A Discussion on the Inversion of Polarity of Lightning Far Electromagnetic Fields

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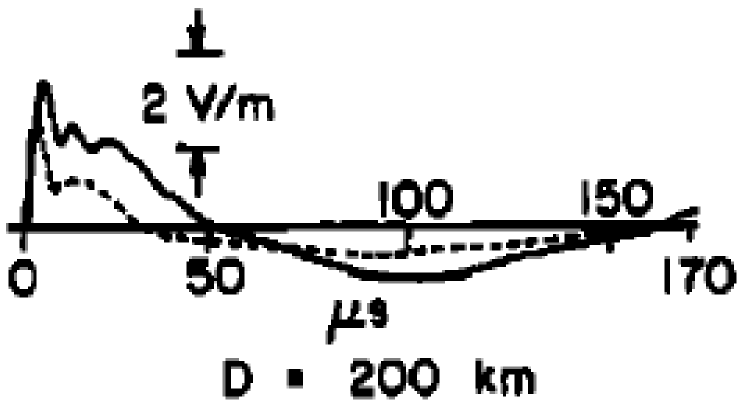
Introduction

- Electric and magnetic fields of a lightning return stroke channel exhibit an smooth polarity reversal at distances of about 50 km or beyond [*Lin, et al., 1979*].



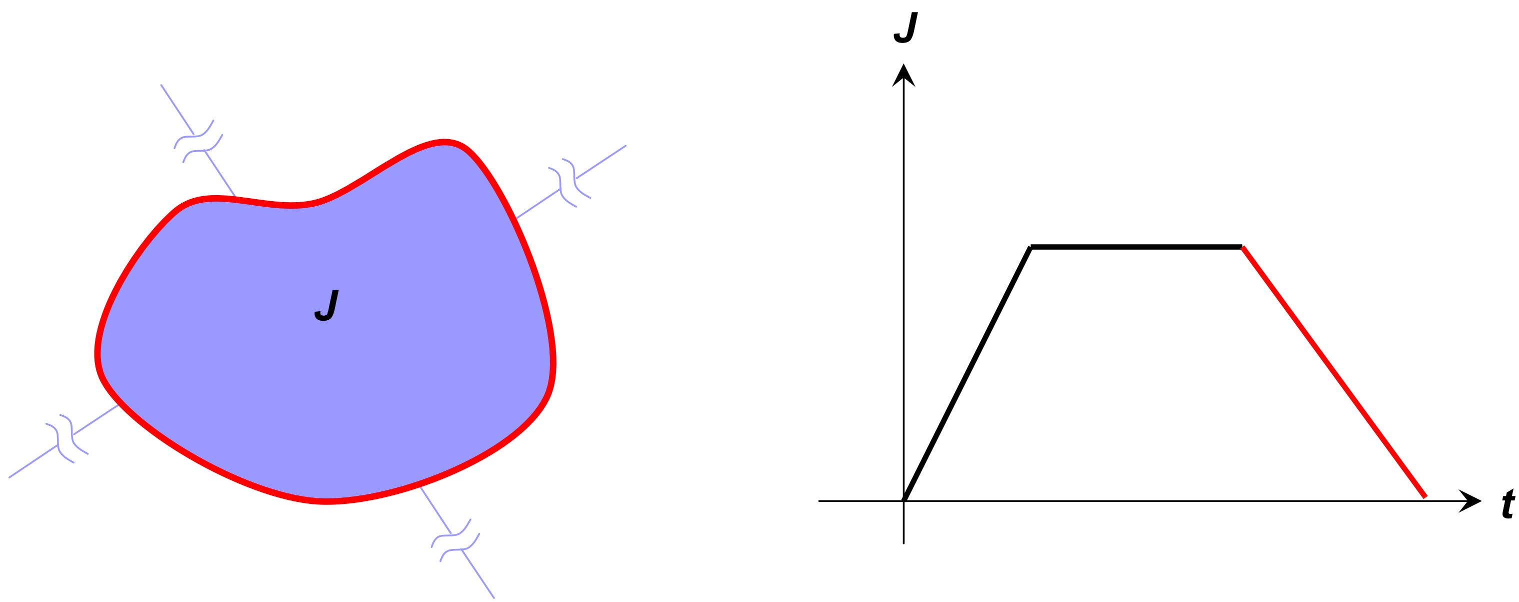
Introduction

- Typical zero crossing times [*Rakov and Uman, 2003*]

First	Subsequent
50 μs	35 μs

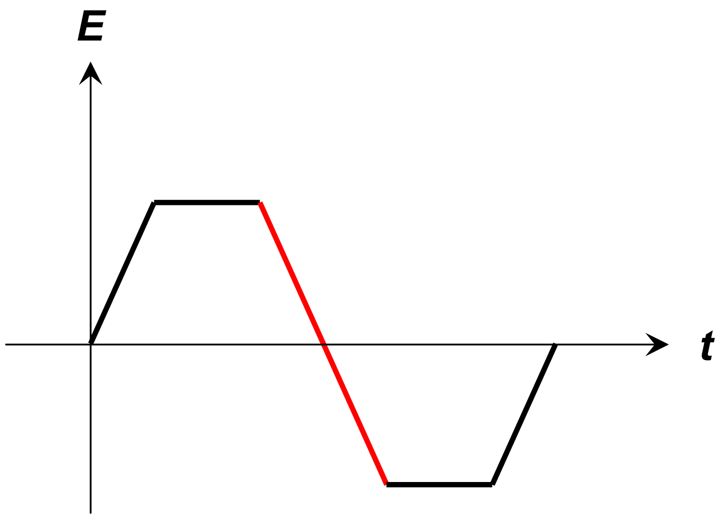
- Characteristic features are used to test the ability of return-stroke models to reproduce the observed electromagnetic fields .

Characteristics of time domain far fields [*Yaghjian and Hansen*, 1996]



Characteristics of time domain far fields [*Yaghjian and Hansen*, 1996]

$$\int_0^\infty E dt = 0$$



Implications

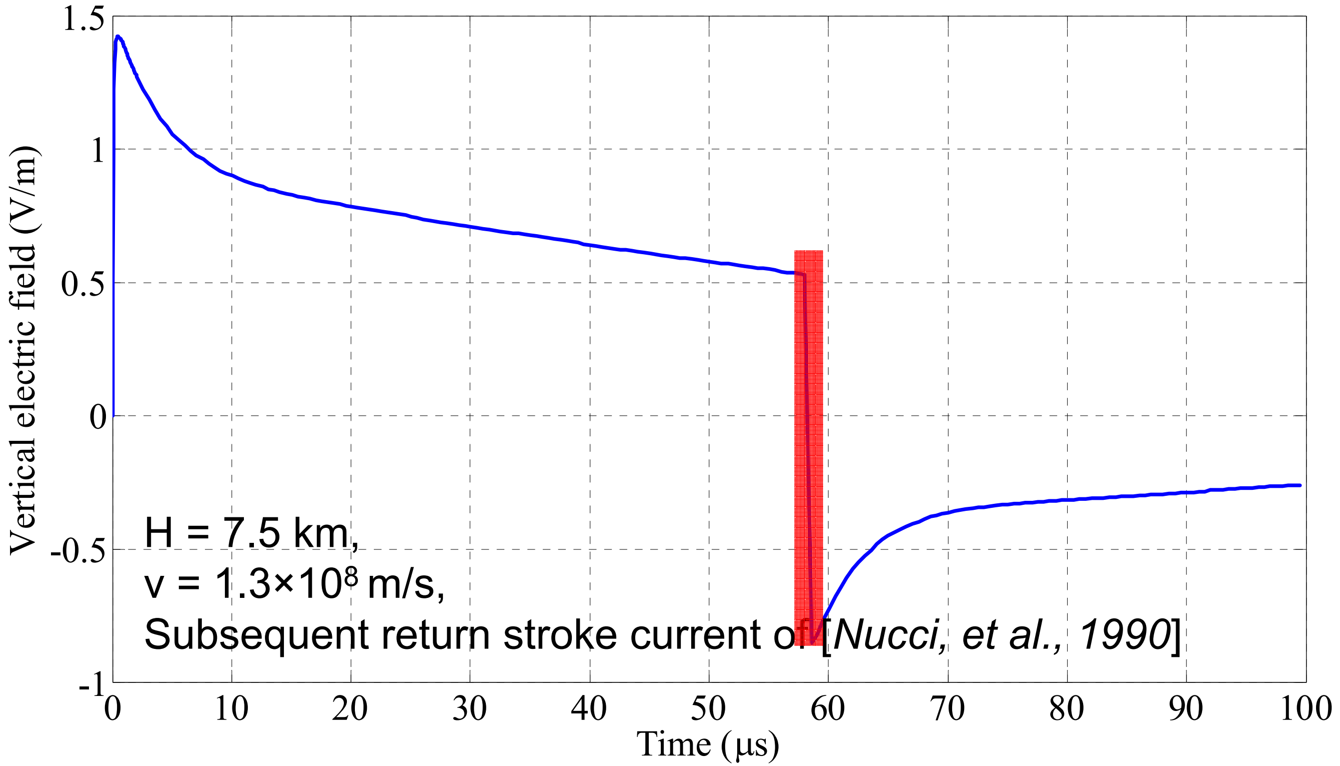
- Any one of the return stroke models including engineering and electromagnetic models should predict a zero crossing.

Implications

- One phenomenon responsible for the far field zero crossing is the boundary conditions at the top of the finite-length channel.
- This condition results in the abrupt polarity reversal of the far electric and magnetic fields.

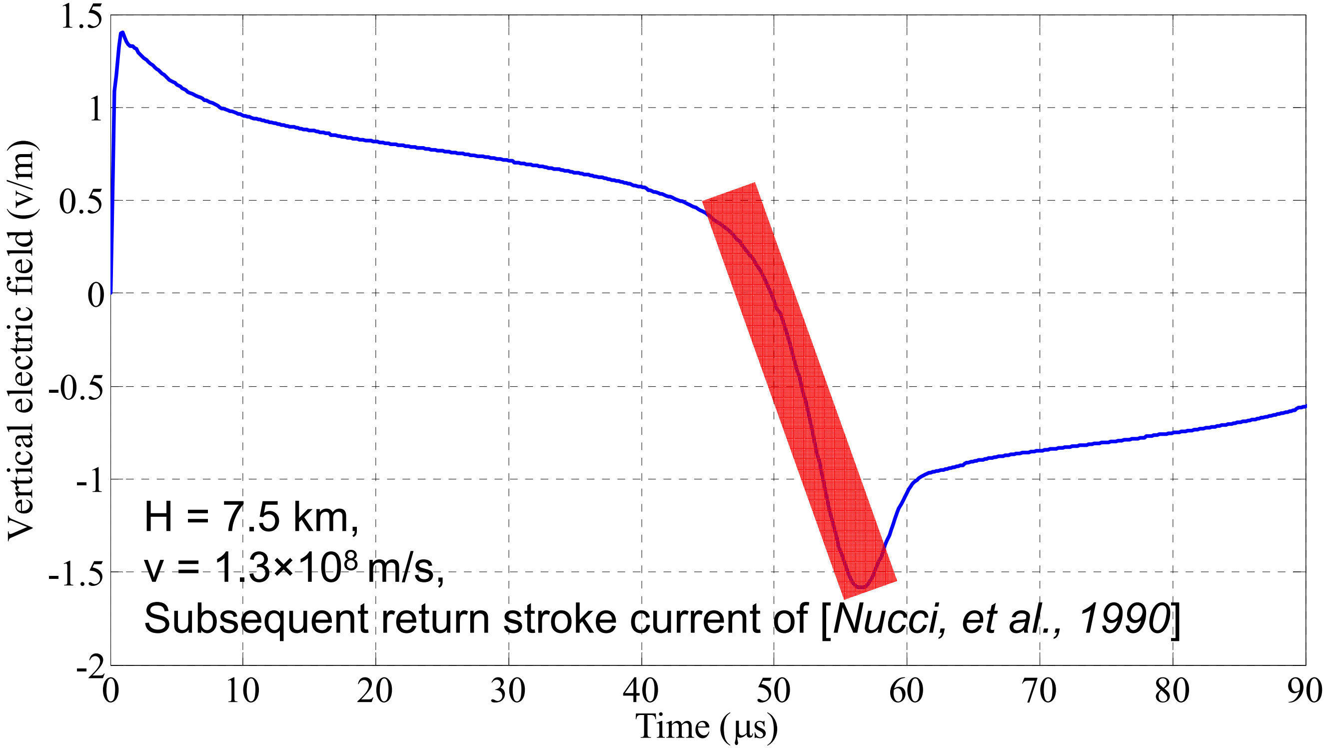
Implications

- For engineering models (like TL), this usually results in the so called "mirror image" effect [*Uman, et al.*, 1975].

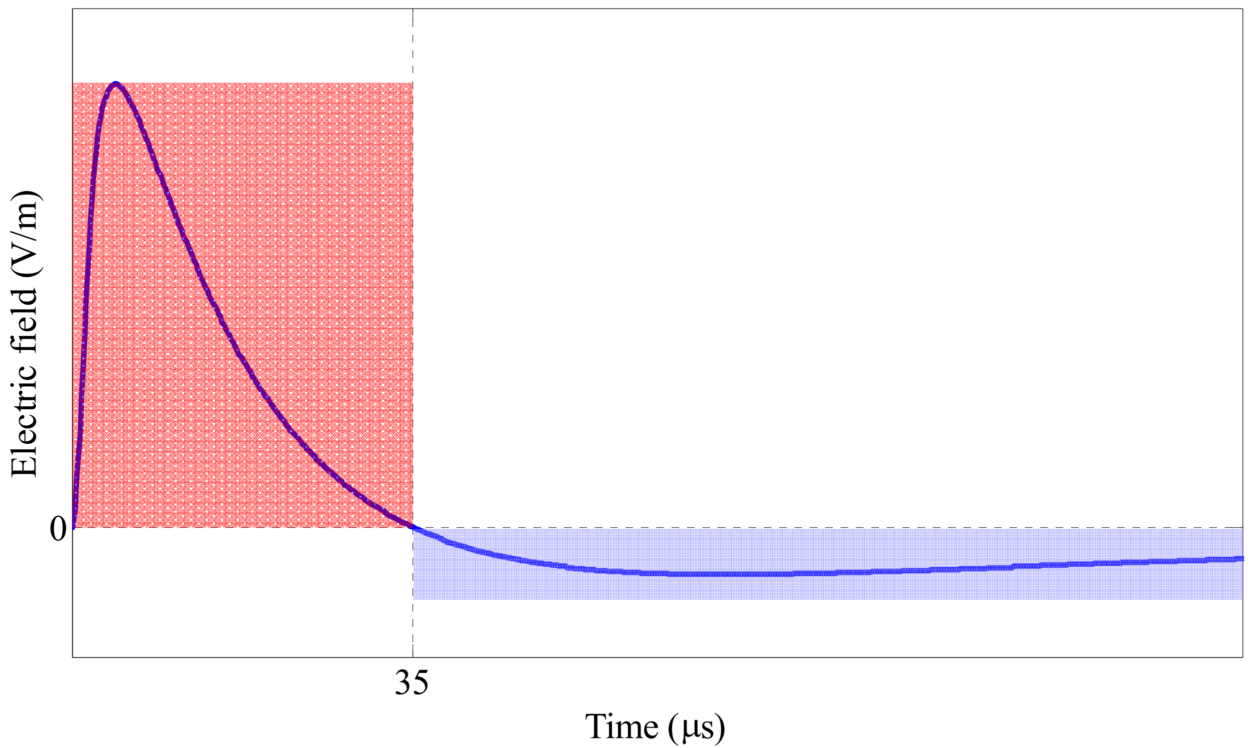


Implications

- For electromagnetic models, this is caused due to the boundary condition at the channel top.



Zero Crossing Compatible with Measurements



Realistic Zero Crossing Requirements

- Zero crossing of the order of 50 μs for first and 35 μs for subsequent return strokes are observed in experimental data.
- This should be smooth and should be observed before the arrival of the current at the channel top.

Responsible Mechanisms

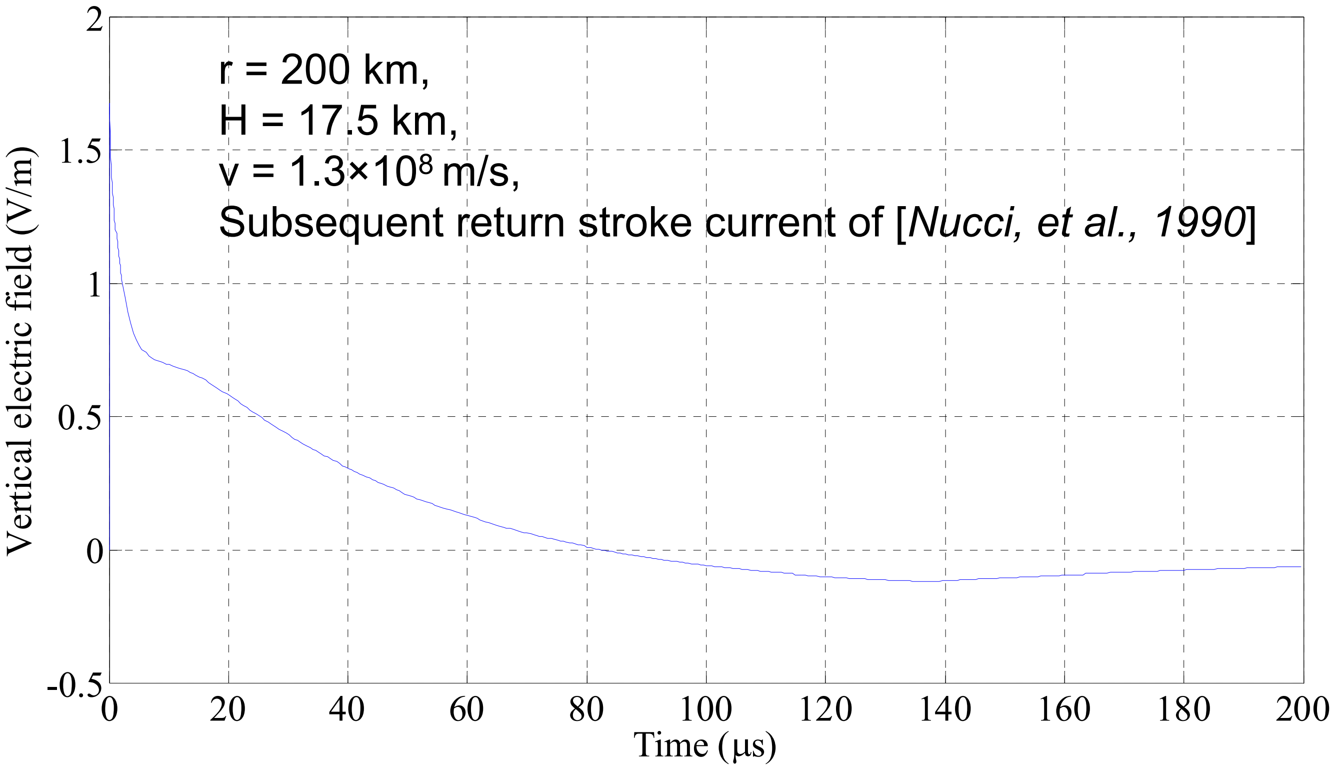
- Current decay rate as it propagates up along the channel.
- Speed of the current as it travels up the channel.
- Duration of the current.

Engineering models

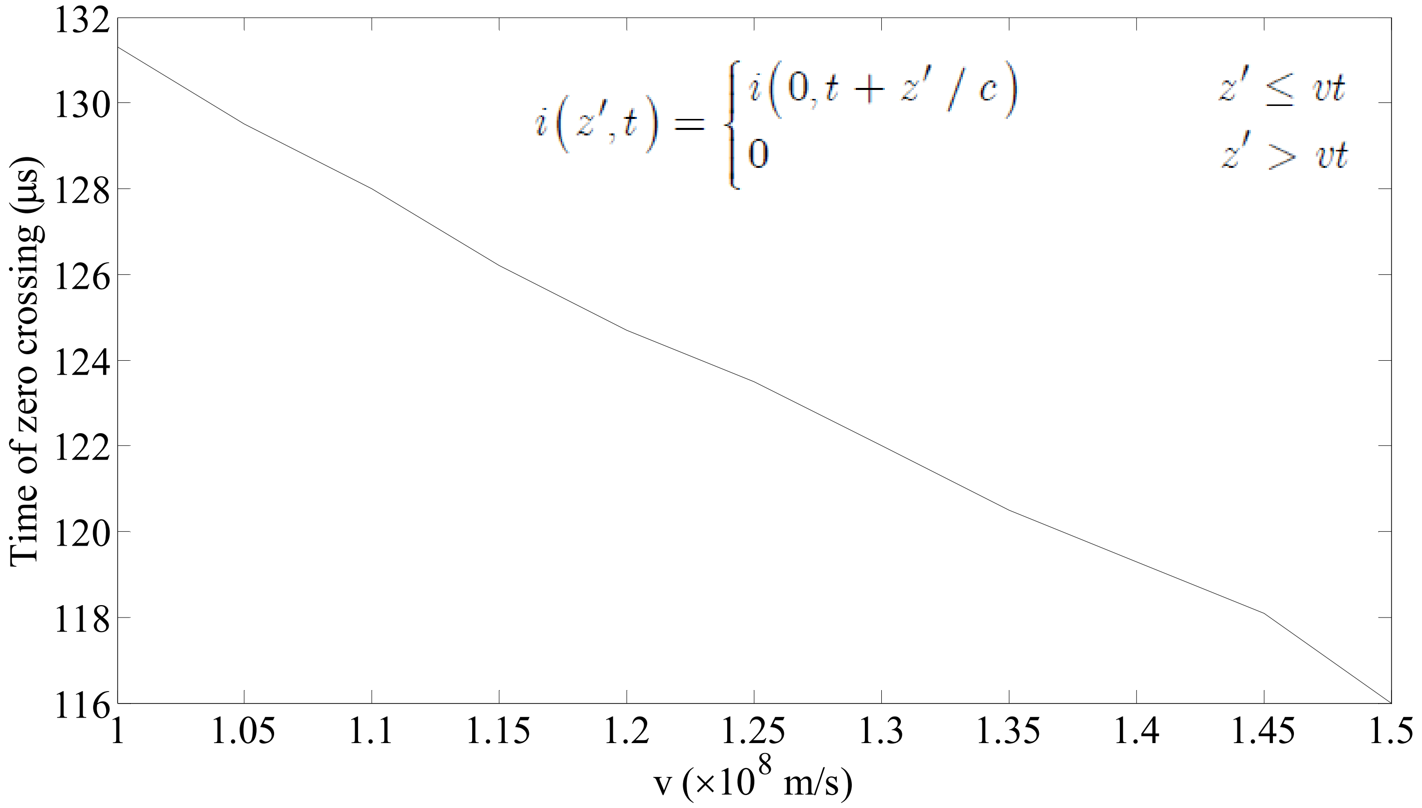
- All models can not provide the required zero crossing times [*Nucci, et al.*, 1990; *Rakov and Uman*, 1998]

☹	BG, TCS, and TL
☺	MTLL and MTLE

TCS Model

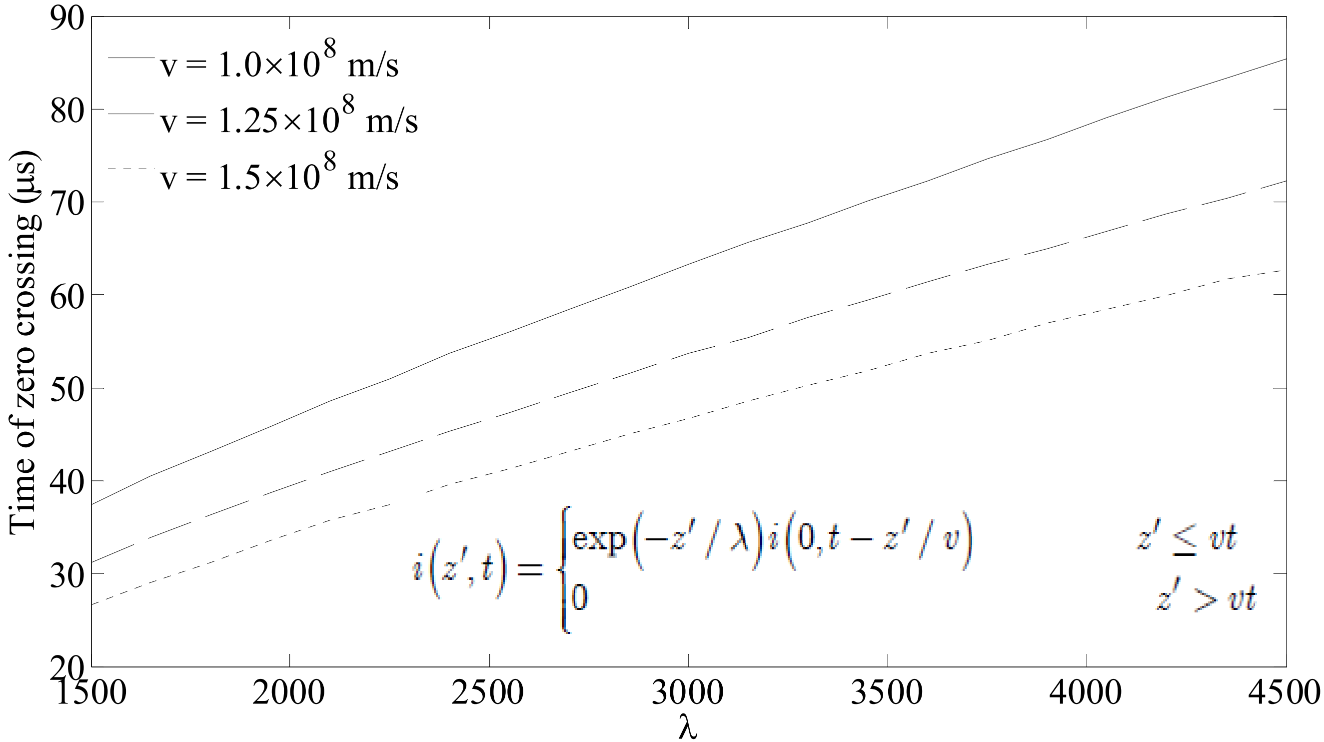

r = 200 km,
H = 17.5 km,
v = 1.3×10⁸ m/s,
Subsequent return stroke current of [Nucci, et al., 1990]
Vertical electric field (V/m)
2
1.5
1
0.5
0
-0.5
0
20
40
60
80
100
120
140
160
180
200
Time (μs)

TCS Model



$i(z',t) = \begin{cases} i(0, t + z'/c) & z' \le vt \\ 0 & z' > vt \end{cases}$
Time of zero crossing (μs)
132
130
128
126
124
122
120
118
116
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
1.45
1.5
v (×10^8 m/s)

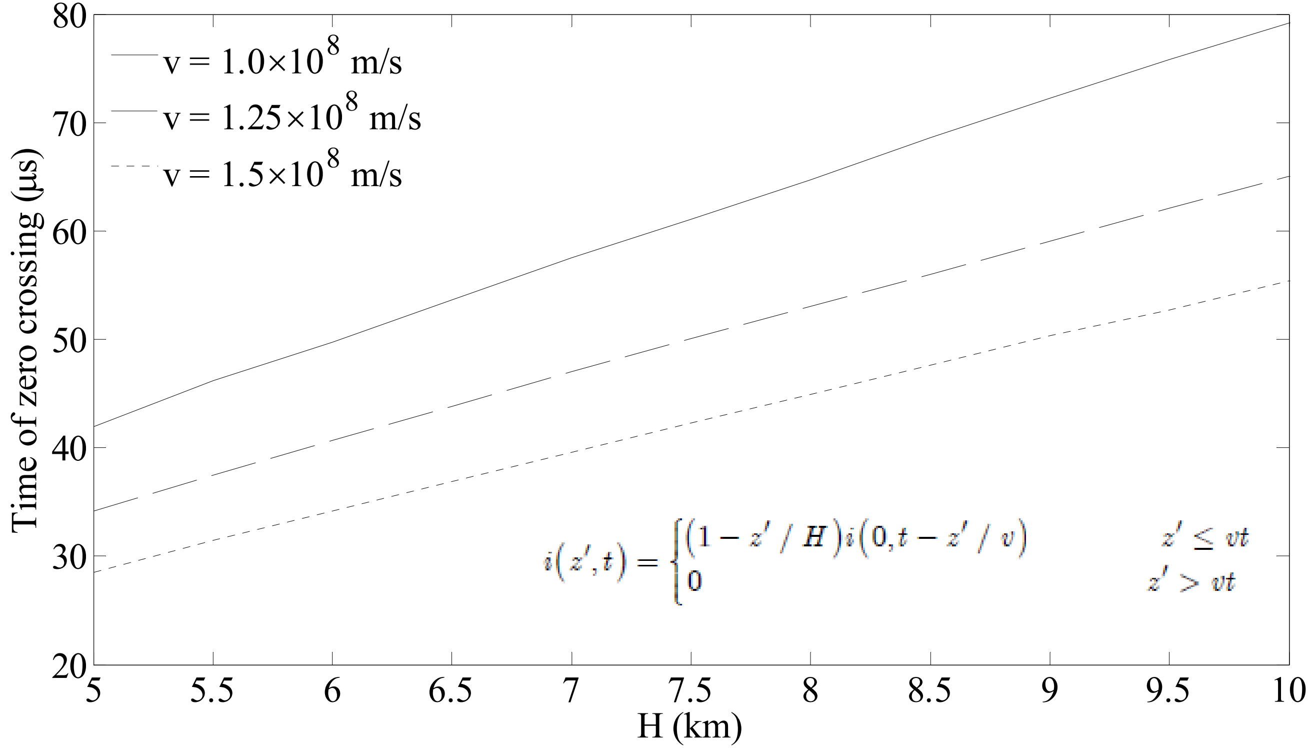
MTLE Model



$$i(z',t) = \begin{cases} \exp(-z'/\lambda)\, i(0, t - z'/v) & z' \le vt \\ 0 & z' > vt \end{cases}$$

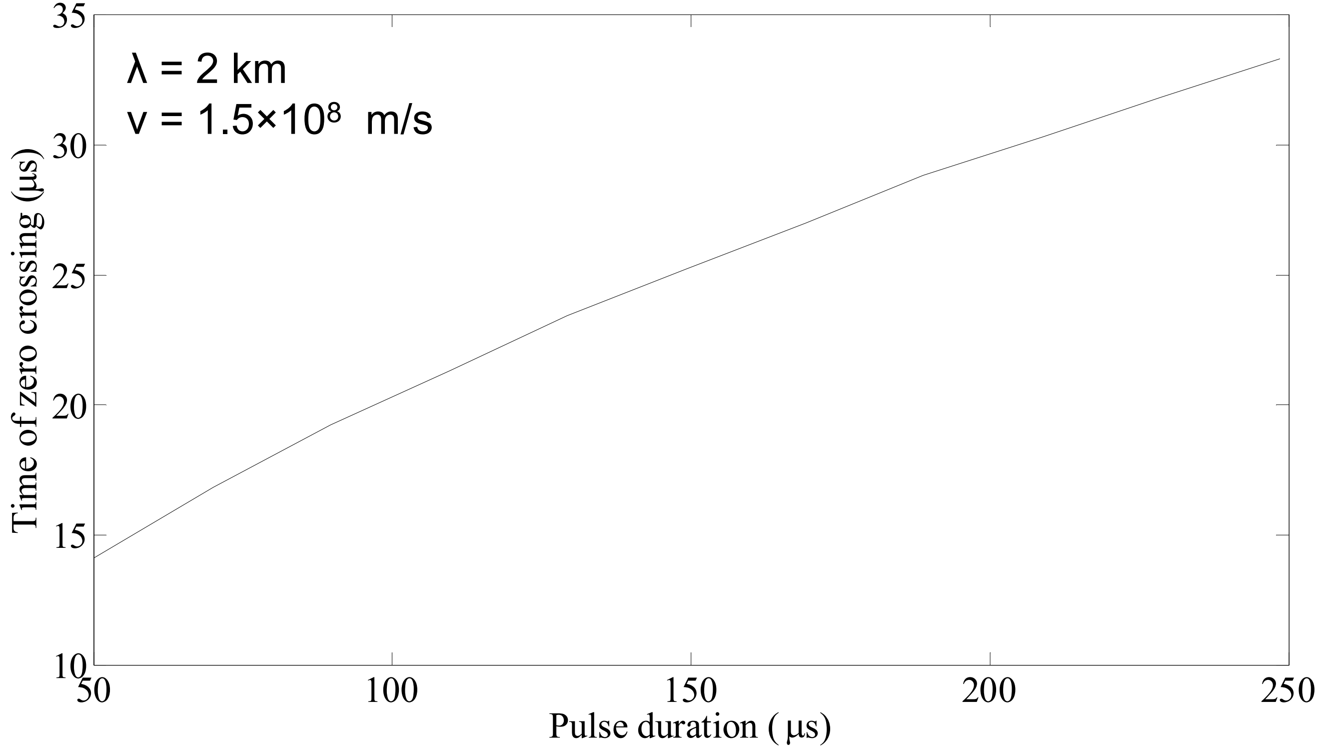
r = 100 km

MTLL Model



r = 100 km

MTLE Model and Effect of Pulse Duration



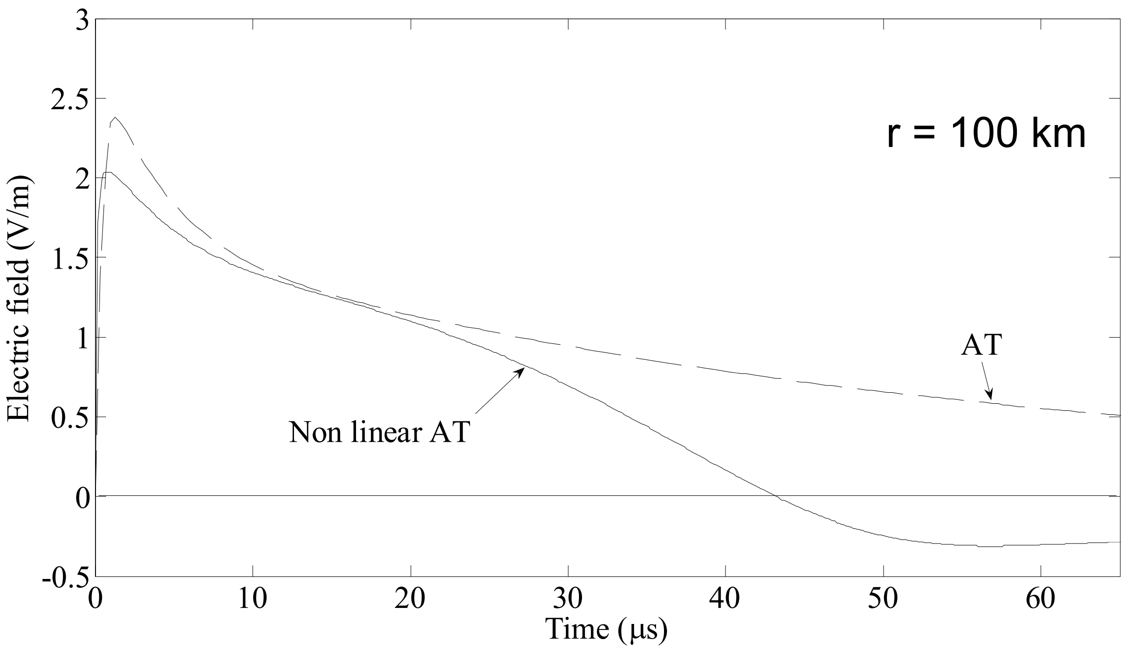
- The same argument holds for all models.

Analytical Expressions for Zero Crossing Times [*Shoory et al. Submitted to IEEE TEMC*]

Model	Expression
BG	$t_{zc_{BG}} = \tau$
TL	$t_{zc_{TL}} = \dfrac{H}{v}$
TCS	$t_{zc_{TCS}} = \dfrac{\tau c}{v} \ln\left(1 + \dfrac{v}{c}\right)$
MTLL	$t_{zc_{MTLL}} = \tau \ln\left(1 + \dfrac{H}{v\tau}\right)$
MTLE	$t_{zc_{MTLE}} = \dfrac{\lambda\tau}{v\tau - \lambda} \ln\left(\dfrac{v\tau}{\lambda}\right)$
DU	$t_{zc_{DU}} = \dfrac{\tau}{k-1} \ln\left[\dfrac{k\left(\tau - \tau_D\right)}{\tau - k\tau_D}\right]$

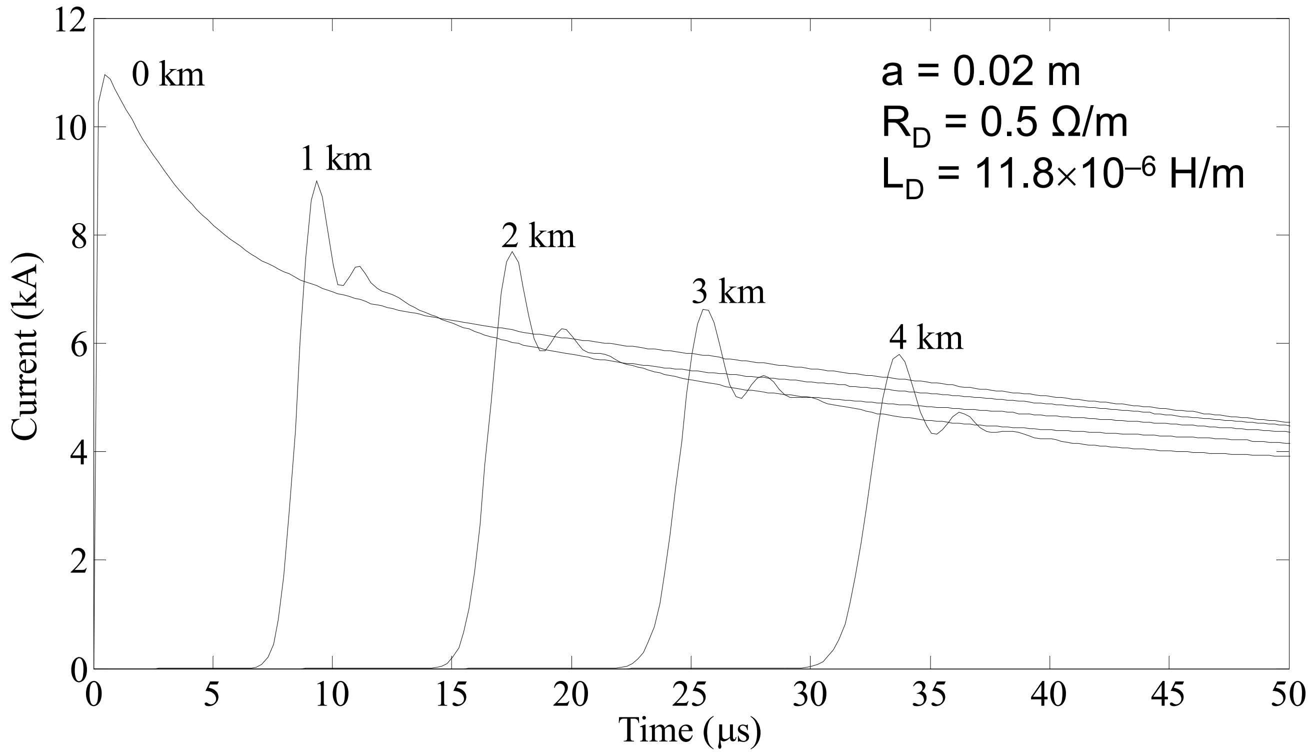
Electromagnetic or Antenna Theory Models

- These models solve the Maxwell's equations [*Baba and Rakov, 2007*].
- One category of AT models solve the EFIE using the MoM [*Moini, et al., 2000*].



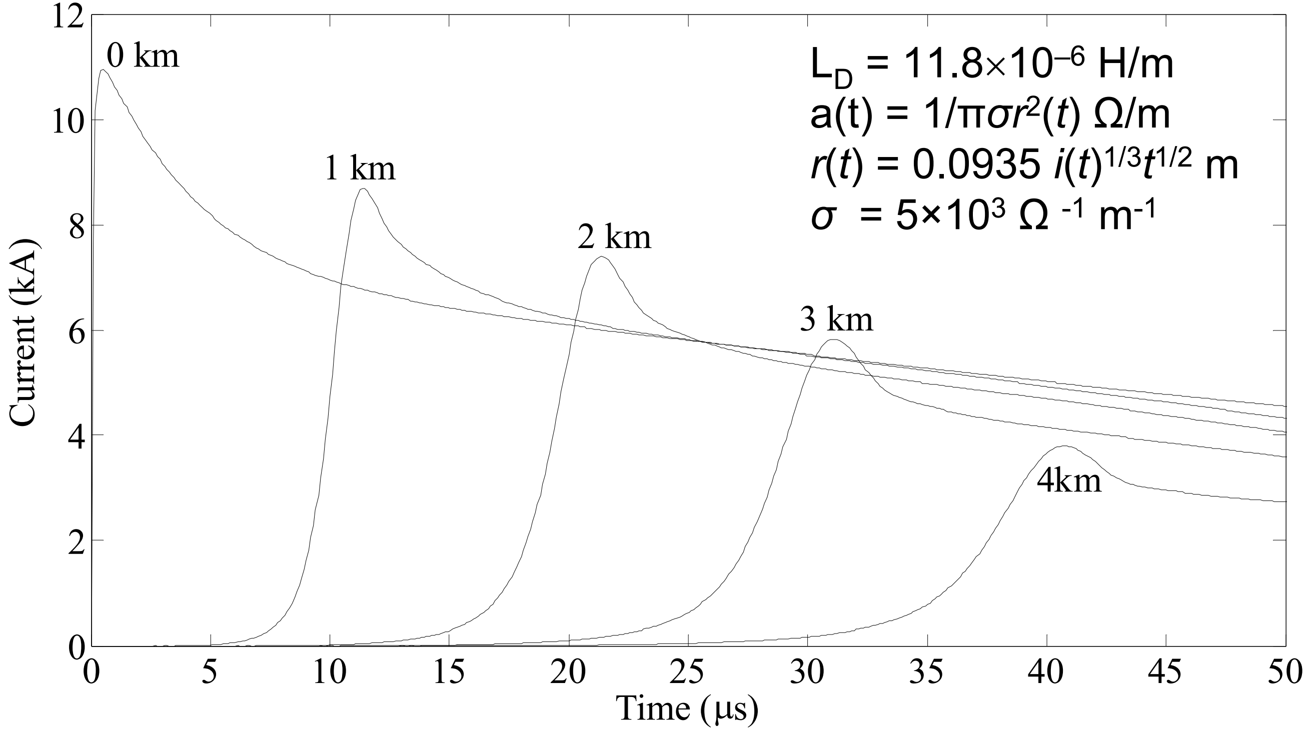
Original AT Model [*Moini, et al., 2000*]

- The dispersion of the current results in an increase of the current pulse duration as it travels up along the channel.



Nonlinear AT Model [*Alaee, et al.*, 2007]

- The increase of the current pulse duration as it propagates upward are almost prevented.



Conclusions

- All models of lightning return stroke models produce a zero crossing of the far electric and magnetic field.
- Among engineering models, only the MTLE and MTLL models are capable of producing smooth zero crossing in the range observed in experimental data.
- Zero crossing time reduces with the increase of attenuation, increase of speed and decrease of current pulse duration.
- Electromagnetic or AT models with linear distributed resistance and inductance of even large values are not capable of producing the desired zero crossing time.
- Only AT models with nonlinear load produce the desired zero crossing time.