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Comparison of ATLOG and Xyce for Bell Labs Electromagnetic Pulse Excitation of Finite-Long Dissipative Conductors over a Ground Plane

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Abstract

This report details the modeling results for the response of a finite-length dissipative conductor interacting with a conducting ground to the Bell Labs electromagnetic pulse excitation. We use both a frequency-domain and a time-domain method based on transmission line theory through a code we call ATLOG – Analytic Transmission Line Over Ground. Results are compared to the circuit simulator Xyce for selected cases.

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1. INTRODUCTION

The purpose of this report is to provide results for the current induced on finite-length dissipative conductors interacting with a conducting ground, when excited by the Bell Labs electromagnetic pulse (EMP). We will make use of both a frequency-domain and a time-domain method based on transmission line theory through a code we call ATLOG – Analytic Transmission Line Over Ground. Results will be compared to the circuit simulator Xyce. We describe the problem at hand in Section 2, report the frequency-domain formulation in Section 3, the time-domain formulation in Section 4, and then proceed with the description of a finite-wire under the Bell Labs EMP in the remainder of this report. This drive waveform is being used here as an example; the theoretical model and ATLOG code are general and can be used to characterize transmission-line output for any pulse waveform.

2. DESCRIPTION OF THE EMP PROBLEM

We aim to model the EMP problem depicted in Figure 1: a finite-length conducting wire located at a distance h from the ground is excited by an EMP plane wave incidence. Our goal is to compute the current excited in the wire from such EMP coupling.

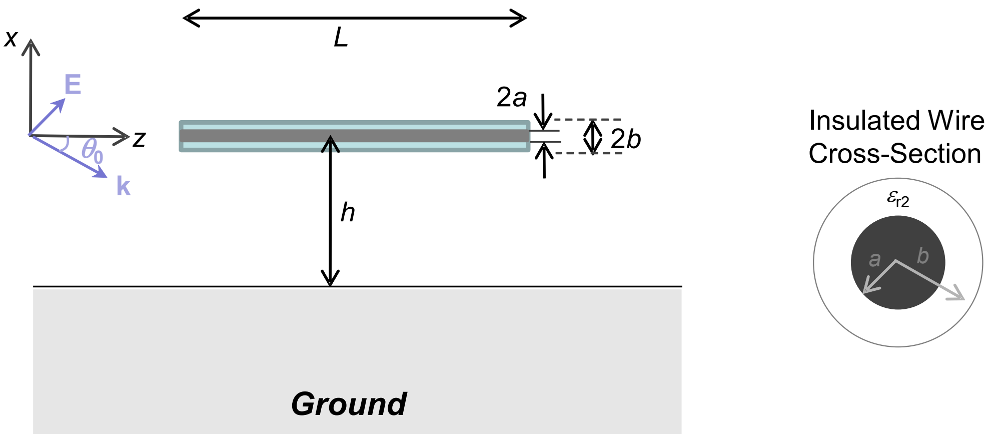

Figure 1. Schematic of the problem: a finite (coated) conducting wire with length *L* is located at a distance *h* from a conducting ground plane. The wire is illuminated by a Bell Labs plane wave excitation as depicted in the figure. The inset shows the wire cross section.

2.1. Bell Labs EMP excitation

We use the Bell Labs electromagnetic pulse waveform as excitation of the transmission line. A double exponential characterization of the waveform is [1]

$$E(t) = E_0\left(e^{-\alpha t} - e^{-\beta t}\right)u(t) \tag{1}$$

with $E_0 = 52.5\,\text{kV/m}$, $\alpha = 4\times10^6\ \text{s}^{-1}$, $\beta = 4.76\times10^8\ \text{s}^{-1}$. The peak amplitude is $50\,\text{kV/m}$, with a 10% to 90% rise time of 4.15 ns, and a fall time from peak to 50% of peak of 175 ns. The spectrum is

$$E(\omega) = \int_{-\infty}^{\infty} E(t)e^{-j\omega t}\,dt = \frac{E_0(\beta-\alpha)}{(\alpha+j\omega)(\beta+j\omega)}. \tag{2}$$

The double exponential waveform has a discontinuity at $\omega = 0$ which artificially enhances the high frequencies. Therefore, it is sometimes more convenient to use a fit without this discontinuity

$$E(t) = E_0\,\frac{de^{\alpha t}}{1+e^{\beta(t-t_p)}}. \tag{3}$$

The choice of parameters which fit the peak amplitude and the rise and fall times of the Bell Labs waveform are [2] $E_0 = 50\,\text{kV/m}$, $\alpha = 10.3\times10^8$ s^{-1}, $\beta = 10.34\times10^8$ s^{-1}, $d = 1.160227115\times10^{-9}$, and $t_p = 20\,\text{ns}$. The corresponding spectrum is

$$E(\omega) = E_0 d \frac{\pi}{\beta} \frac{e^{(\alpha - j\omega)t_p}}{\sin[(\alpha - j\omega)\pi/\beta]}. \tag{4}$$

2.2. Frequency-domain ATLOG model

The coupling to the transmission line mode from an incident plane wave is considered. This is the same calculation as carried out previously in [3-5] and references therein and is summarized here briefly for convenience. The transmission line equations are

$$\frac{dV}{dz} = -ZI + E_z^{\text{inc}}, \qquad \frac{dI}{dz} = -YV, \tag{5}$$

with the impedance given as the sum of three terms as $Z = Z_0 + Z_2 + Z_4$ and the admittance given as the sum of two terms as $\frac{1}{Y} = \frac{1}{Y_e} + \frac{1}{Y_4}$ with $Y_e = G_e + j\omega C_e$, $G_e = \frac{2\pi\sigma_{\text{air}}}{\ln(2h/b)}$ for $h >> b$, σ_{air} is the air conductivity, and all the other parameters are defined in [3-5].
The solution of Eq. (5) for finite lines is given by

$$\begin{aligned} I(z) &= [K_1 + P(z)]e^{-\gamma_L z} + [K_2 + Q(z)]e^{\gamma_L z} \\ V(z) &= \sqrt{\frac{Z}{Y}}\left\{[K_1 + P(z)]e^{-\gamma_L z} - [K_2 + Q(z)]e^{\gamma_L z}\right\}, \end{aligned} \tag{6}$$

with $P(z) = \frac{1}{2}\sqrt{\frac{Y}{Z}}\int_{z_-}^{z} e^{\gamma_L z} E_z^{\text{inc}}(z)dz$, $Q(z) = \frac{1}{2}\sqrt{\frac{Y}{Z}}\int_{z}^{z_+} e^{-\gamma_L z} E_z^{\text{inc}}(z)dz$, and $\gamma_L^2 = ZY$. Equations for other parameters are reported in [3].

2.3. Time-domain ATLOG model

The coupling to the transmission line mode from an incident plane wave is considered. This is the same calculation as carried out previously in [6] and is summarized here briefly for convenience.
The ladder network equations governing the current I and the voltage V are given by

$$\begin{aligned} \frac{\delta V}{\delta z} &= E_z^{\text{inc}} - RI - L\frac{\delta I}{\delta t} - \int_0^t \varsigma_g(t-\tau)\frac{\delta I(\tau)}{\delta z}d\tau \\ \frac{\delta I}{\delta z} &= -GV - C\frac{\delta V}{\delta t} \end{aligned} \tag{7}$$

which can be numerically integrated. In Eq. (7), we assume we know the distribution of the drive field E_z^{inc} (without the wire) along the line. The parameters R, L, G, and C represent the per-unit-length resistance, inductance, conductance, and capacitance. For simplicity in this section we assume that the wire has radius $a = b$, i.e. no dielectric coating. The resistance R accounts for losses in the wire as

$$R = \frac{1}{\sigma_0 \pi a^2} \tag{8}$$

where σ_0 is the wire conductivity and a the wire radius. The conductance G appears only if the air became ionized during the burst, leading to conductivity in the air σ_{air} for which

$$G = \frac{2\pi\sigma_{\text{air}}}{\log\left(\frac{h}{b} + \sqrt{\left(\frac{h}{b}\right)^2 - 1}\right)} \tag{9}$$

where h is the height at which the wire is located, and b represents the radius of an insulation layer, if present; otherwise, $b = a$. The capacitance C is given by

$$C = \frac{2\pi\varepsilon_{\text{air}}\varepsilon_0}{\log\left(\frac{h}{b} + \sqrt{\left(\frac{h}{b}\right)^2 - 1}\right)} \tag{10}$$

where ε_{air} is the relative permittivity of the air and ε_0 is the absolute permittivity of vacuum. The inductance L is given by

$$L = \frac{\mu_0}{2\pi} \log\left(\frac{h}{b} + \sqrt{\left(\frac{h}{b}\right)^2 - 1}\right) \tag{11}$$

where μ_0 is the absolute permeability of vacuum. The ground impedance ς_g is given by [7]

$$\varsigma_g(t) = e^{-\alpha_1 t}\varsigma_{g,E}(t) + \left(1 - e^{-\alpha_1 t}\right)\varsigma_{g,L}(t) \tag{12}$$

where $\alpha_1 = 80/\tau_L$ is a fitting parameter, with $\tau_L = 1/f_L$, $f_L = \min\left(\frac{0.1\sigma_g}{2\pi\varepsilon_g}, \frac{0.1c}{2\pi h}\right)$, c is the speed of light, and $\varsigma_{g,E}(t)$ and $\varsigma_{g,L}(t)$ are early and late time approximations as

$$\begin{aligned} \varsigma_{g,E}(t) &= \frac{\sqrt{\mu_0/\varepsilon_g}}{2\pi h} e^{-\sigma_g t/(2\varepsilon_g)} I_0\left(\sigma_g t/(2\varepsilon_g)\right) \\ \varsigma_{g,L}(t) &= \frac{\mu_0}{\pi\tau_g}\left[\frac{\beta}{2\sqrt{\pi}} + \frac{1}{4}\left(e^{\beta^2}\operatorname{erfc}(\beta) - 1\right)\right] \end{aligned} \tag{13}$$

with $\beta = \sqrt{\tau_g/t}$, $\tau_g = h^2\sigma_g\mu_0$, σ_g the ground conductivity, ε_g the absolute ground permittivity, and I_0 the modified Bessel function of the first kind of order 0.

To numerically integrate Eq. (7), we break up the length into discrete distances $z_n = n\Delta = nl/N$, (with $n = 0,1,\ldots,N$, l the wire length, and N the number of segments) and half distances $z_{n-1/2} = (n-1/2)\Delta = (n-1/2)l/N$ (with $n = 1,2,\ldots,N$). Since we are initially interested in open circuit end conditions, we place the currents at the nodal locations and the voltages at the half nodal locations

$$
\begin{aligned}
I_n &= I(z_n) \\
V_n^{\text{inc}} &= \Delta E_z^{\text{inc}}(z_n) \\
L_n &= \Delta L(z_n) \\
R_n &= \Delta R(z_n) \\
V_{n-1/2} &= V(z_{n-1/2}) \\
G_{n-1/2} &= \Delta G(z_{n-1/2}) \\
C_{n-1/2} &= \Delta C(z_{n-1/2})
\end{aligned}
\tag{14}
$$

with

$$
\begin{aligned}
\Delta \frac{\delta I}{\delta z}(z_{n-1/2}) &= I(z_n) - I(z_{n-1/2}) = I_n - I_{n-1} \\
\Delta \frac{\delta V}{\delta z}(z_n) &= V(z_{n+1/2}) - V(z_{n-1/2}) = V_{n+1/2} - V_{n-1/2}
\end{aligned}
\tag{15}
$$

Thus, following Eq. (7) we can write the transmission line equations as

$$
\begin{aligned}
V_{n+1/2} - V_{n-1/2} &= V_n^{\text{inc}} - R_n I_n - L_n \frac{\delta I_n}{\delta t} - \int_0^t \varsigma_g (t-\tau) \frac{\delta I(\tau)}{\delta z} d\tau \\
I_n - I_{n-1} &= -G_{n-1/2} V_{n-1/2} - C_{n-1/2} \frac{\delta V_{n-1/2}}{\delta t}
\end{aligned}
\tag{16}
$$

Putting these into standard form for the ODE solver, we get

$$
\begin{aligned}
\frac{\delta I_n}{\delta t} &= \frac{V_n^{\text{inc}}}{L_n} - \frac{R_n}{L_n} I_n - \frac{(V_{n+1/2} - V_{n-1/2})}{L_n} - \frac{1}{L_n}\int_0^t \varsigma_g (t-\tau) \frac{\delta I(\tau)}{\delta z} d\tau \quad , \quad n = 1,\ldots,N-1 \\
\frac{\delta V_{n-1/2}}{\delta t} &= -\frac{G_{n-1/2}}{C_{n-1/2}} V_{n-1/2} - \frac{(I_n - I_{n-1})}{C_{n-1/2}} \quad , \quad n = 1,\ldots,N
\end{aligned}
\tag{17}
$$

where for open circuit conditions we have for all time that $I_0 = I_N = 0$ which implies $\frac{\partial I_0}{\partial t} = \frac{\partial I_N}{\partial t} = 0$. We have $2N-1$ equations in $N-1$ unknown currents and N unknown voltages.

3. SIMULATION RESULTS FOR FINITE WIRES

In this section we report results from the Bell Labs EMP excitation in Section 2.1. The parameters we first take in this section on the simulations are as follows: lossy ground with $\varepsilon_4 = 10\varepsilon_0$ and $\sigma_4 = 0.0015\,\text{S/m}$ or PEC ground, $\varepsilon_2 = \varepsilon_0$ (i.e. no coating), $a = b = 1.27\,\text{cm}$, and $\sigma_0 = \dfrac{1}{R\pi a^2} = 2.9281\times10^7\,\text{S/m}$ using $R = 6.74\times10^{-5}\,\Omega/\text{m}$. We consider a 100 m long wire above ground with $h = 10\,\text{m}$. The finite line is left open-circuited at both ends.

The induced current in the middle of the 100 m line computed using the two implementations of ATLOG in Section 2.2 and Section 2.3 and Xyce [8, 9] is reported in Figure 2 to Figure 5 for various ground and air conductivity conditions as described in the figure caption. Great agreement is observed among the different methods. Note that Xyce currently allows modeling PEC ground only. Note that $R = \dfrac{1}{\sigma_0\pi a^2}$ is taken as a constant in the time domain solution whereas the resistance per unit length R (and the internal inductance) of the wire vary in the frequency domain solution.

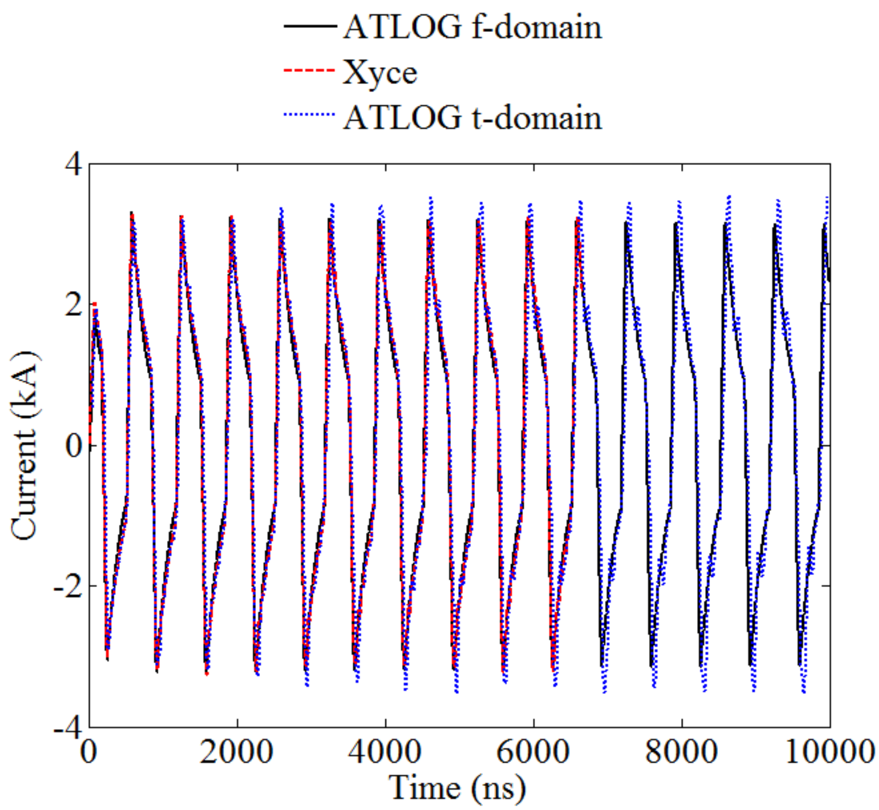

Figure 2. Current versus time for the Bell Labs excitation for a 100 m long line with PEC ground, no air conductivity. Results are based on the time-domain ATLOG model, the frequency-domain ATLOG model, and the Xyce circuit simulator. The current is evaluated at the center of the wire.

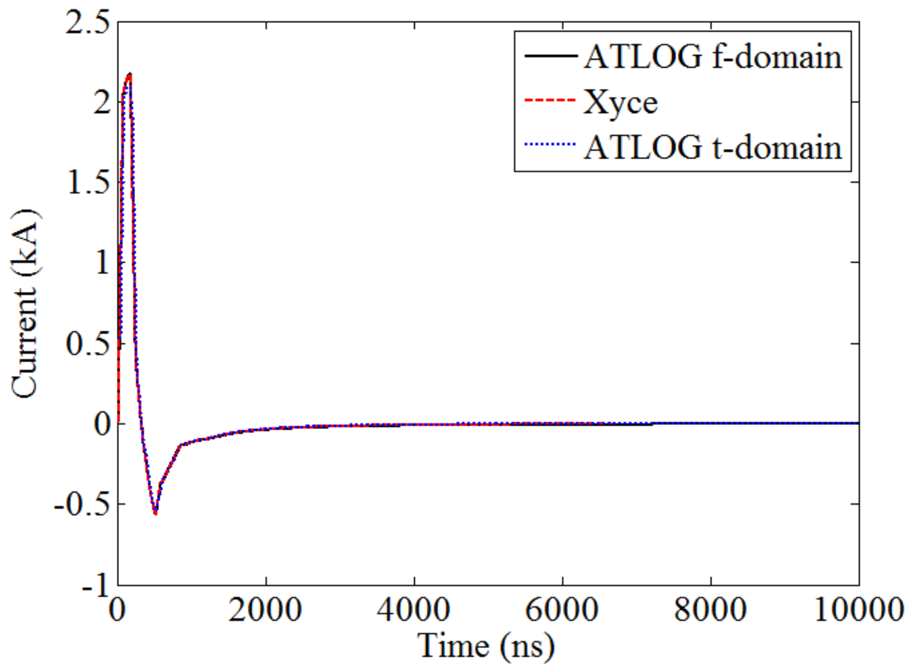

Figure 3. Current versus time for the Bell Labs excitation for a 100 m long line with PEC ground, 10^{-4} S/m constant air conductivity. Results are based on the time-domain ATLOG model, the frequency-domain ATLOG model, and the Xyce circuit simulator. The current is evaluated at the center of the wire.

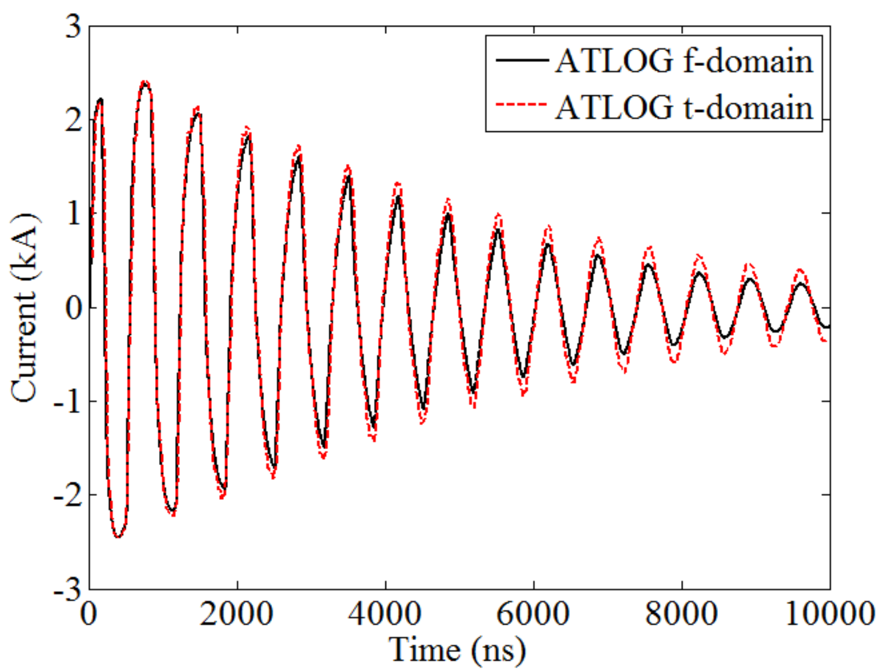

Figure 4. Current versus time for the Bell Labs excitation for a 100 m long line with lossy ground, no air conductivity. Results are based on

the time-domain ATLOG model and the frequency-domain ATLOG model. The current is evaluated at the center of the wire.

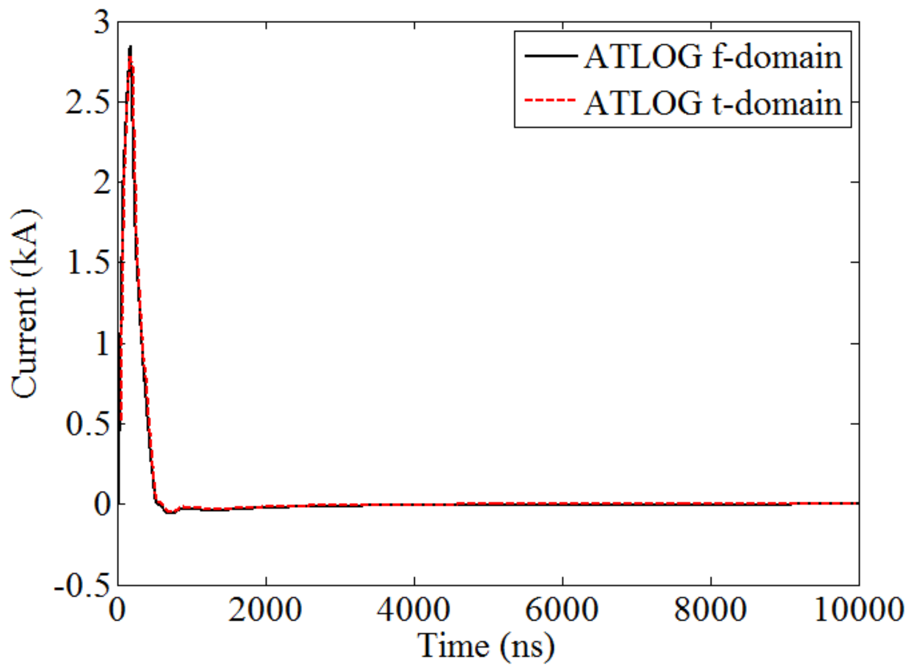

Figure 5. Current versus time for the Bell Labs excitation for a 100 m long line with lossy ground, 10^{-4} S/m constant air conductivity. Results are based on the time-domain ATLOG model and the frequency-domain ATLOG model. The current is evaluated at the center of the wire.

4. CONCLUSIONS

In this report we computed results for the current induced on finite-length conductors interacting with a conducting ground when excited by the Bell Labs electromagnetic pulse (EMP). We used both the frequency-domain and the time-domain ATLOG models, and compared these results to ones computed using the circuit simulator Xyce. Great agreement has been observed between the three models. The ATLOG model allows for the treatment of finite or infinite lossy, coated wires and lossy grounds. This capability in conjunction with the ability to treat a variety of different transmission-line scenarios (cable above ground, resting on the ground, and buried beneath the ground) makes our model general and a more complete tool for TL consequence assessment. The ATLOG method is offered as an alternative option to a full-wave solution, as opposed to a wholesale replacement method. It is our experience that this type of faster-running tool is extremely useful to quickly assess a wide variety of scenarios and determine relative impact over a wide parameter space. In addition, this type of tool may be of value because it does not necessarily require an expert user and, combined with other toolsets, can be used in an operator-mode for damage assessment.

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