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Finite and Infinite Lossy Conductors over a Lossy Ground Plane Excited by an Electromagnetic Pulse

Salvatore Campione, Larry K. Warne, Lorena I. Basilio, C. David Turner, Keith L. Cartwright, and Kenneth C. Chen

Electromagnetic Theory Department, Sandia National Laboratories, Albuquerque NM USA

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Motivation and background

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- The purpose of this talk is to provide results for the current on finite- and infinite-length conductors interacting with a conducting ground when excited by an electromagnetic pulse (EMP)
  - We focus here on the frequency-domain transmission line model, referred to as ATLOG – Analytic Transmission Line Over Ground
  - With the approximate transmission line model we can treat
    - Overhead cables
    - Buried cables
    - Insulated cables resting on the ground

Campione et al., *Journal of Electromagnetic Waves and Applications* **31**, 209-224, 2017

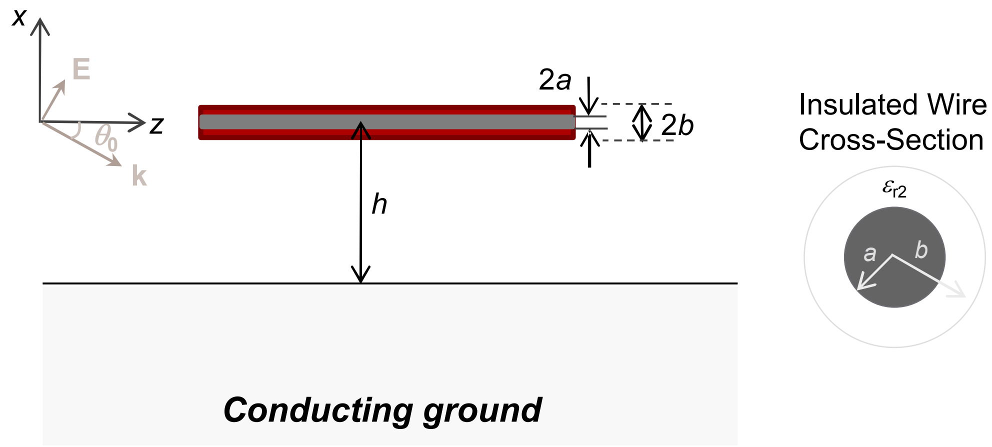
- We aim to obtain simple results for the current induced by the EMP radiation when the wire is either above, below, or resting on the ground

- When compared to the generally slow response of full-wave simulators, a benefit of the proposed ATLOG method is that it provides fast and reliable results. In particular, ATLOG allows one to more fully explore the scenario space and quickly determine impact. Due to the varying mesh scales required to resolve the problem (such as a jacketed cable over a lossy earth) with a full-wave tool, the problem size and solution run time can severely limit the ability to evaluate a wide variety of scenarios (e.g. parameterization studies) to more fully understand, for example, best-case/worst-case type situations.

- We consider the presence of losses for both the wire and the ground plane, usually not treated in previous works; some considerations toward this problem were treated in Paknahad et al., *IEEE Trans. Electromagn. Compat.* **56**, 1522-1529, 2014, but not for the general cases we analyze here that consider finite or infinite lossy, coated wires and lossy grounds, as well as wires above, below, or resting on the ground

Overview of ATLOG

- Analytical, frequency-domain code based on transmission line theory
  - ATLOG models wires interacting with a ground to an electromagnetic pulse (EMP) excitation
    - Lossy or perfectly-conducting ground can be considered
  - ATLOG treats:
    - Uncoated and coated infinite wires above ground, resting on the ground, or buried within the ground
    - Uncoated and coated finite wires above a ground, resting on the ground, and buried within the ground



- Summary of ATLOG capabilities:
  - Losses (constant) in the wire (coating or conductor) can be accounted for
  - Plane wave (Bell Labs waveform or Sine Squared waveform) illumination and specified electric field drive
  - Losses (constant) in the ground can be accounted for to emulate dry/moist dirt
  - Various (constant) air conductivities can be accounted for
  - Either infinite or finite lines can be considered
  - An attenuating plane wave along finite wire can be treated

Campione et al., *Journal of Electromagnetic Waves and Applications* **31**, 209-224, 2017

Infinite lines in ATLOG

- We start with the transmission line equations

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

$Z = Z_0 + Z_2 + Z_4$

Z_0 above ground term

Z_2 wire insulation

Z_4 ground conductivity

$\frac{1}{Y} = \frac{1}{Y_e} + \frac{1}{Y_4}$

Y_e external admittance

Y_4 ground conductivity

- Eliminating the voltage gives

$$\left(\frac{d^2}{dz^2} + k_L^2\right) I = -Y E_z^{\text{inc}}$$

- Whose solution is

$$I = -\frac{Y A_n e^{-jzk_0 \cos\theta_0}}{k_L^2 - k_0^2 \cos^2\theta_0}$$

- We inverse Fourier transform the current to obtain its temporal dependence

Warne and Chen, *SANDIA technical report SAND2004-0872*, 2004

Campione et al., *Journal of Electromagnetic Waves and Applications* **31**, 209-224, 2017

Finite lines in ATLOG

- A solution of the transmission line equation

$$\left(\frac{d^2}{dz^2}-\gamma_L^2\right)I=-YE_z^{\mathrm{inc}}$$

- Is given by

$$I(z)=\left[K_1+P(z)\right]e^{-\gamma_L z}+\left[K_2+Q(z)\right]e^{\gamma_L z}$$

$$V(z)=\sqrt{\frac{Z}{Y}}\left\{\left[K_1+P(z)\right]e^{-\gamma_L z}-\left[K_2+Q(z)\right]e^{\gamma_L z}\right\}$$

$$P(z)=\frac{1}{2}\sqrt{\frac{Y}{Z}}\int_{z_-}^{z}e^{\gamma_L z}E_z^{\mathrm{inc}}(z)dz \qquad Q(z)=\frac{1}{2}\sqrt{\frac{Y}{Z}}\int_{z}^{z_+}e^{-\gamma_L z}E_z^{\mathrm{inc}}(z)dz$$

$$K_1=\rho_-e^{\gamma_L z_-}\frac{\rho_+P(z_+)e^{-\gamma_L z_+}-Q(z_-)e^{\gamma_L z_+}}{e^{\gamma_L(z_+-z_-)}-\rho_-\rho_+e^{-\gamma_L(z_+-z_-)}}+\frac{\rho_-V_0(z_+)e^{\gamma_L z_-}\Big/\left(\sqrt{\frac{Z}{Y}}+Z_L^+\right)+V_0(z_-)e^{\gamma_L z_+}\Big/\left(\sqrt{\frac{Z}{Y}}+Z_L^-\right)}{e^{\gamma_L(z_+-z_-)}-\rho_-\rho_+e^{-\gamma_L(z_+-z_-)}}$$

$$K_2=\rho_+e^{-\gamma_L z_+}\frac{\rho_-Q(z_-)e^{\gamma_L z_-}-P(z_+)e^{-\gamma_L z_-}}{e^{\gamma_L(z_+-z_-)}-\rho_-\rho_+e^{-\gamma_L(z_+-z_-)}}-\frac{\rho_+V_0(z_-)e^{-\gamma_L z_+}\Big/\left(\sqrt{\frac{Z}{Y}}+Z_L^-\right)+V_0(z_+)e^{-\gamma_L z_-}\Big/\left(\sqrt{\frac{Z}{Y}}+Z_L^+\right)}{e^{\gamma_L(z_+-z_-)}-\rho_-\rho_+e^{-\gamma_L(z_+-z_-)}}$$

E. F. Vance, *Coupling to shielded cables*: R.E. Krieger, 1987

Campione et al., *Journal of Electromagnetic Waves and Applications* **31**, 209-224, 2017

ATLOG results for infinite lines with large ground conductivity

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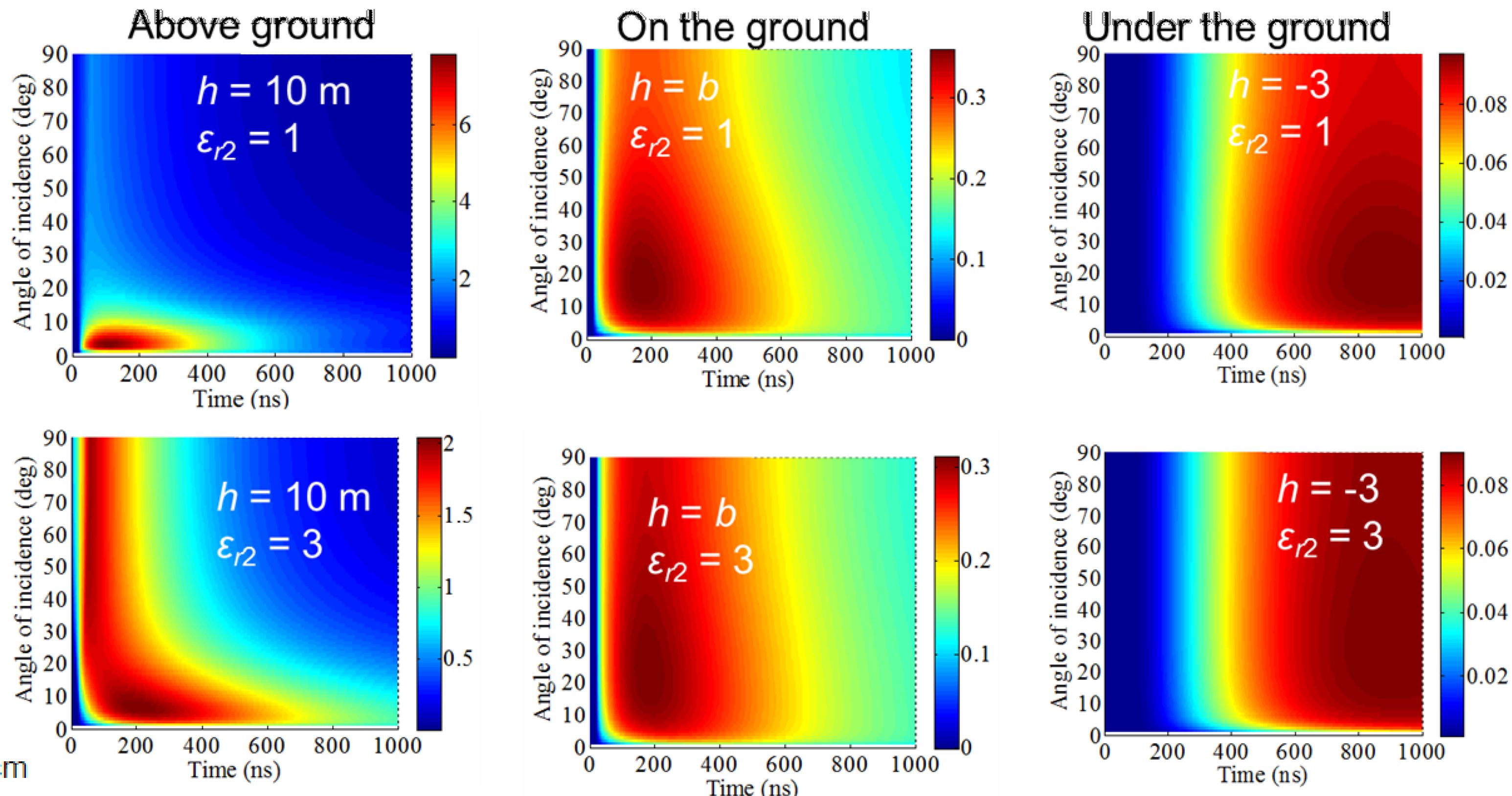
- ❑ We show here a subset of cases to demonstrate the capabilities of ATLOG

No coating

With coating



b = 2 cm

a = 1 cm

ε_{r4} = 20

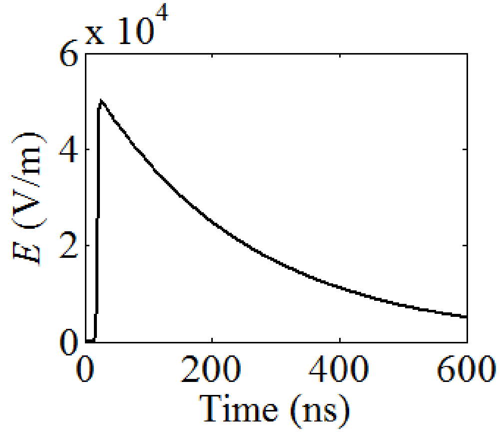
σ_4 = 0.1 S/m

- ❑ A dielectric coating of eps = 3 leads to a reduction of current of about a factor of 4 for above ground
- ❑ Larger peak currents are induced on the wire when it is above ground versus on the ground or under
- ❑ Results demonstrate that there is a preferable angle of incidence of the incoming radiation for above ground

EMP excitation employed in this presentation

- Bell Labs EMP

$$E(t) = E_0 \frac{d e^{\alpha t}}{1 + e^{\beta (t - t_p)}}$$



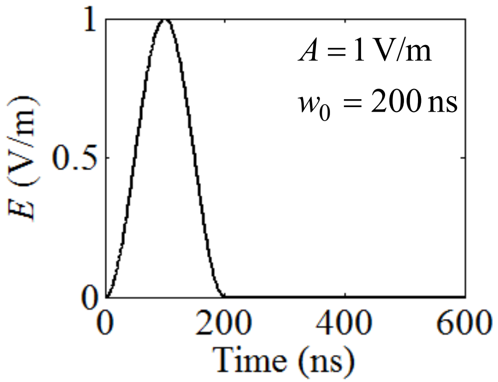
$$E(\omega) = E_0 d \frac{\pi}{\beta} \frac{e^{(\alpha - j\omega) t_p}}{\sin[(\alpha - j\omega)\pi / \beta]}$$

Warne and Chen, IEEE Trans. Electromagn. Compat. **36**, 149-154, 1994
Campione et al., *Journal of Electromagnetic Waves and Applications* **31**, 209-224, 2017

- Sine squared EMP

$$E(t) = A \sin^2\left(\frac{\pi t}{w_0}\right)$$

$$0 < t < w_0$$



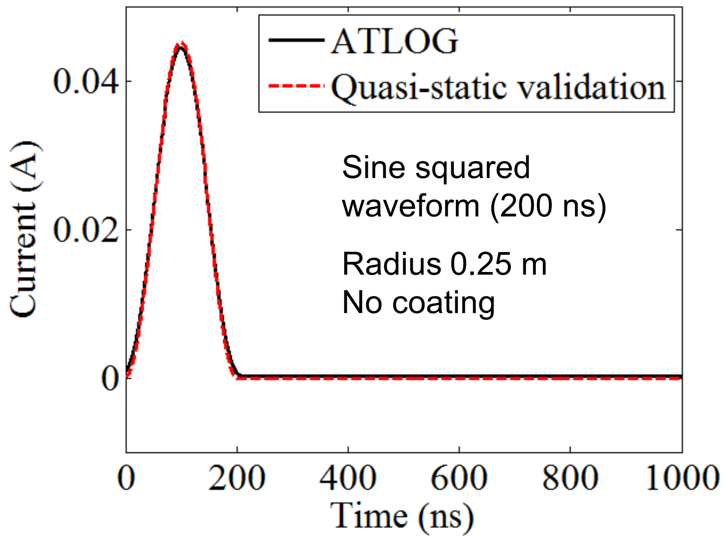
$$E(\omega) = \frac{A}{2 j \omega}\left(1 - e^{-j\omega w_0}\right) \frac{1}{\left(1 - \frac{\omega^2 w_0^2}{4\pi^2}\right)}$$

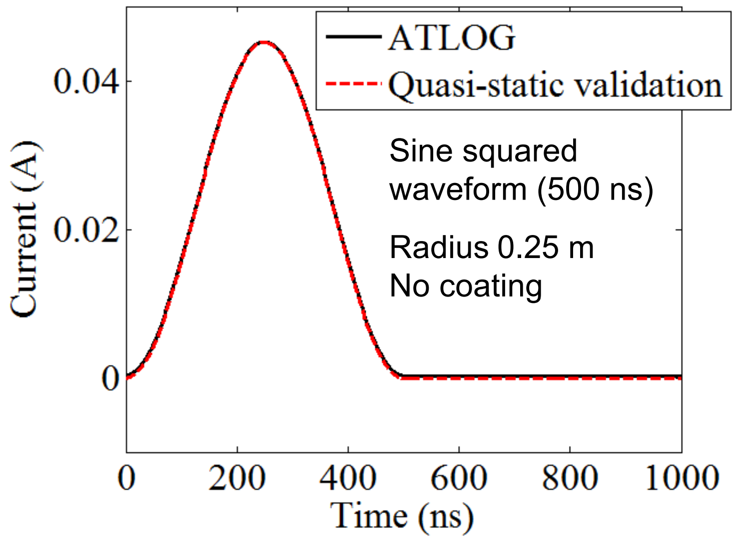
Campione et al., *Journal of Electromagnetic Waves and Applications* **31**, 209-224, 2017

ATLOG and Quasi-static approximation for infinite lines

- Assumption: Slowly rising waveform impinging on the infinite wire is quasi-static as far as the line height is concerned
- We take a contour *C* to be along the wire over a differential length *dz*, with a return path on the ground plane of length *dz*, with vertical segments between the wire and ground plane separated by *dz*. From Faraday's law the magnetic flux penetrating the surface enclosed by this contour *C* must nearly cancel. This let's us compute the current through the magnetic flux and the inductance per unit length of the wire

$$I = \frac{\phi}{L} \qquad \phi = \mu_0 h 2 H_{\text{inc}} \qquad L = \frac{\mu_0}{2\pi} \operatorname{arccosh}(h/a)$$





- Very good agreement between ATLOG and the Quasi-static approximation is observed

ATLOG results for infinite lines with medium ground conductivity

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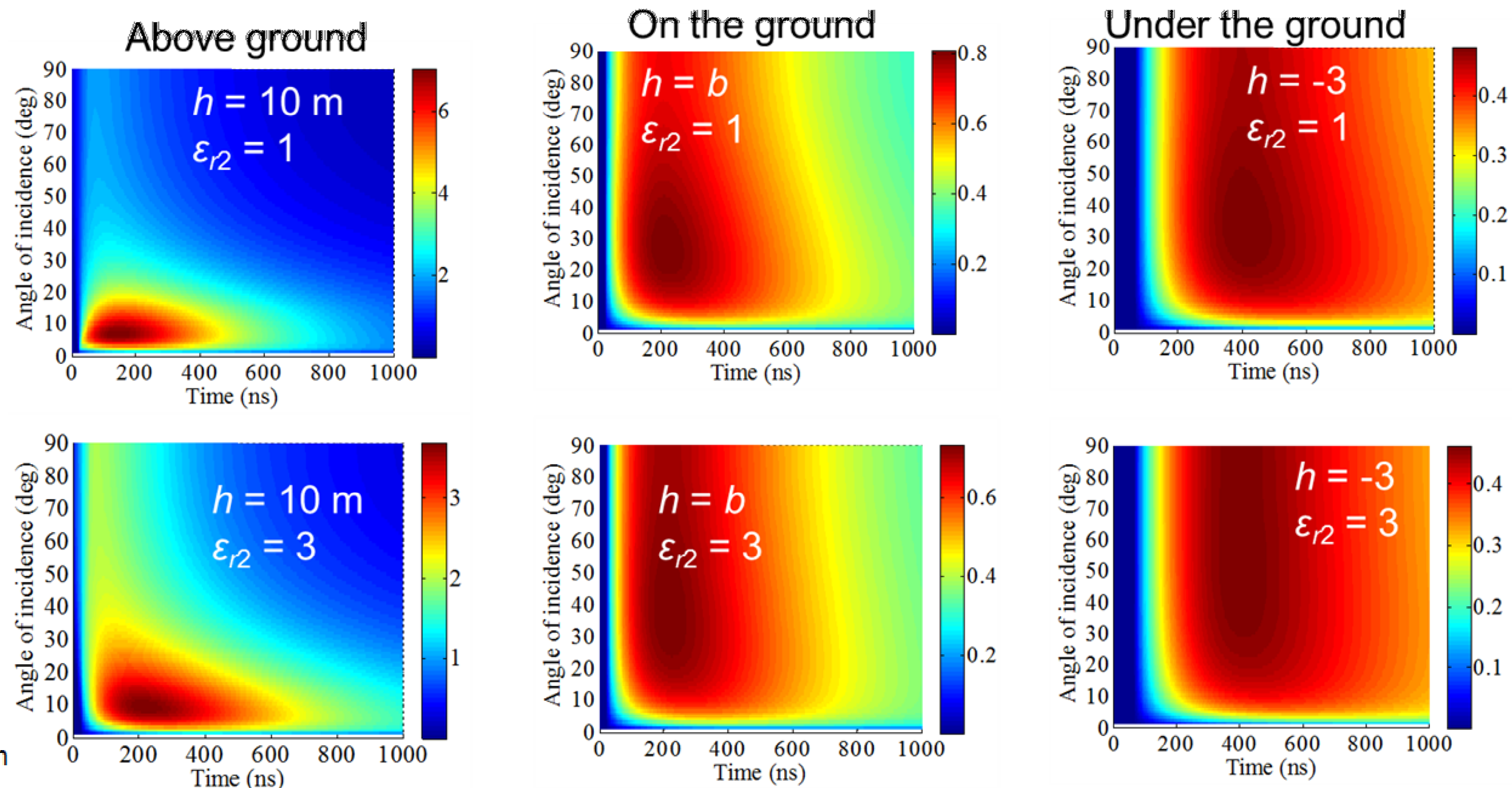
No coating

With coating



b = 2 cm

a = 1 cm

ε_{r4} = 20

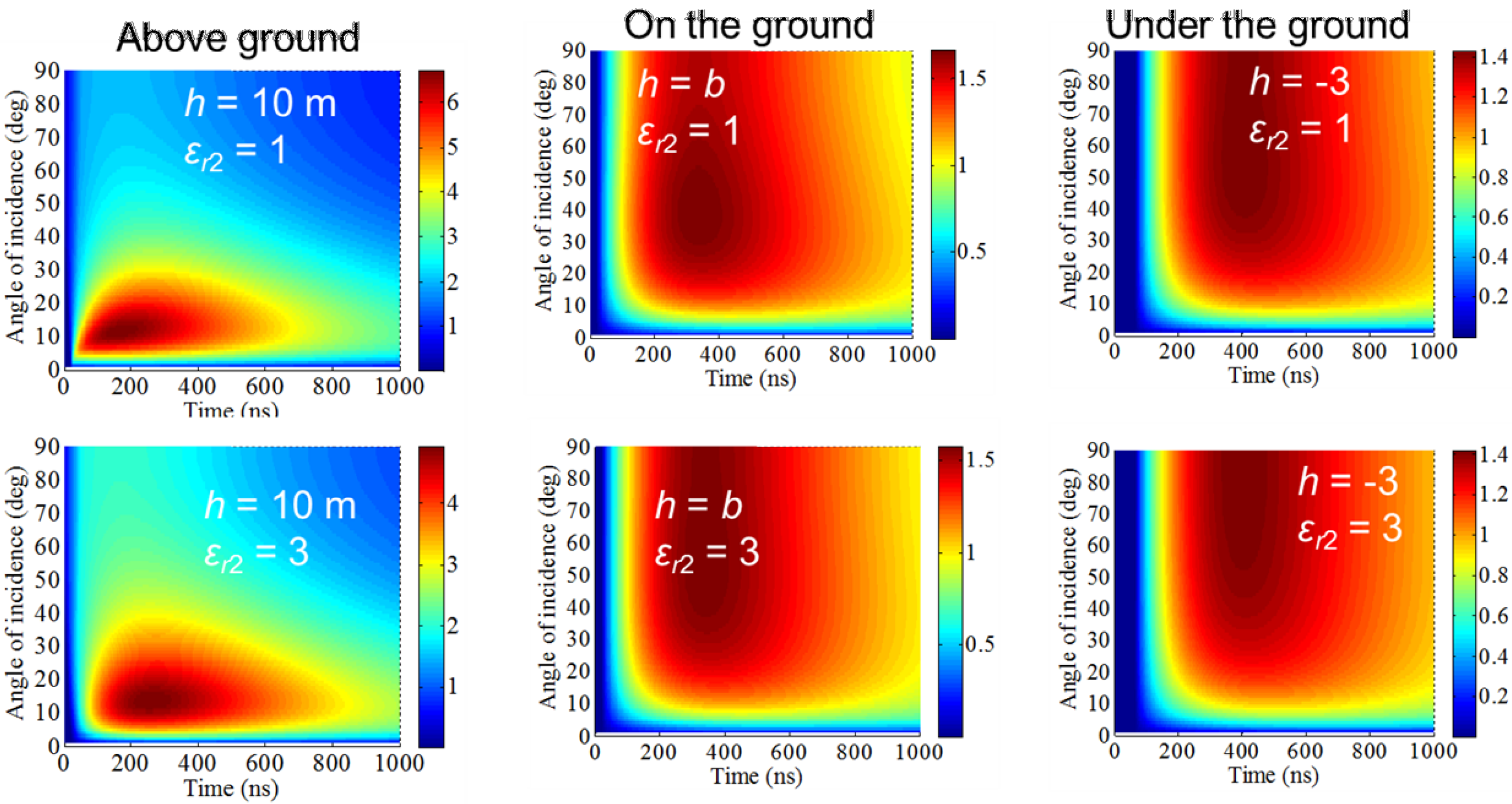
σ_4 = 0.01 S/m

- ❑ A dielectric coating of eps = 3 leads to a reduction of current of about a factor of 2 for above ground
- ❑ Larger peak currents are induced on the wire when it is above ground versus on the ground or under
- ❑ Results demonstrate that there is a preferable angle of incidence of the incoming radiation for above ground

ATLOG results for infinite lines with small ground conductivity

No coating

With coating



b = 2 cm

a = 1 cm

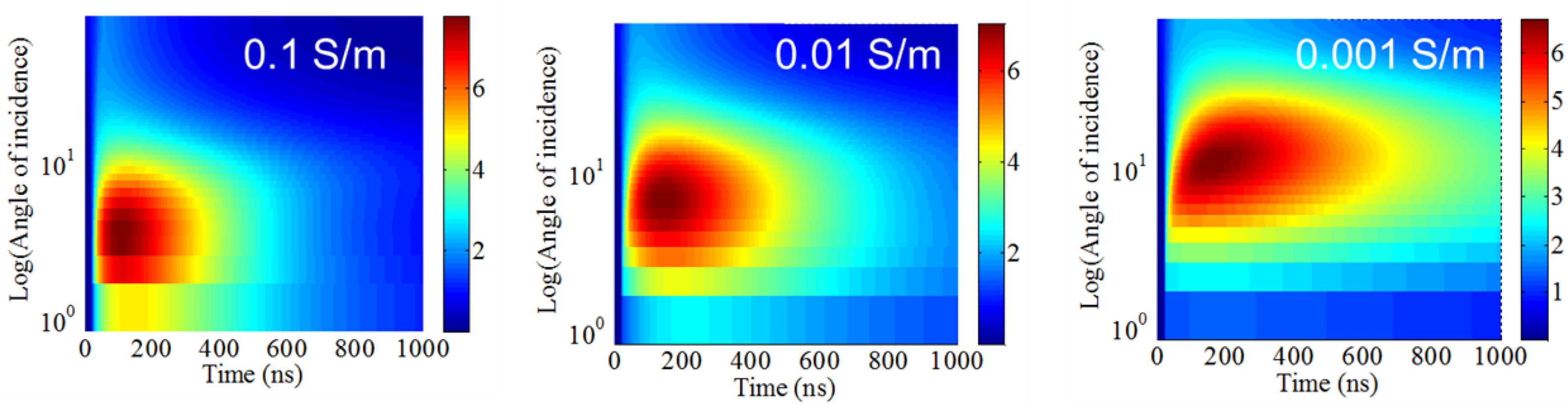
ε_{r4} = 20

σ_4 = 0.001 S/m

- ❑ A dielectric coating of eps = 3 leads to a reduction of current of about a factor of 1.4 for above ground
- ❑ Larger peak currents are induced on the wire when it is above ground versus on the ground or under
- ❑ Results demonstrate that there is a preferable angle of incidence of the incoming radiation for above ground

ATLOG results for infinite lines above ground, no coating versus ground conductivity

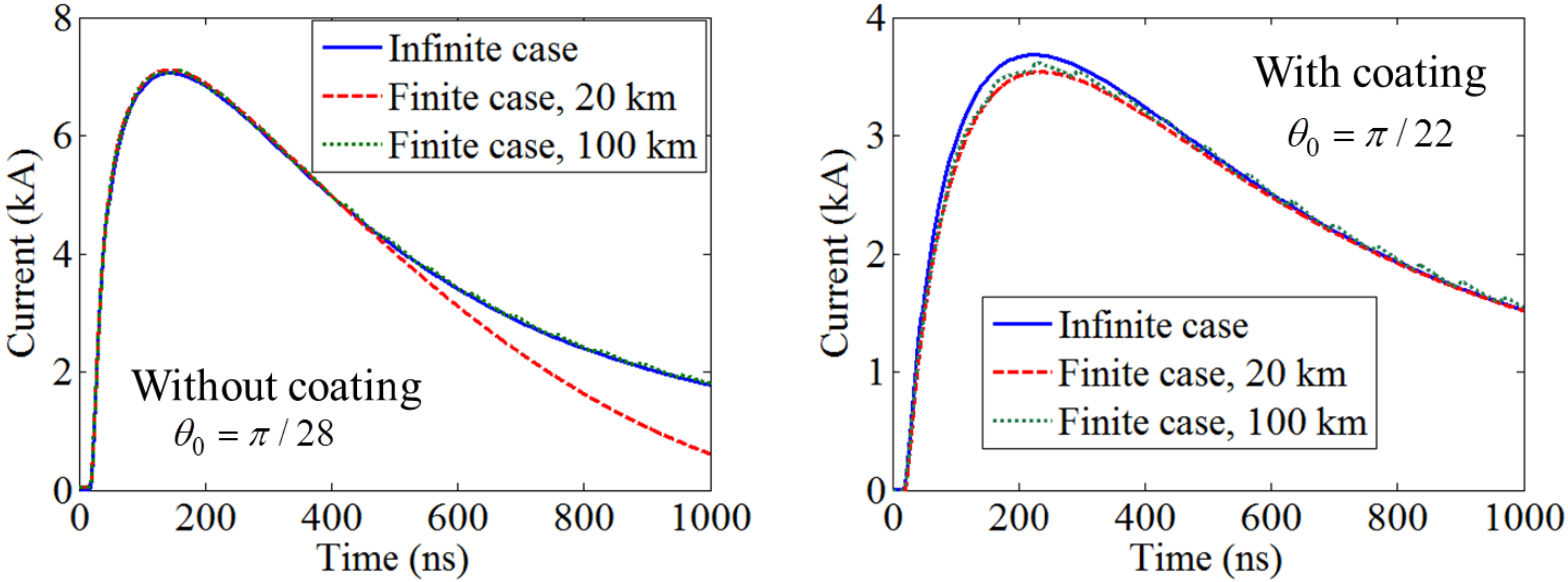
No coating



❑ The angle of incidence of the peak increases for decreasing ground conductivity

Finite-line ATLOG code verification

- We validate the finite line code against the infinite line solution

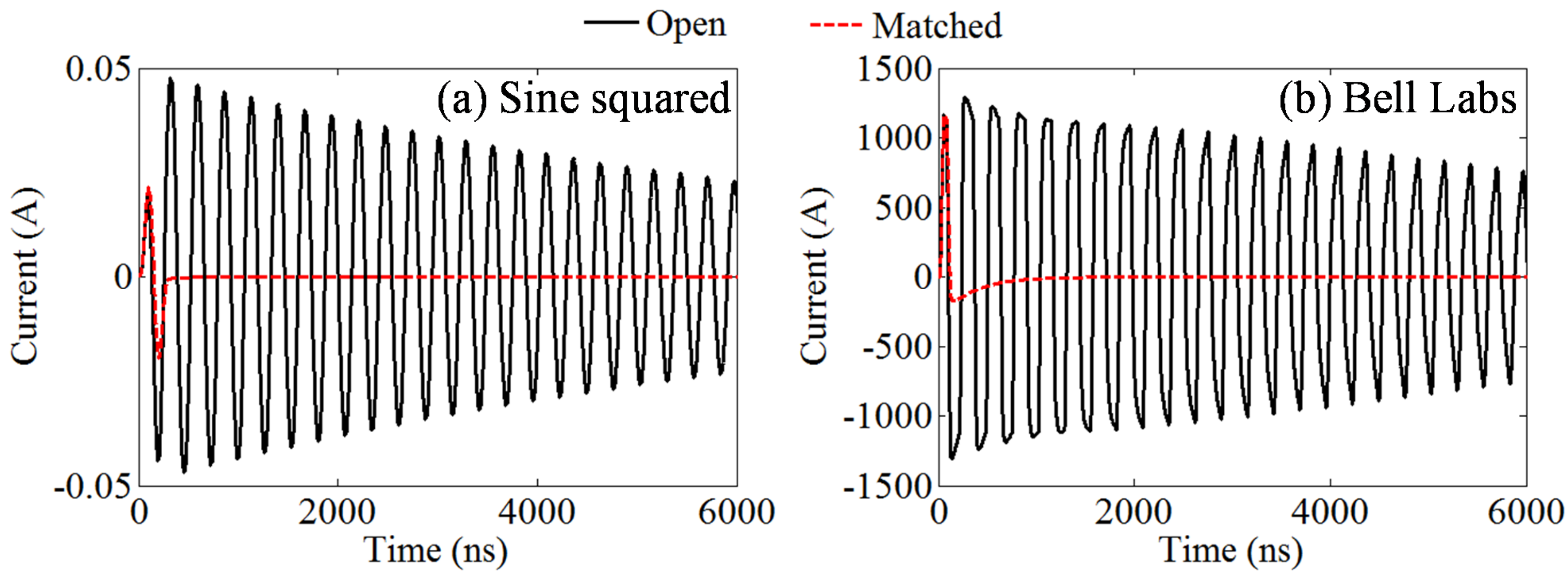


- The agreement shows that the finite line code is well implemented
  - Results merge with the infinite case as the length of the wire increases

- Disagreement at later times are due to the finite length of the line. (As expected, longer lines show better agreement.)

ATLOG results for finite lines

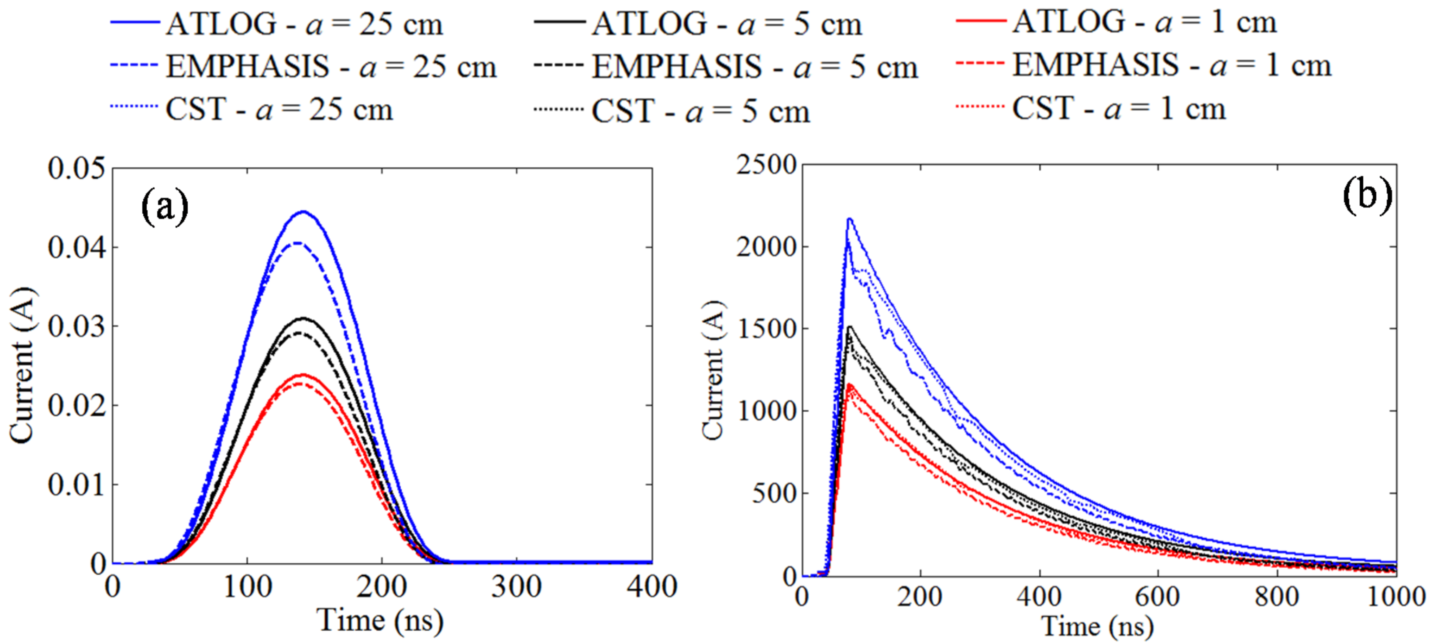
- 40 m long line, height of 5 m



- Very different behavior is observed for open-circuited versus matched finite lines
- Ringing is due to the finite extent of the line for the open-circuited case
- Damping is due to the wire and ground conductivities

ATLOG and full-wave solver EMPHASIS for infinite lines

- The ATLOG code is compared to the full-wave simulator EMPHASIS



PEC ground/wire

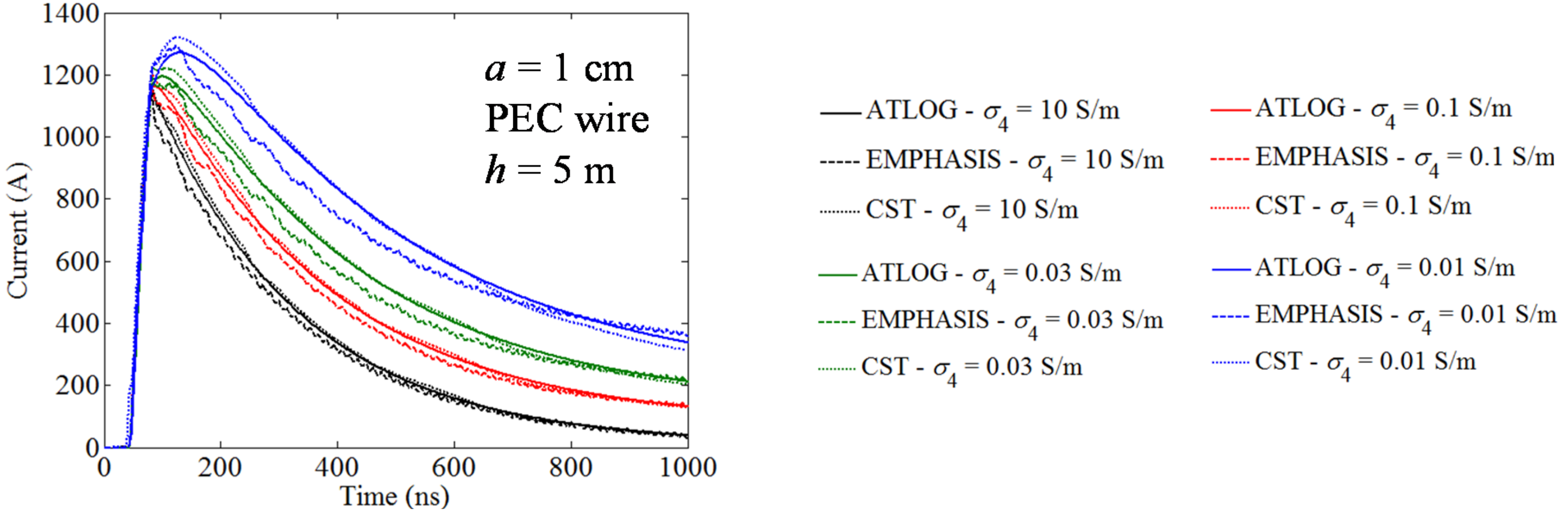
10 m height

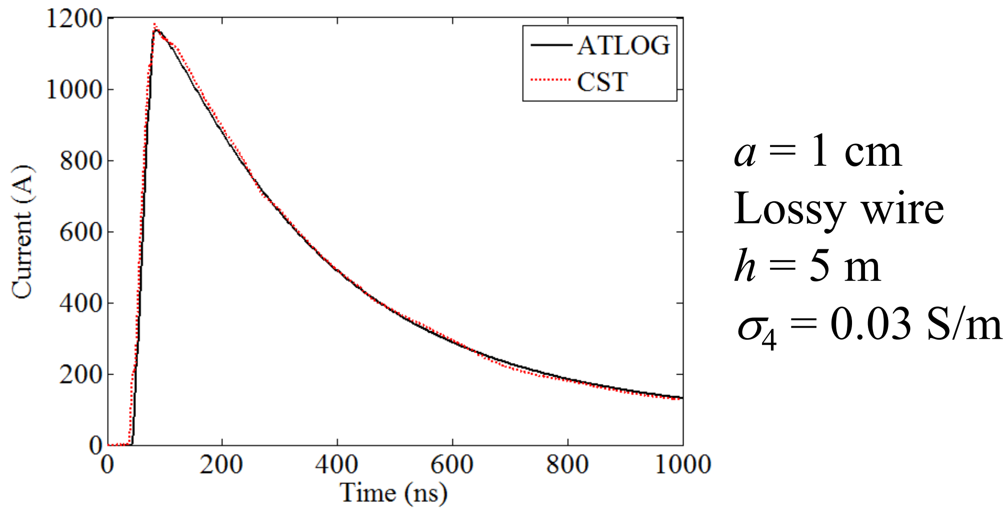
No coating

- Good agreement is observed
  - Note that the ATLOG result has been delayed by 41.67 ns to match the EMPHASIS simulation condition
- EMPHASIS results are based on a thin-wire approximation – This explains why better agreement between ATLOG and EMPHASIS is observed for smaller radii
  - The wire algorithm in EMPHASIS could be extended to account for fatter wires and better agreement would be observed
- The disagreement for small radii is also likely due to the way the thin-wire approximation implemented in EMPHASIS

ATLOG and full-wave solvers EMPHASIS and CST Microwave Studio for infinite lines

- The ATLOG code is compared to the full-wave simulators EMPHASIS and CST Microwave Studio

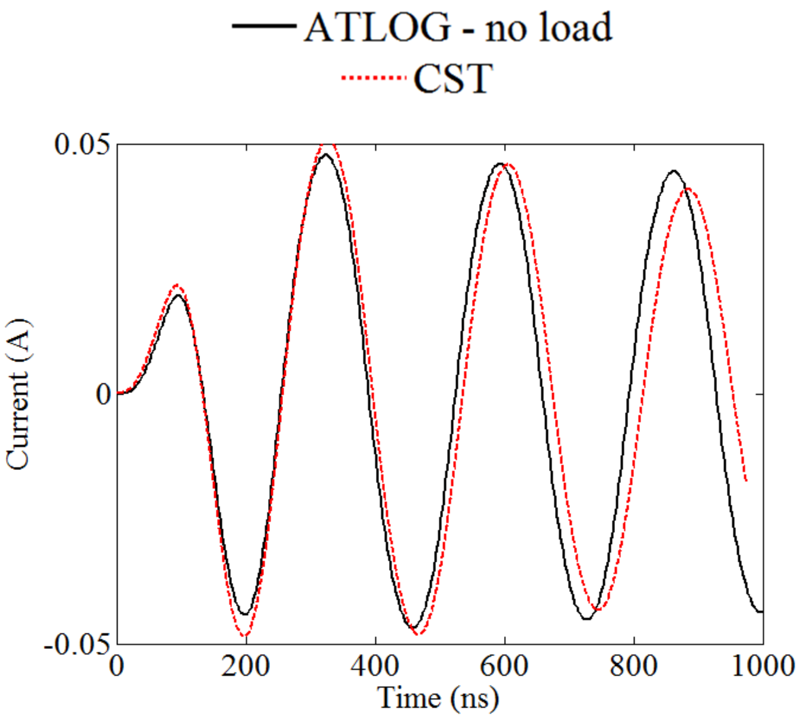


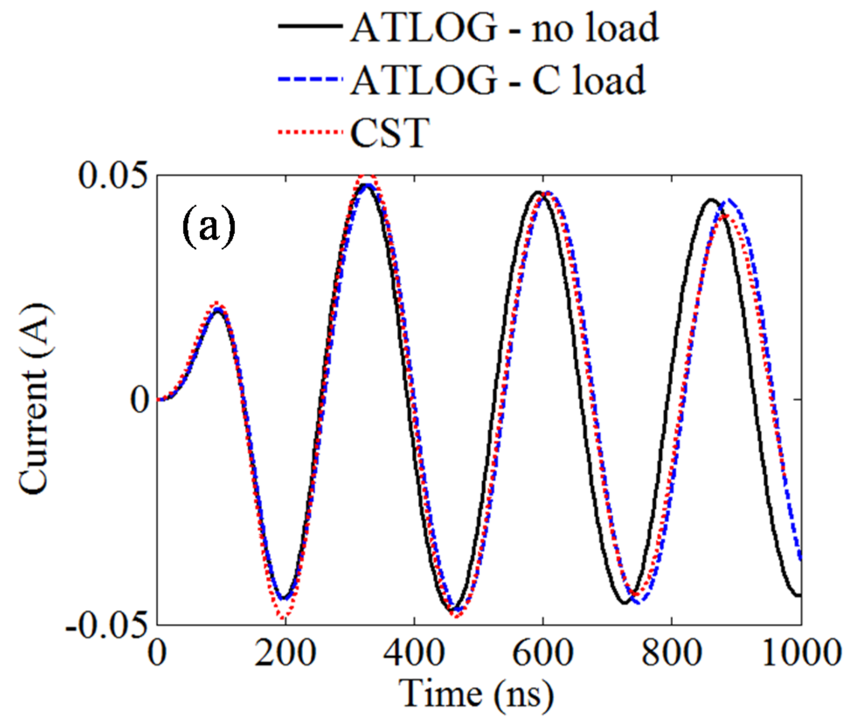


- Good agreement is observed

ATLOG and full-wave solver CST Microwave Studio for finite lines

- The ATLOG code is compared to the full-wave simulator CST Microwave Studio for a 40m long wire





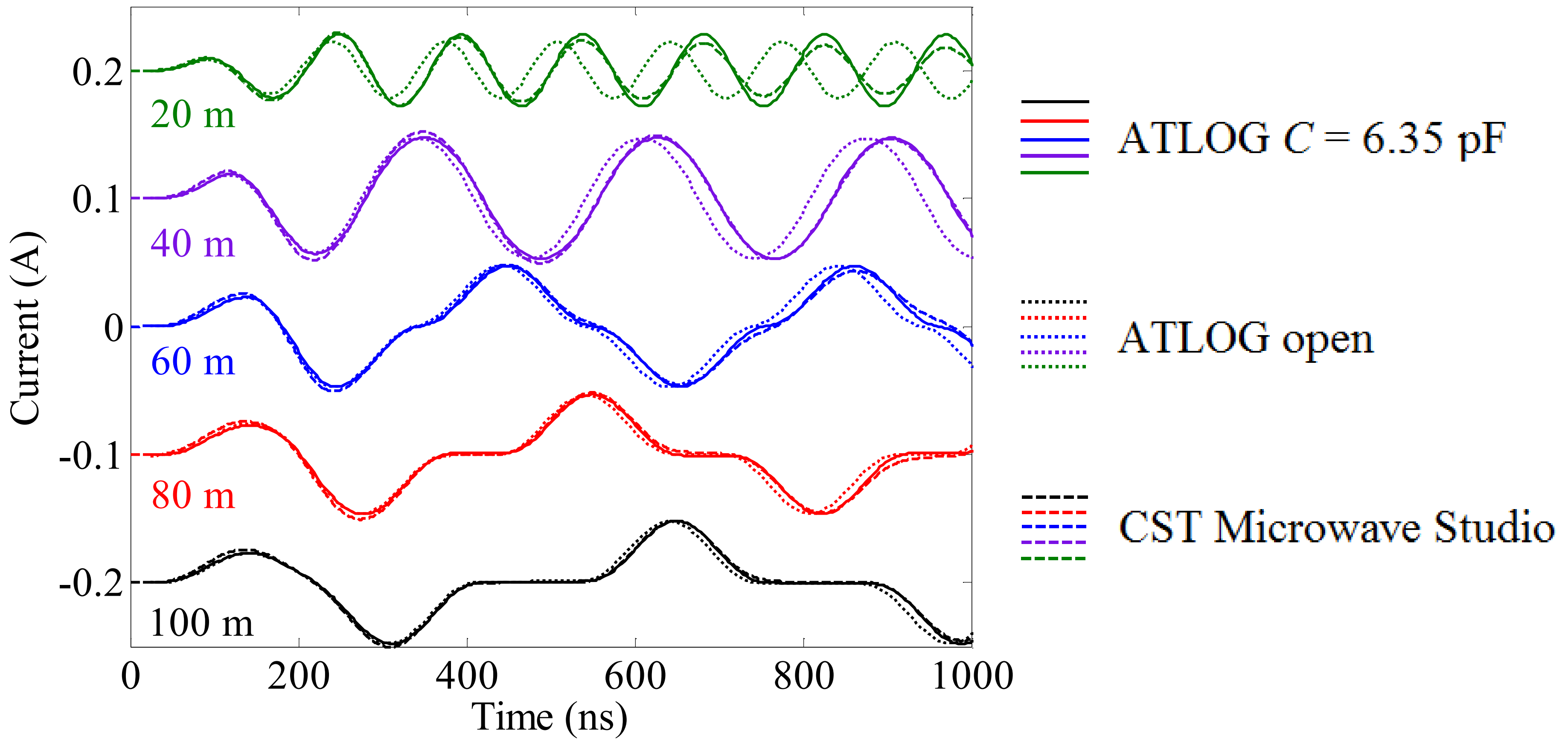
- Although we simulated an open-circuited finite wire in CST, one can see disagreement with ATLOG at late times

- This is because the terminated line does not act precisely as an open-circuit --- rather, because of the fringing electric fields, a capacitive load of 6.35 pF is needed to recover the full-wave result

- The inclusion of capacitive loads restores the agreement with CST

ATLOG and full-wave solver CST Microwave Studio for finite lines

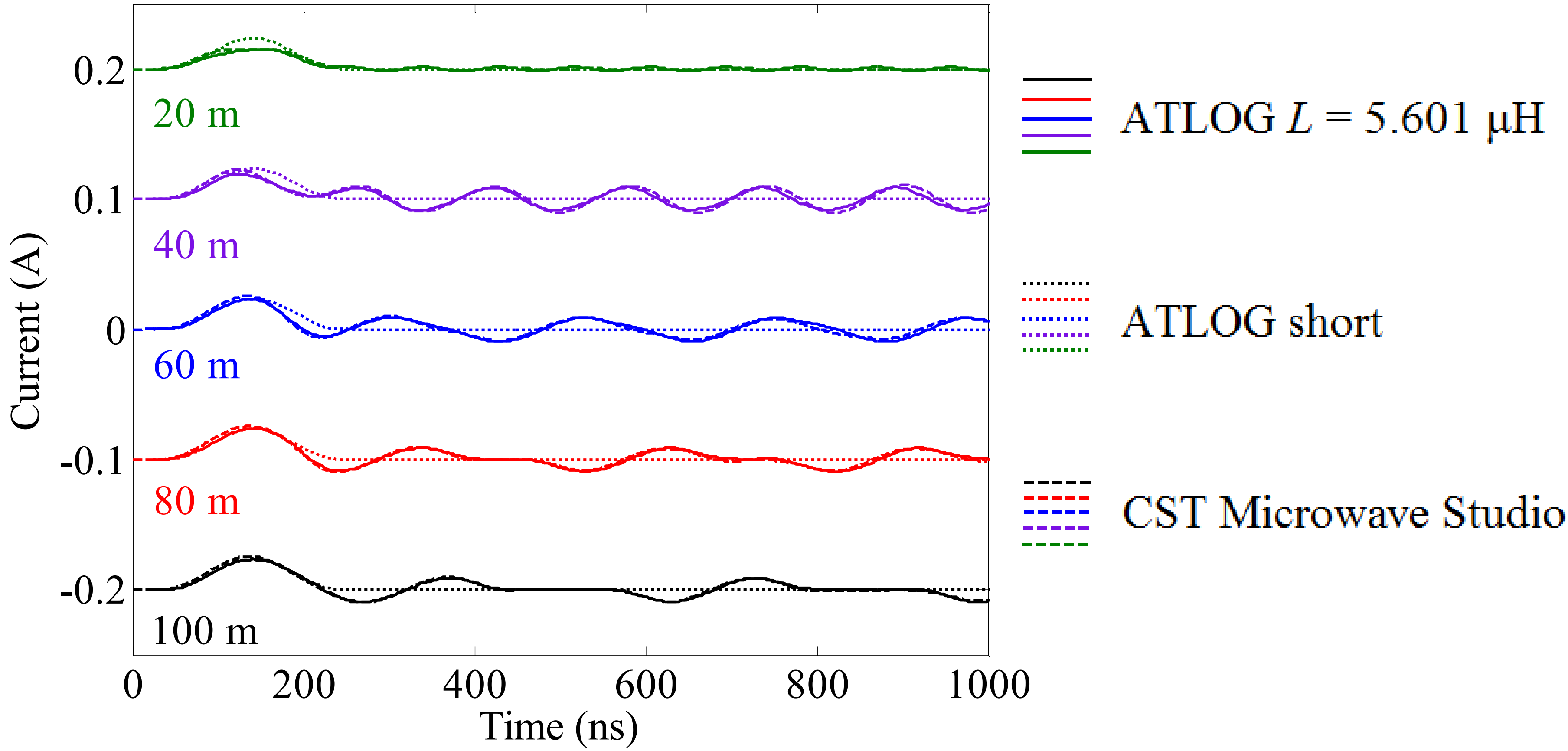
- The ATLOG code is compared to the full-wave simulator CST Microwave Studio
- Various lengths long lines, 1 cm radius, PEC wire, 5 m height, open terminations, normal incidence sine squared excitation, PEC ground



- Good agreement is observed
- For shorter lines, radiation effects may start affecting the result --- hence, some discrepancies appear for the 20 m line

ATLOG and full-wave solver CST Microwave Studio for finite lines

- The ATLOG code is compared to the full-wave simulator CST Microwave Studio
- Various lengths long lines, 1 cm radius, PEC wire, 5 m height, down conductor terminations, normal incidence sine squared excitation, PEC ground



- Good agreement is observed
- For shorter lines, radiation effects may start affecting the result --- hence, some discrepancies appear for the 20 m line

Conclusions

- We formulated a frequency-domain transmission-line model, named ATLOG, for the response of a finite- or an infinitely-long wire interacting with a conducting ground to an electromagnetic pulse excitation

- We can treat finite or infinite lossy, coated wires and lossy grounds

- This capability in conjunction with the ability to treat the cases of wire above ground, resting on the ground, and buried beneath the ground makes our model general and a complete tool for the analysis of this problem

- The ATLOG method in this talk is offered as an alternative option to a full-wave solution, as opposed to a 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

Campione et al., *Journal of Electromagnetic Waves and Applications* **31**, 209-224, 2017

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