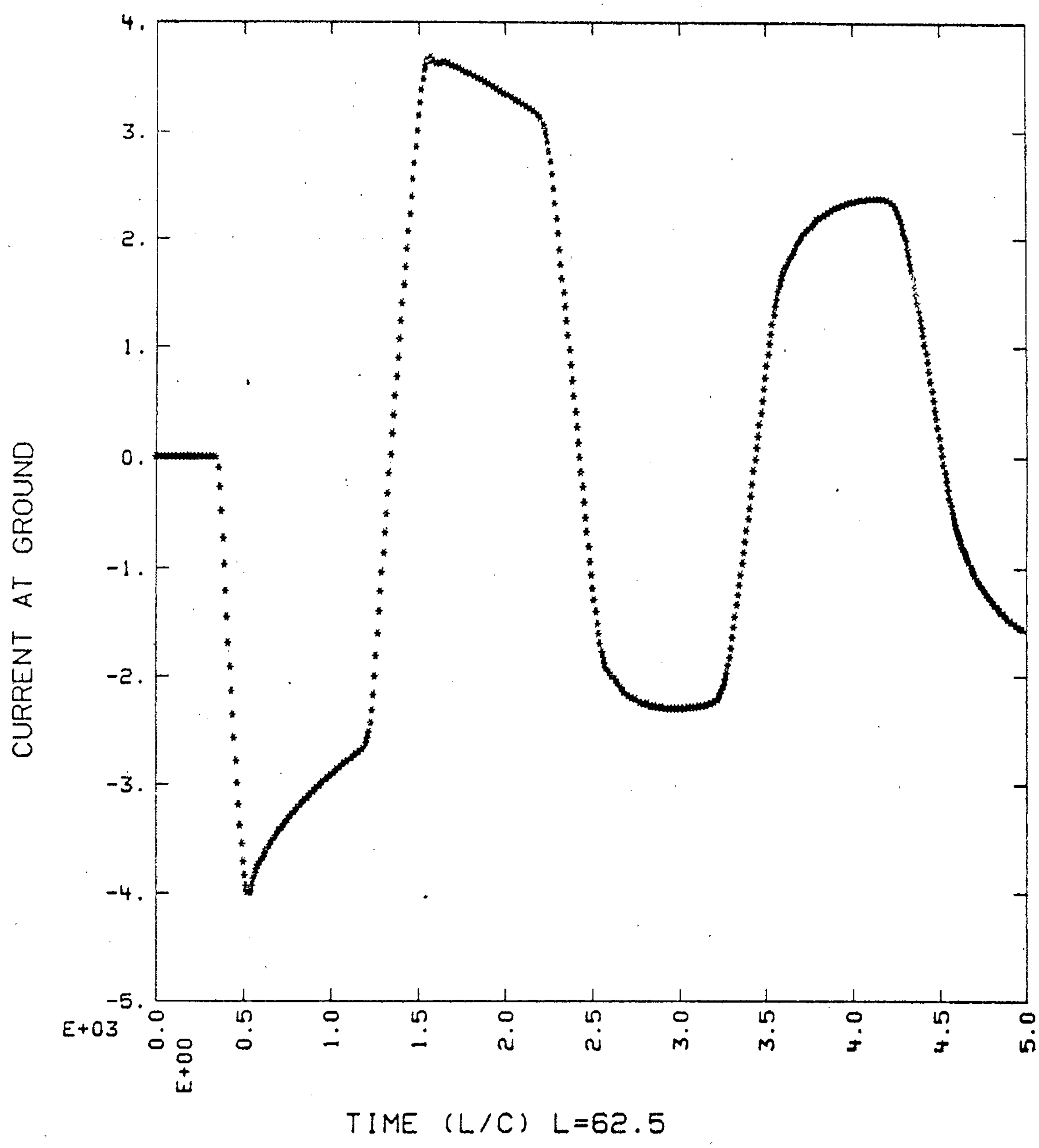

FIGURE 7. Current at ground level for a monopole above a perfect ground with an EMP plane wave incident.

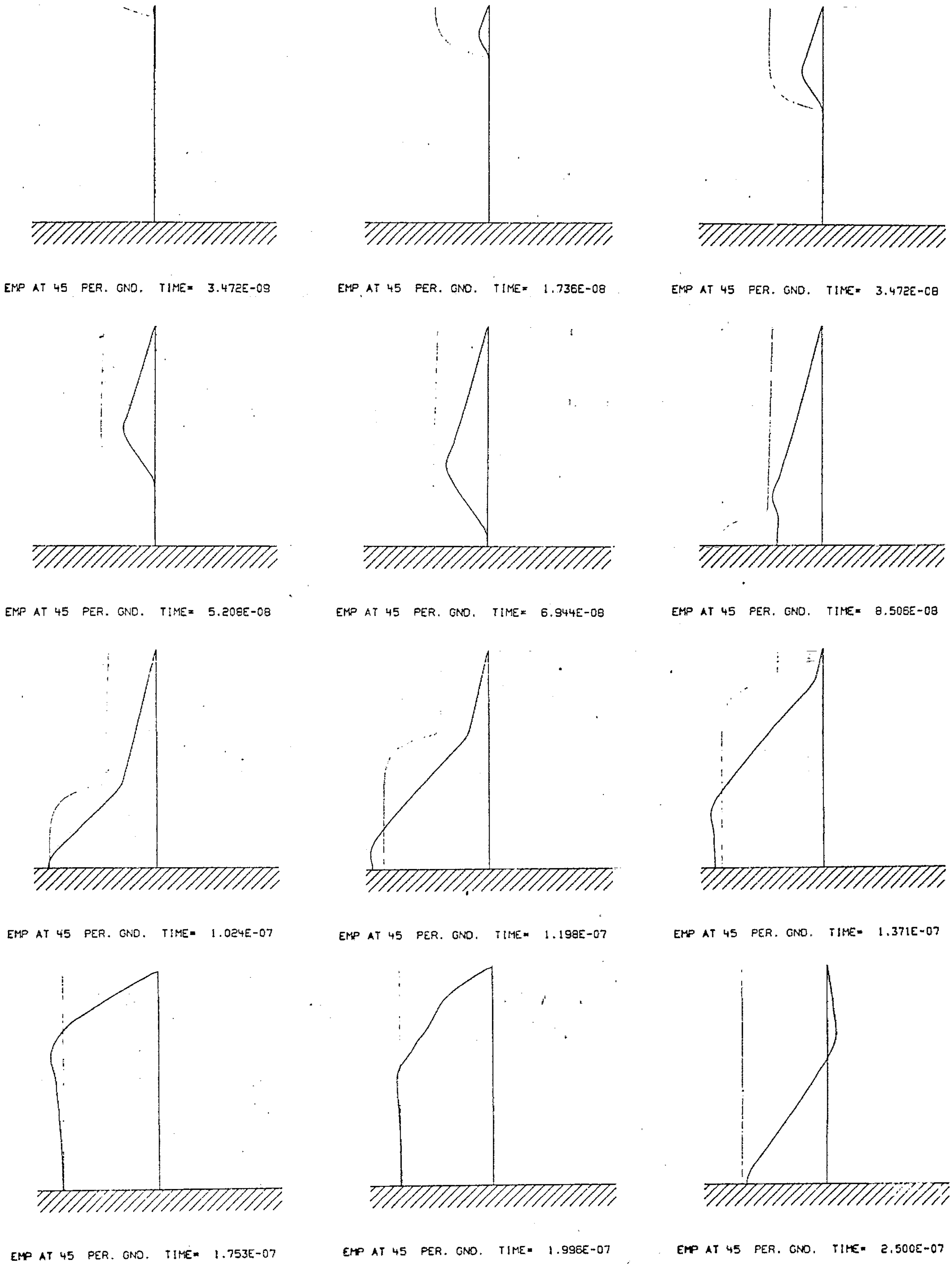

FIGURE 8. Development of current for a monopole above a perfect ground.