

## Voltages induced by cloud discharges on overhead power lines

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# Outline of presentation

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- 1. Introduction: Aim of the study**
- 2. Characteristics of CD**
- 3. Calculation of voltages induced by CD on overhead power lines**
- 4. Sensitivity analysis: current waveform**
- 5. Sensitivity analysis: CD geometry**
- 6. Sensitivity analysis: speed of wavefront**
- 7. Conclusions**

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# Aim of the study

Lightning-induced voltages in overhead power lines are generally analyzed in the literature by taking into account only cloud-to-ground (CG) discharges. Aim of this study is to extend such an analysis to the estimation of lightning-induced voltages to the case of LEMP (Lighting Electromagnetic Pulse) radiated by cloud-discharges (CD).

To achieve such an estimation, a procedure for the calculation of the LEMP associated to generally-oriented CD discharge paths has been developed.

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# Characteristics of CD

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A typical CD moves tens of coulombs of charge over a distance of 5 to 10 km and is thought to consist of a breakdown phase followed by a continuously propagating leader that generates weak return strokes (recoil streamers) when the leader contacts with pockets of opposite space charge. The associated E field changes (k changes) are thought to be similar to the ones that occur in the intervals between return strokes in CG discharge.

Speed of the initial streamer:  $10^4 \div 10^5$  m/s

Speed of the k changes:  $10^6 \div 10^7$  m/s

Height of CD: 1  $\div$  12 km

No experimental data available in literature on spatial and temporal current distribution

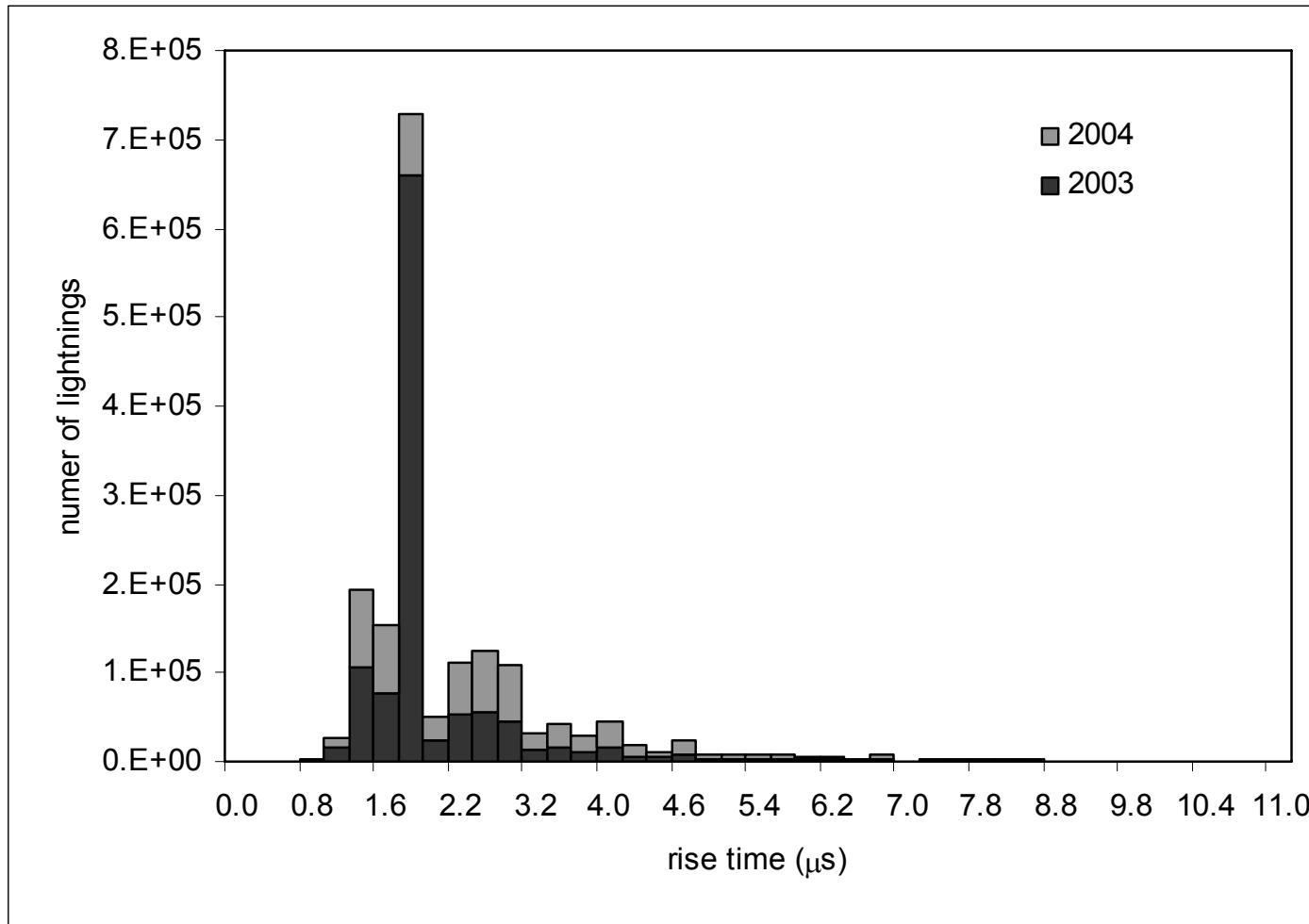
# Characteristics of CD

Distribution of CD current amplitudes detected by CESI SIRF in 2003-2004:

	positive	negative
Number of CD evaluated	868863	535484
amplitude		
5%	2.37 kA	2.29 kA
50%	6.50 kA	7.1 kA
95%	17 kA	19.2 kA

# Characteristics of CD

Distribution of CD current times to peak detected by CESI SIRF in 2003-2004:



$Tr_{5\%} = 0.7 \mu\text{s}$   
 $Tr_{50\%} = 1.9 \mu\text{s}$   
 $Tr_{95\%} = 4.9 \mu\text{s}$

# Calculation of voltages induced by CD

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In:

H.J. Price, A.K. Agrawal, “The Response of a Transmission Line Illuminated by Lightning-Induced Electromagnetic Fields”, IEEE Trans. on Electromagn. Compat., Vol. 22, No. 3, pp. 150-156, Aug. 1980.

the response of a transmission line illuminated by a discharge along a horizontal straight line, has been evaluated under the following assumption:

- current amplitude: 20 kA
- speed of the wavefront:  $2 \times 10^7$  m/s
- spatial-temporal current distribution: TL model
- perfectly conducting ground and lossless transmission line

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# Calculation of voltages induced by CD

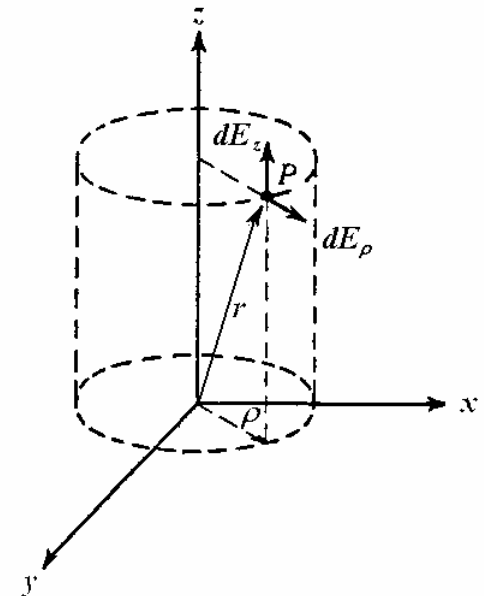
The electric field originated by a CD is obtained through integration along CD channel of the electric field, in cylindrical coordinates, of a vertical dipole of infinitesimal length  $dz'$ :

$$dE_{\rho}(\rho, r, z, t) = \frac{1}{4\pi\epsilon} dz' \rho z \left[ \frac{3}{cr^4} i(z', t - r/c) + \frac{1}{c^2 r^3} \frac{\partial i(z', t - r/c)}{\partial t} + \frac{3}{r^5} \int i(z', t - r/c) dt \right]$$

$$dE_z(r, z, t) = \frac{1}{4\pi\epsilon} dz' \left[ \left( \frac{3z^2}{cr^4} - \frac{1}{cr^2} \right) i(z', t - r/c) + \left( \frac{z^2}{c^2 r^3} - \frac{1}{c^2 r} \right) \frac{\partial i(z', t - r/c)}{\partial t} + \left( \frac{3z^2}{r^5} - \frac{1}{r^3} \right) \int i(z', t - r/c) dt \right]$$

As for the spatial-temporal distribution of the lightning current the Transmission Line model is assumed:

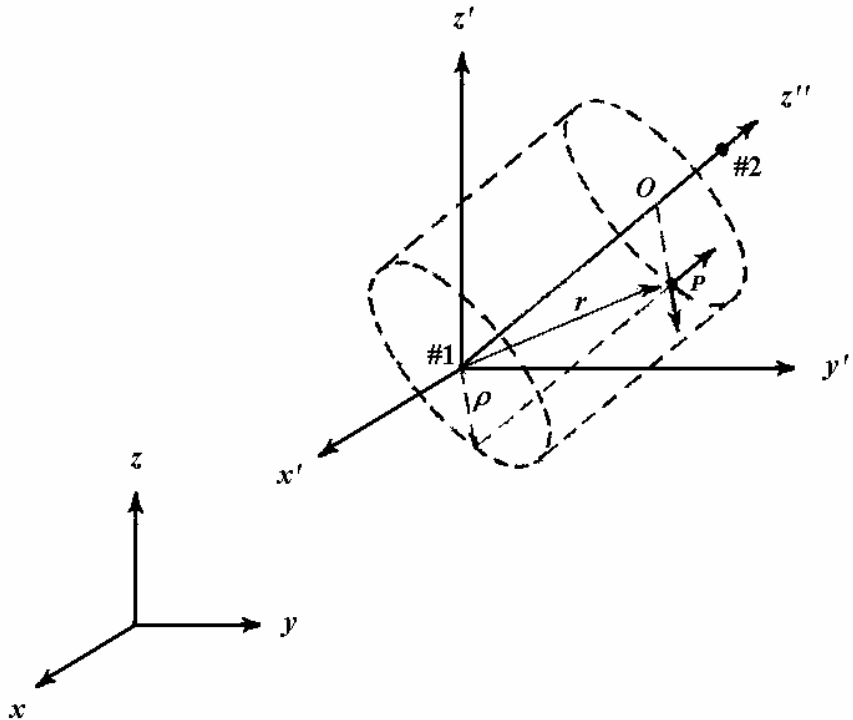
$$i\left(z', t - \frac{r}{c}\right) = i\left(0, t - \frac{r}{c} - \frac{z'}{v}\right)$$



# Calculation of voltages induced by CD

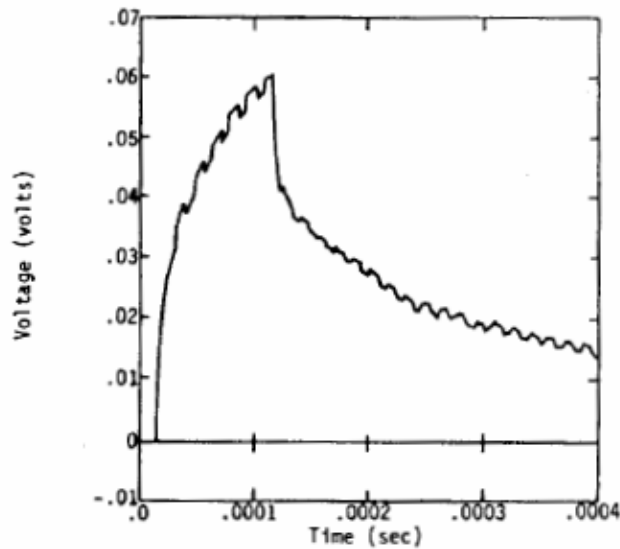
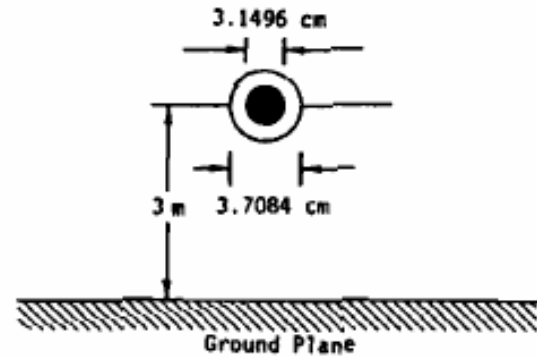
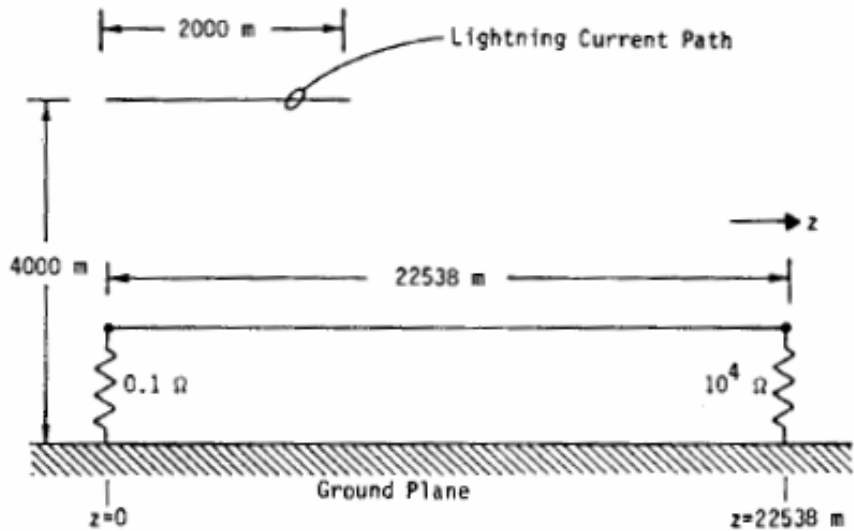
For a generally oriented CD path, defined by the coordinates  $(x_1, y_1, z_1)$  and  $(x_2, y_2, z_2)$  of the starting point #1 and the ending point #2 respectively, cosine directors are used to find the cylindrical coordinates  $(\rho_P, r_P, z''_P)$  of the point  $P(x_P, y_P, z_P)$  and, once obtained  $E_\rho$  and  $E_{z''}$ , to find the components of  $E$  in the original Cartesian system.

Concerning the Field-to-transmission line coupling, time-domain transmission line equations, in terms of the scattered and total voltages, are integrated by finite differences method.

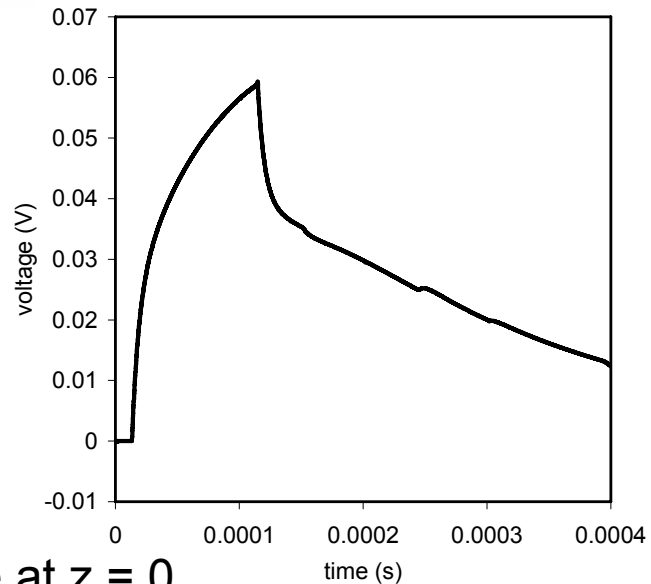


# Calculation of voltages induced by CD

Comparison with the results reported in *Price and Agrawal 1980*

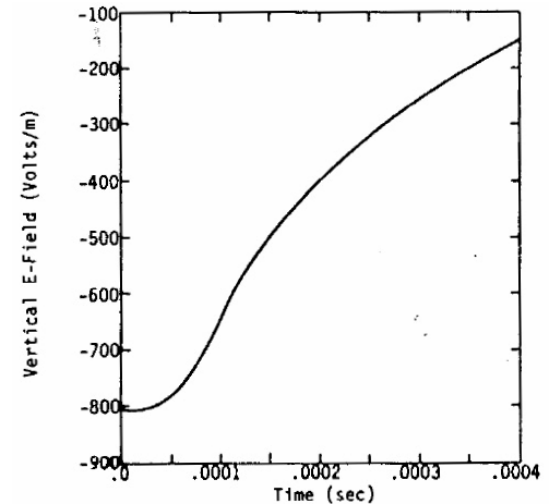
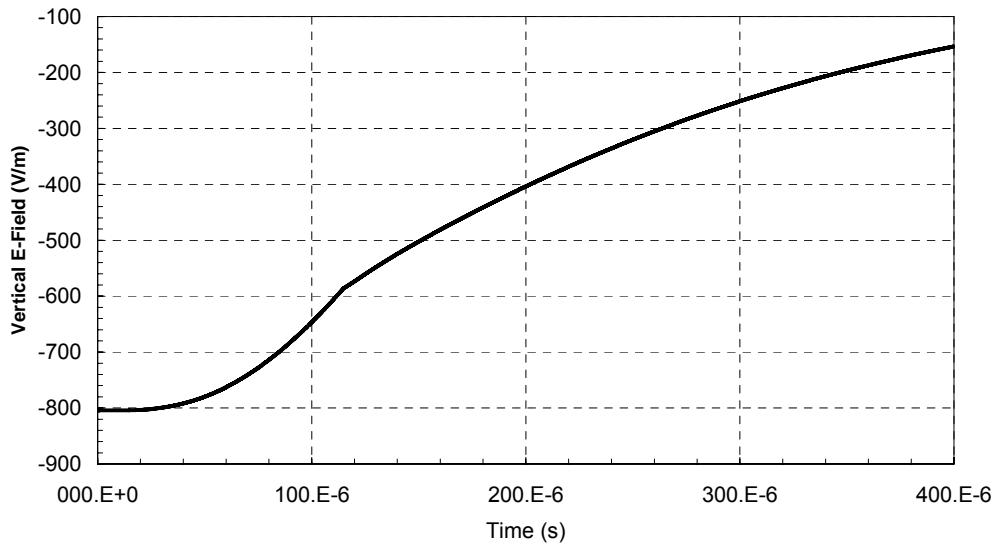
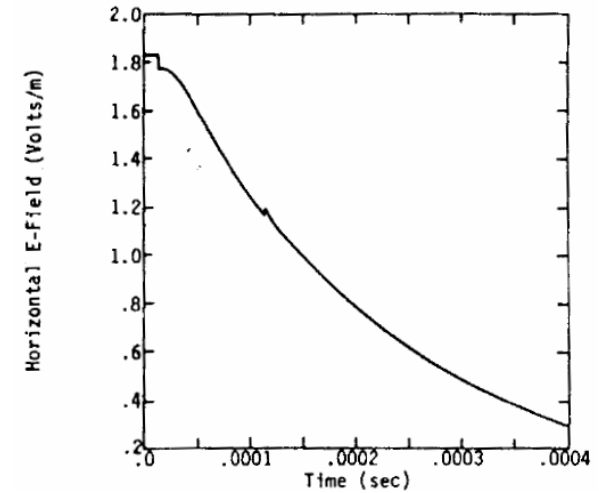
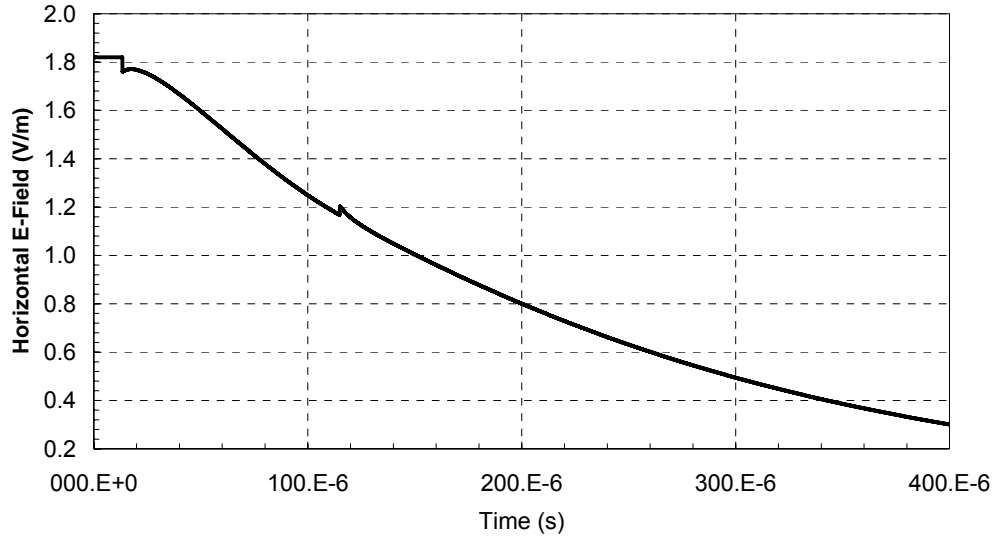


total voltage at  $z = 0$



# Calculation of voltages induced by CD

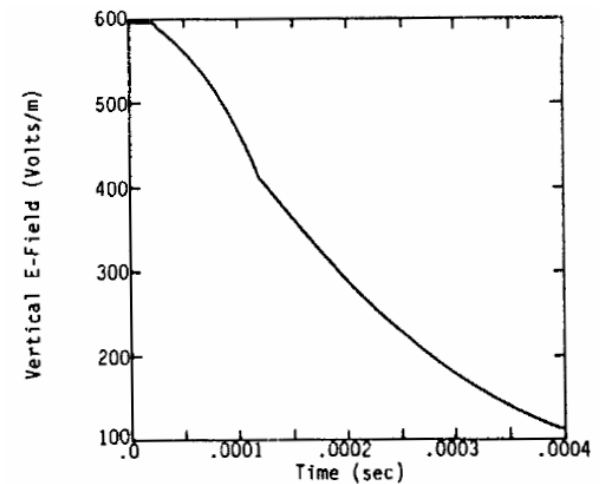
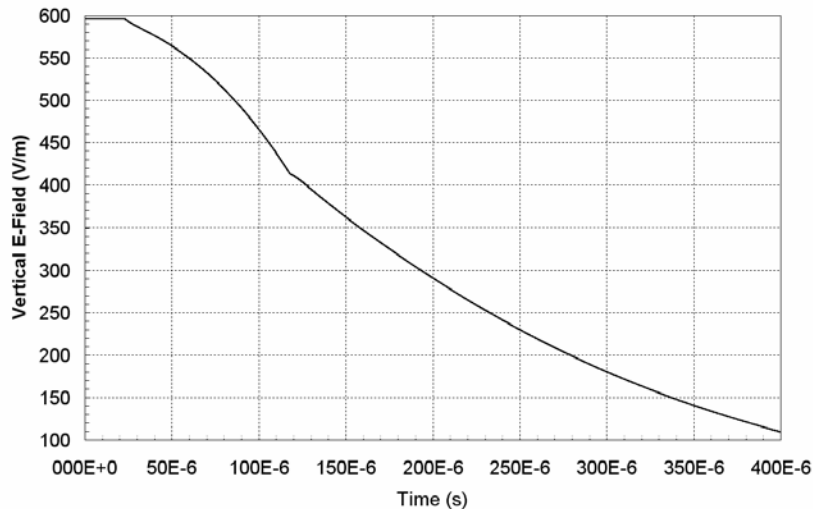
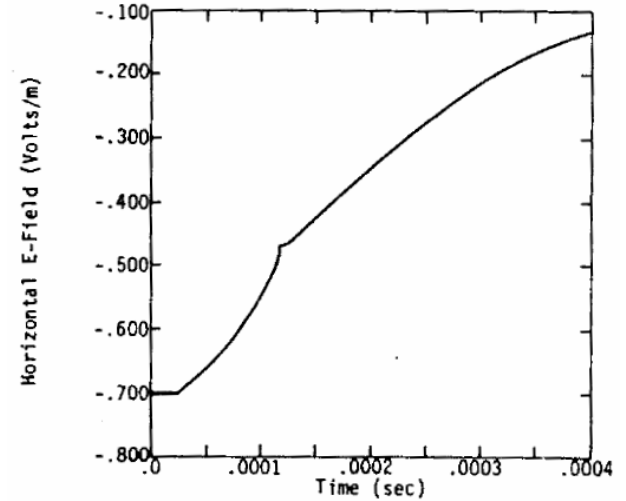
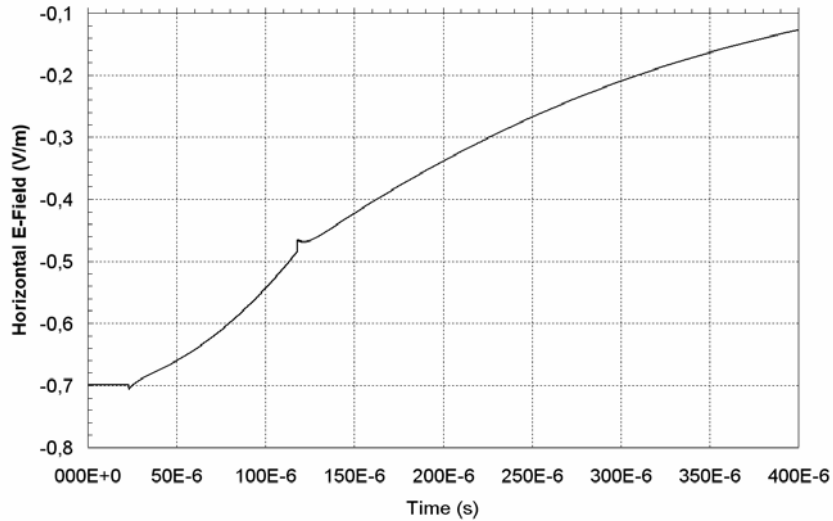
Comparison with the results reported in *Price and Agrawal 1980*



Incident Electric field at  $z = 0$

# Calculation of voltages induced by CD

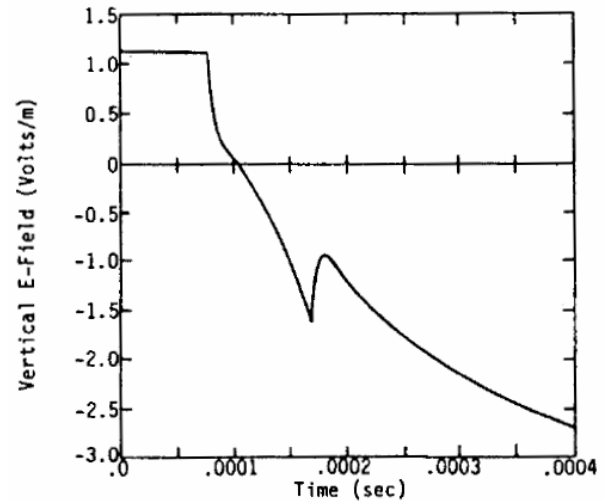
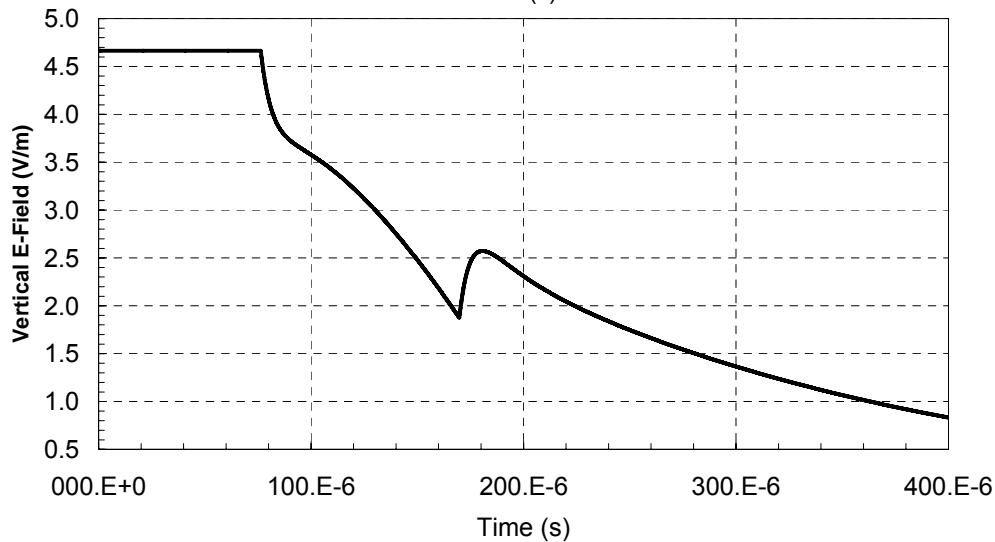
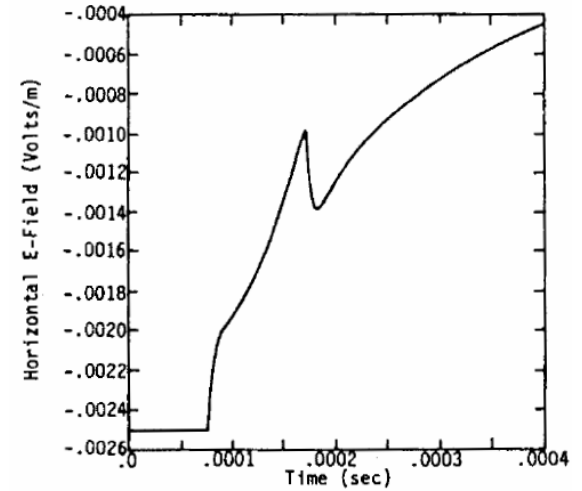
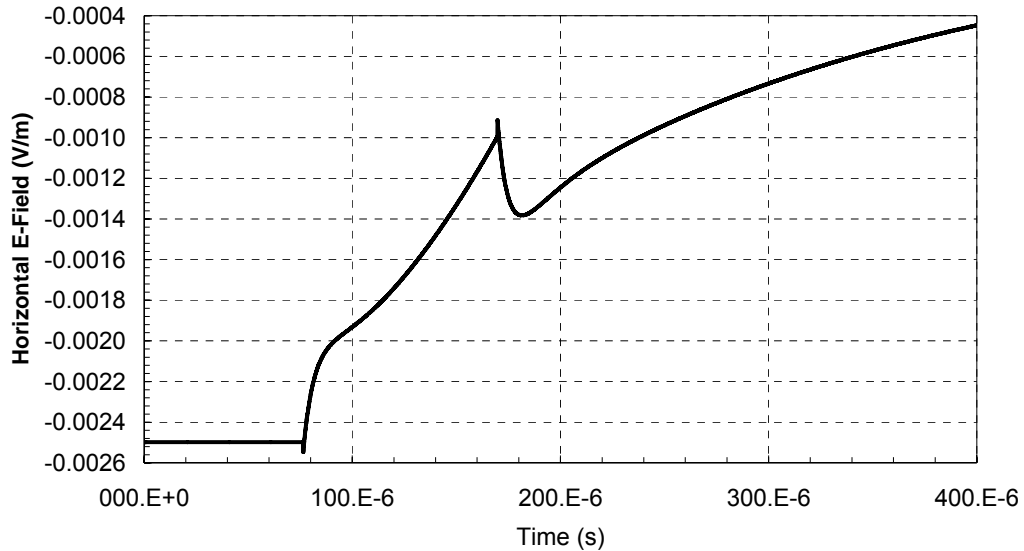
Comparison with the results reported in *Price and Agrawal 1980*



Incident Electric field at  $z = 5634$  m

# Calculation of voltages induced by CD

Comparison with the results reported in *Price and Agrawal 1980*



Incident Electric field at  $z = 22538$  m

# Calculation of voltages induced by CD

The model has been validated, as for vertical discharges, by comparison with the results of the LIOV:

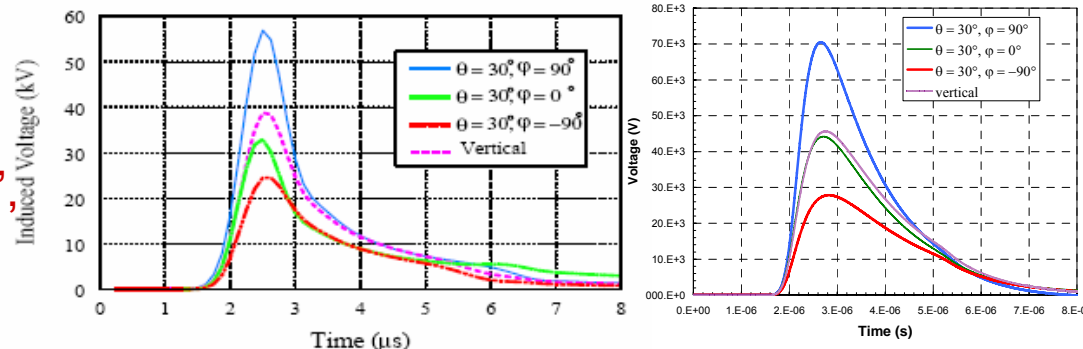
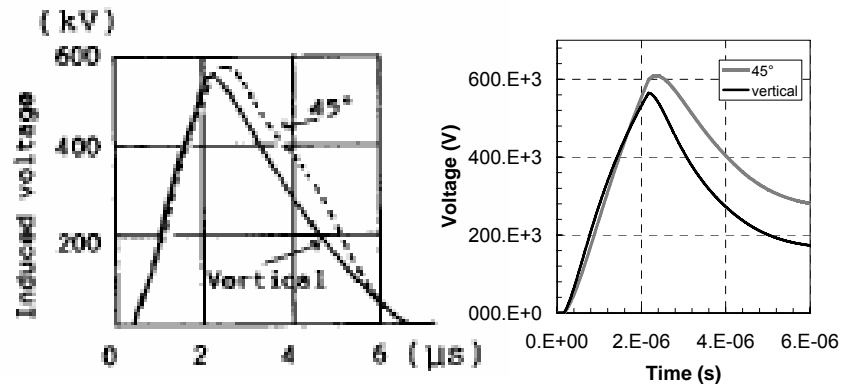
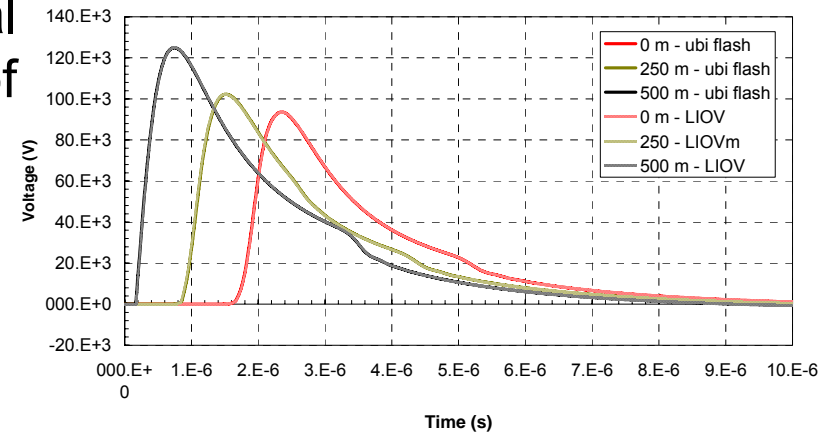
C.A. Nucci, F. Rachidi, M. Ianoz, C. Mazzetti, "Lightning-induced voltages on overhead power lines", IEEE Trans. EMC, Vol. 35-1, 1993 pp. 75-86.

and, as for inclined CG, by comparing with the results reported in:

A. Sakakibara, "Calculation of induced voltages on overhead lines caused by inclined lightning strokes", IEEE Trans. Power Delivery, Vol. 4, No. 1, pp. 683-693, Jan. 1989.

and in:

B. Kordi, R. Moini and F. Rachidi, "Modeling an inclined lightning return stroke channel using antenna theory", 14th Intern. Zurich Symp. on Electr. Comp., pp. 331-334, February 2001.



# Outline of presentation

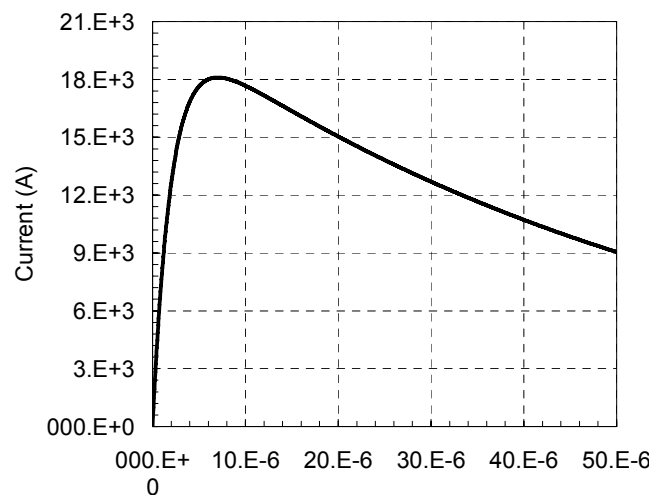
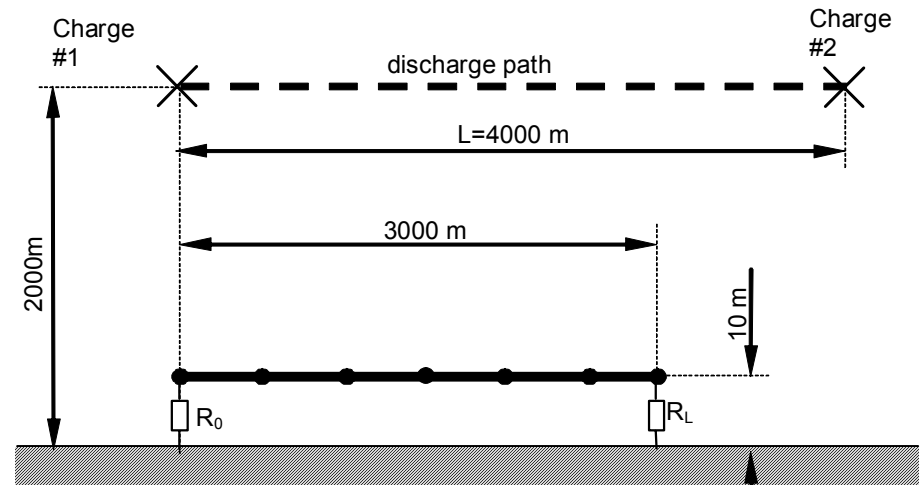
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4. **Sensitivity analysis: current waveform**
5. Sensitivity analysis: CD geometry
6. Sensitivity analysis: speed of wavefront
7. Conclusions

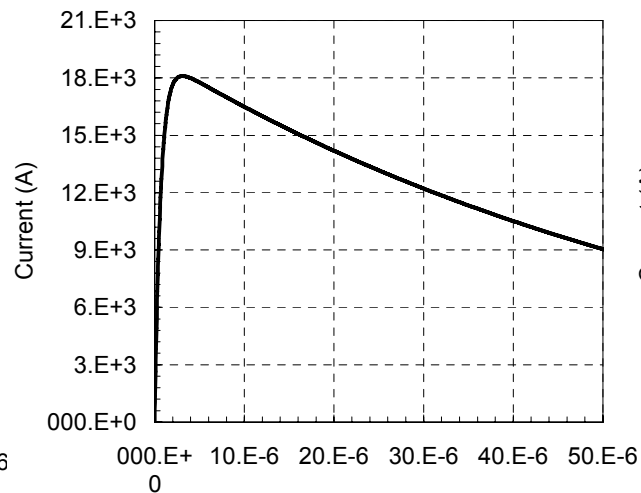
# Sensitivity analysis of CD induced voltages: current waveform

Sensitivity analysis against time to peak conduced with double exponential currents, found by means of next approximations.

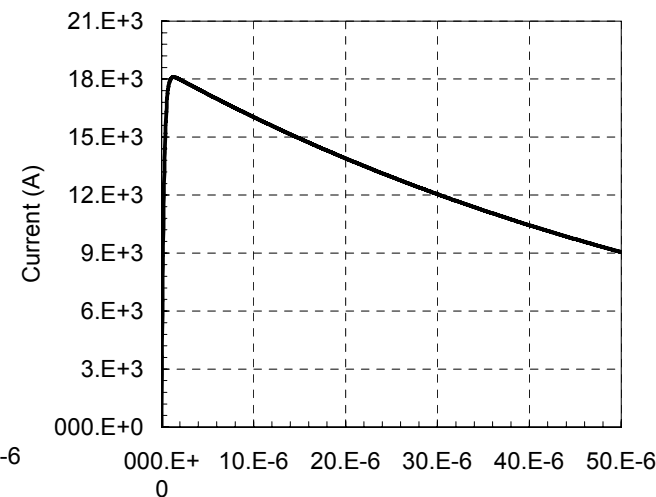
(time to half value  $50 \mu\text{s}$ , speed  $10^7 \text{ m/s}$ , matched ends)



$$Tr_{95\%} = 4.9 \mu\text{s}$$

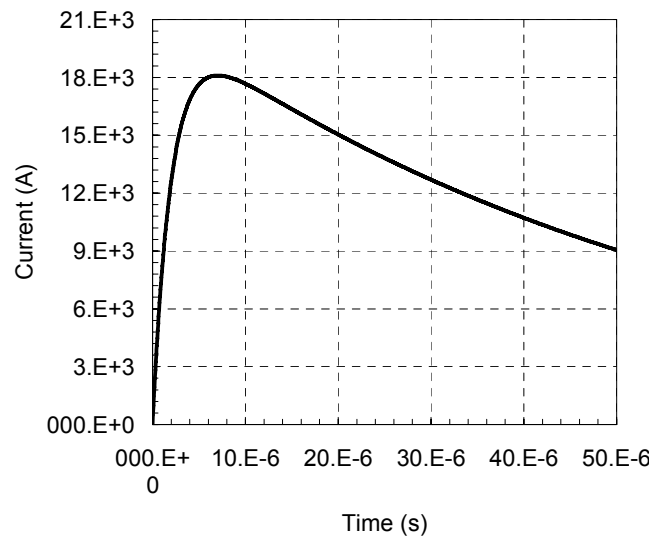
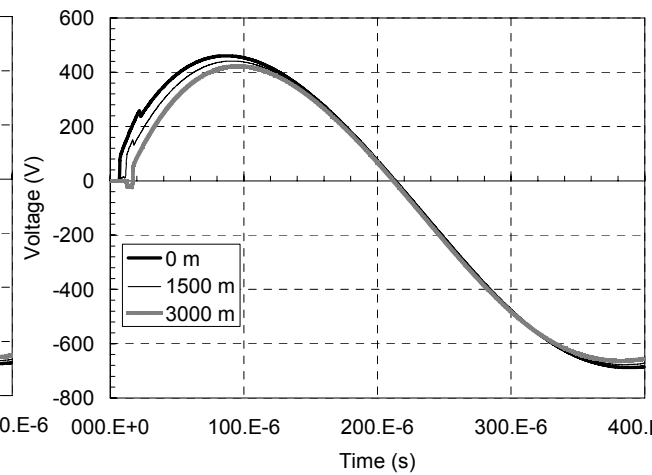
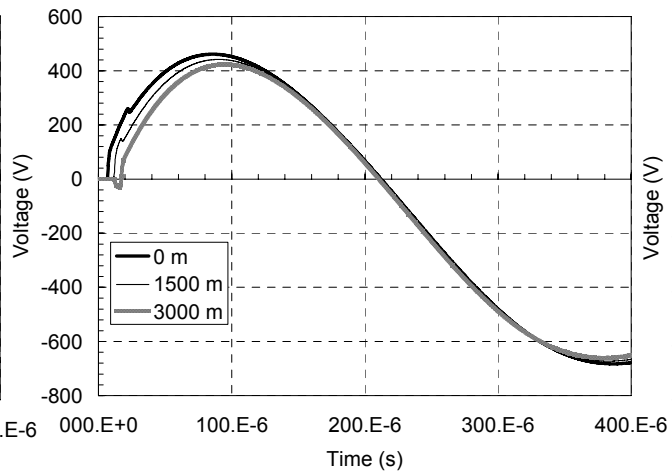
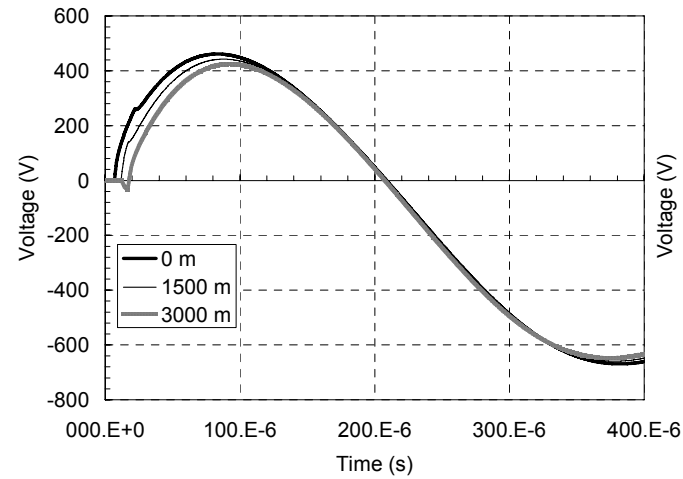


$$Tr_{50\%} = 1.9 \mu\text{s}$$

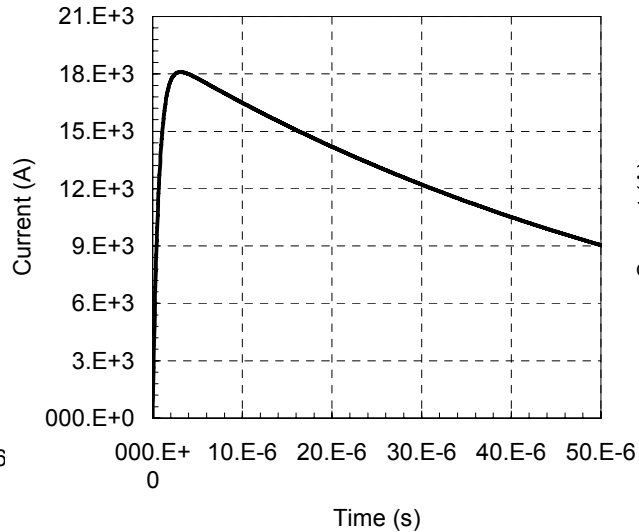


$$Tr_{5\%} = 0.7 \mu\text{s}$$

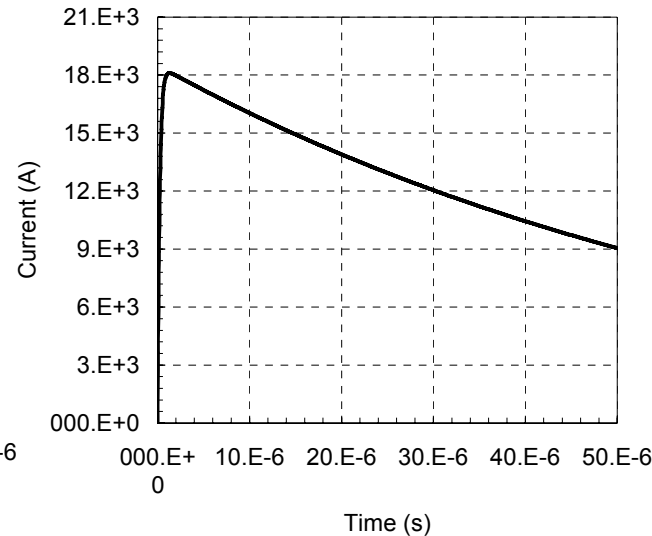
# Sensitivity analysis of CD induced voltages: current waveform



$Tr_{95\%} = 4.9 \mu\text{s}$

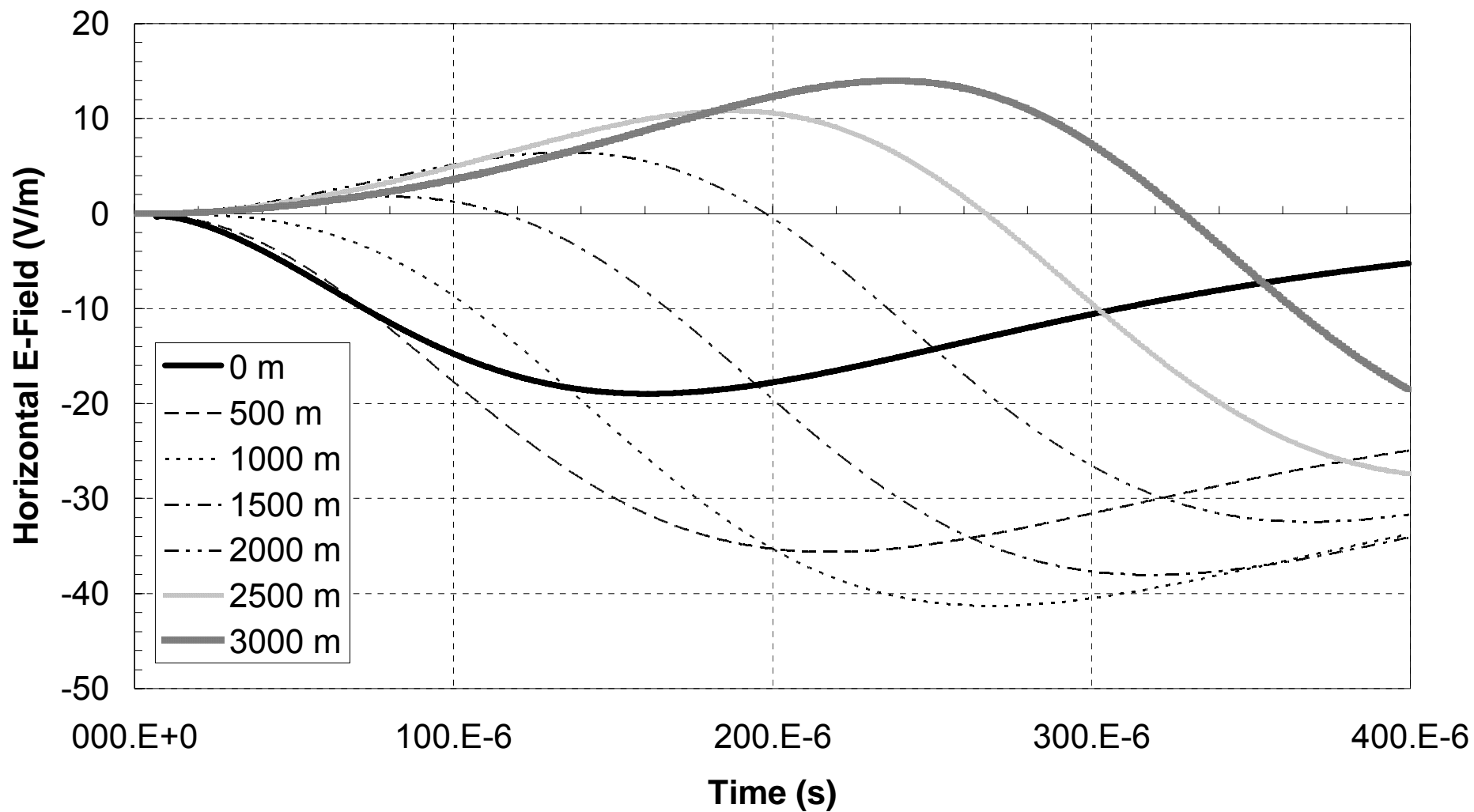


$Tr_{50\%} = 1.9 \mu\text{s}$



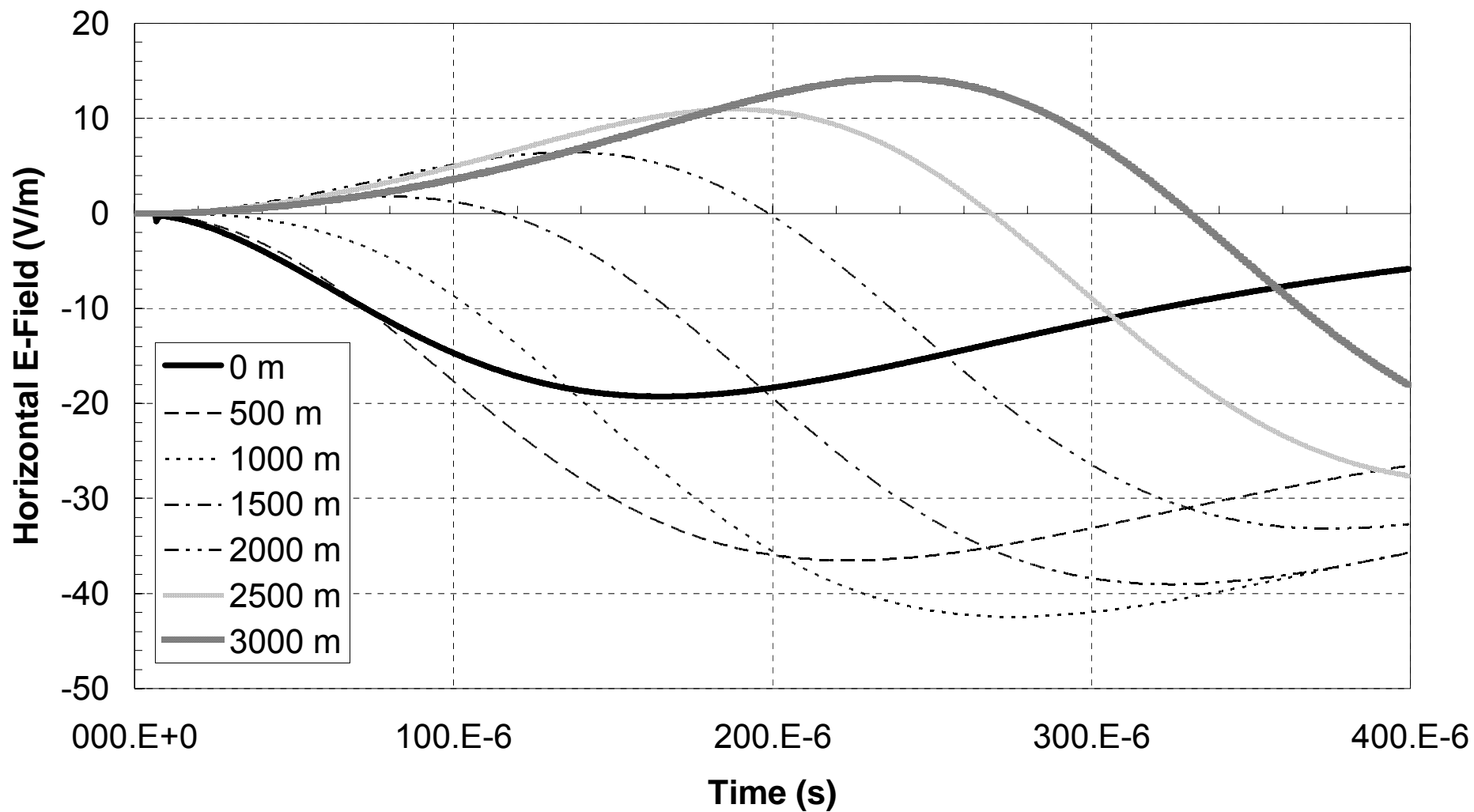
$Tr_{5\%} = 0.7 \mu\text{s}$

# Sensitivity analysis of CD induced voltages: current waveform



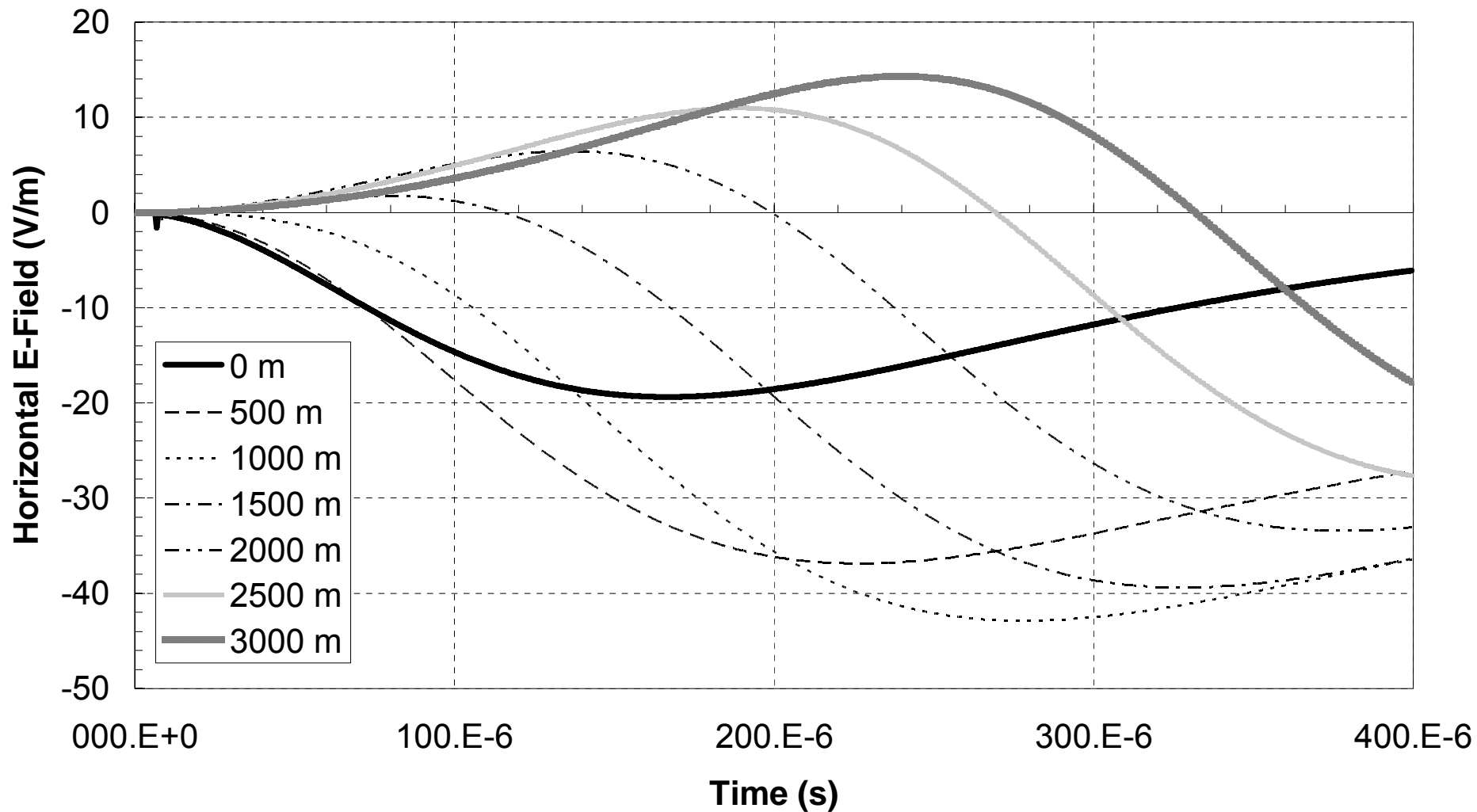
$Tr_{95\%} = 4.9 \mu s$

# Sensitivity analysis of CD induced voltages: current waveform



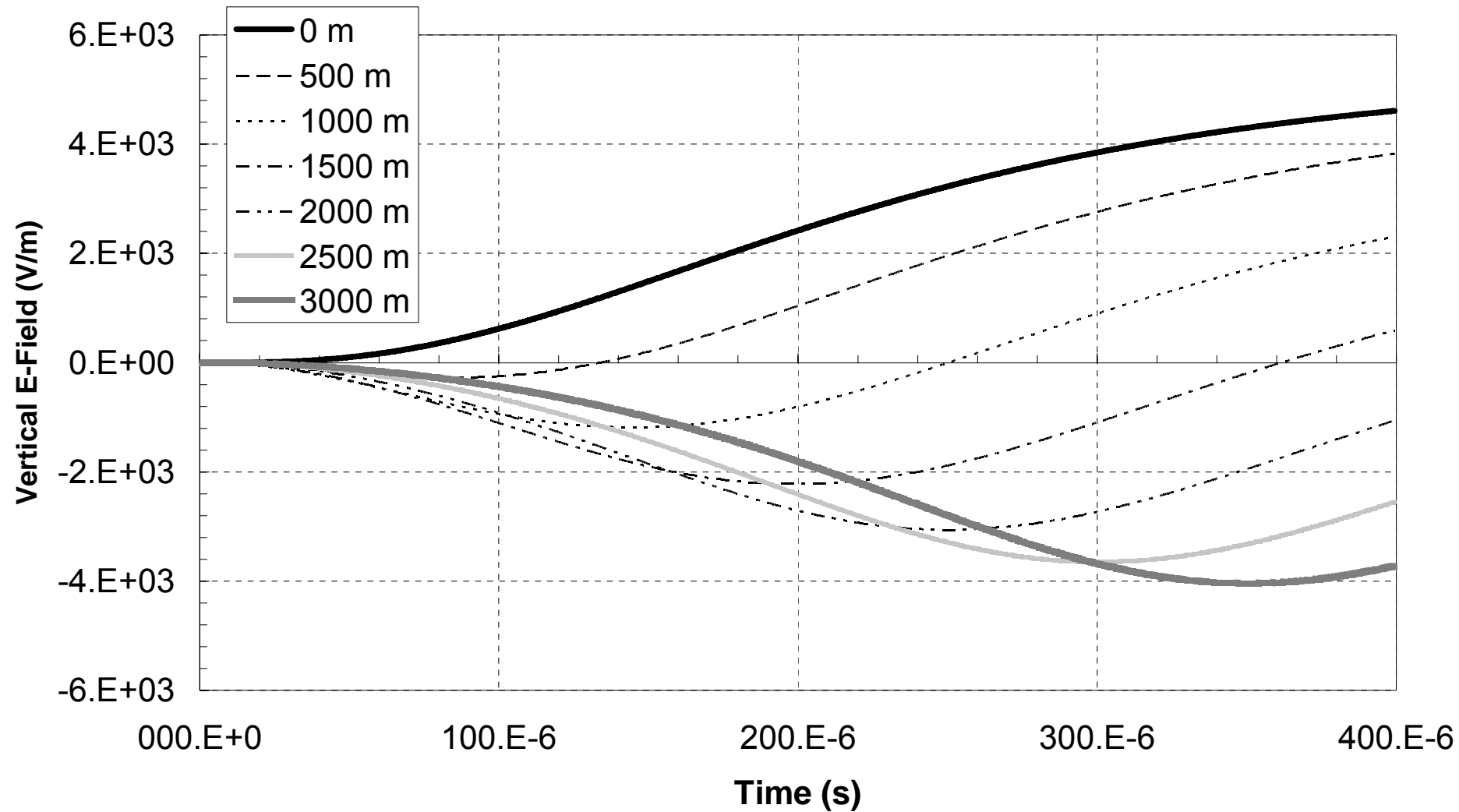
$Tr_{50\%} = 1.9 \mu s$

# Sensitivity analysis of CD induced voltages: current waveform



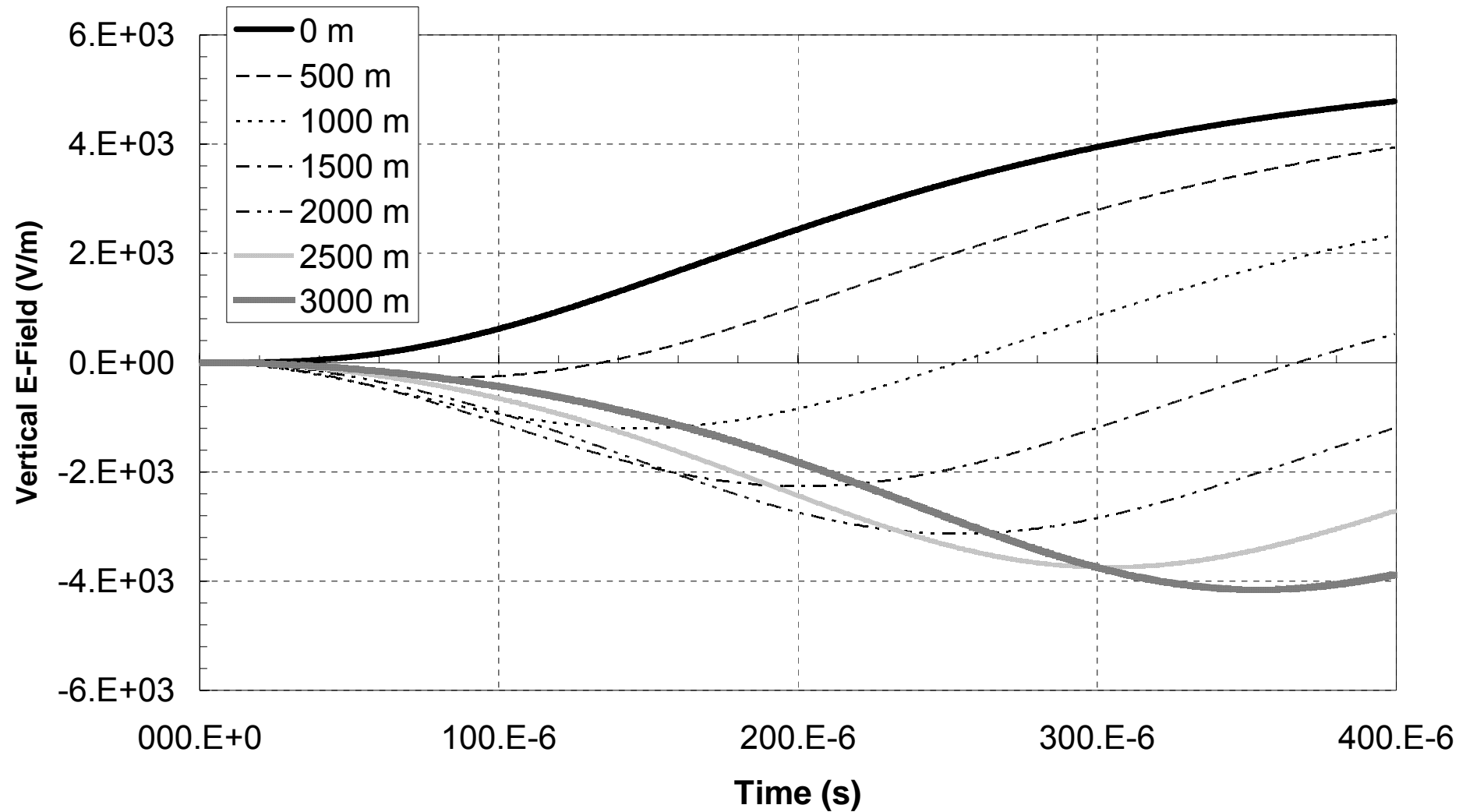
$\tau_{5\%} = 0.7 \mu\text{s}$

# Sensitivity analysis of CD induced voltages: current waveform



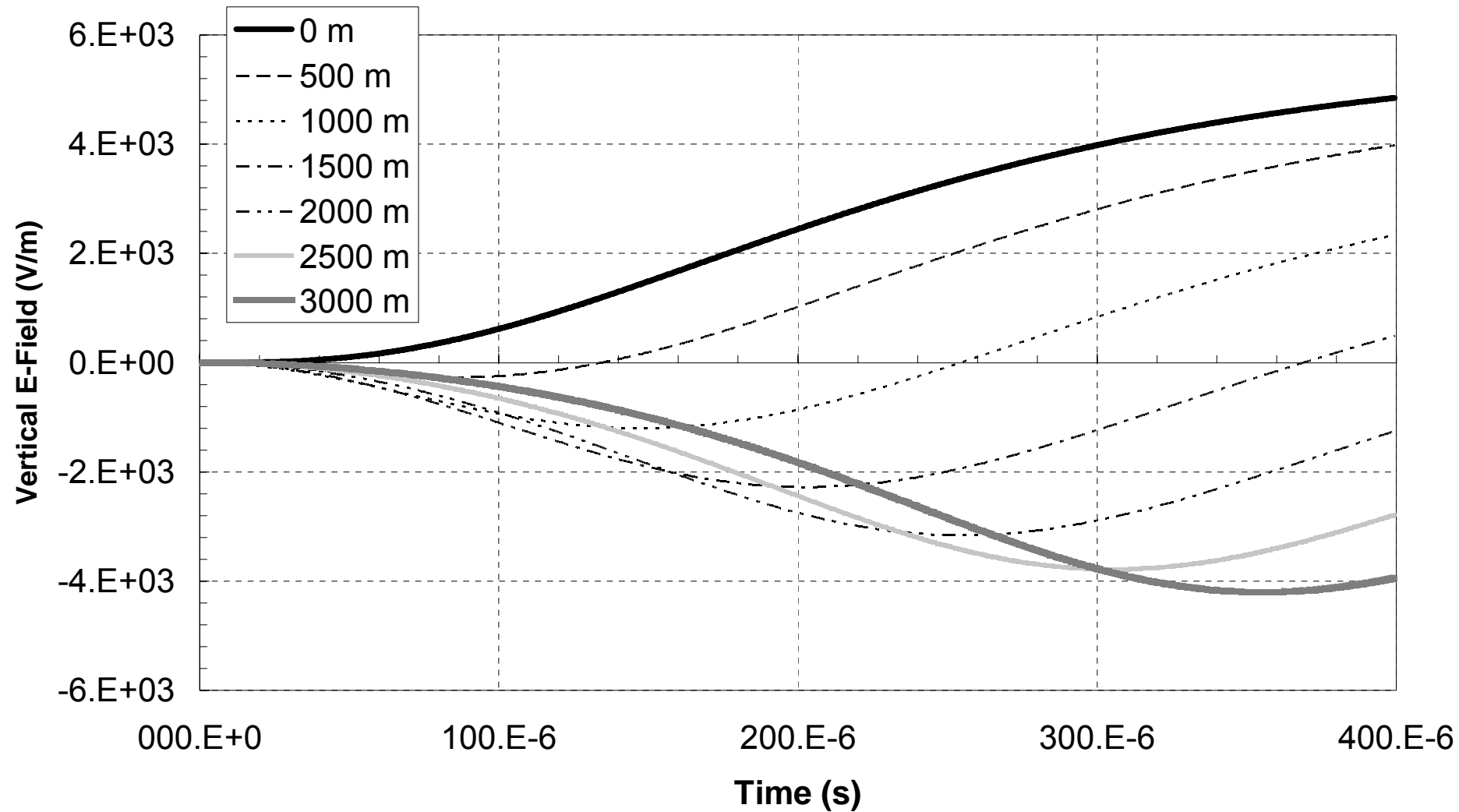
$Tr_{95\%} = 4.9 \mu\text{s}$

# Sensitivity analysis of CD induced voltages: current waveform



$Tr_{50\%} = 1.9 \mu s$

# Sensitivity analysis of CD induced voltages: current waveform

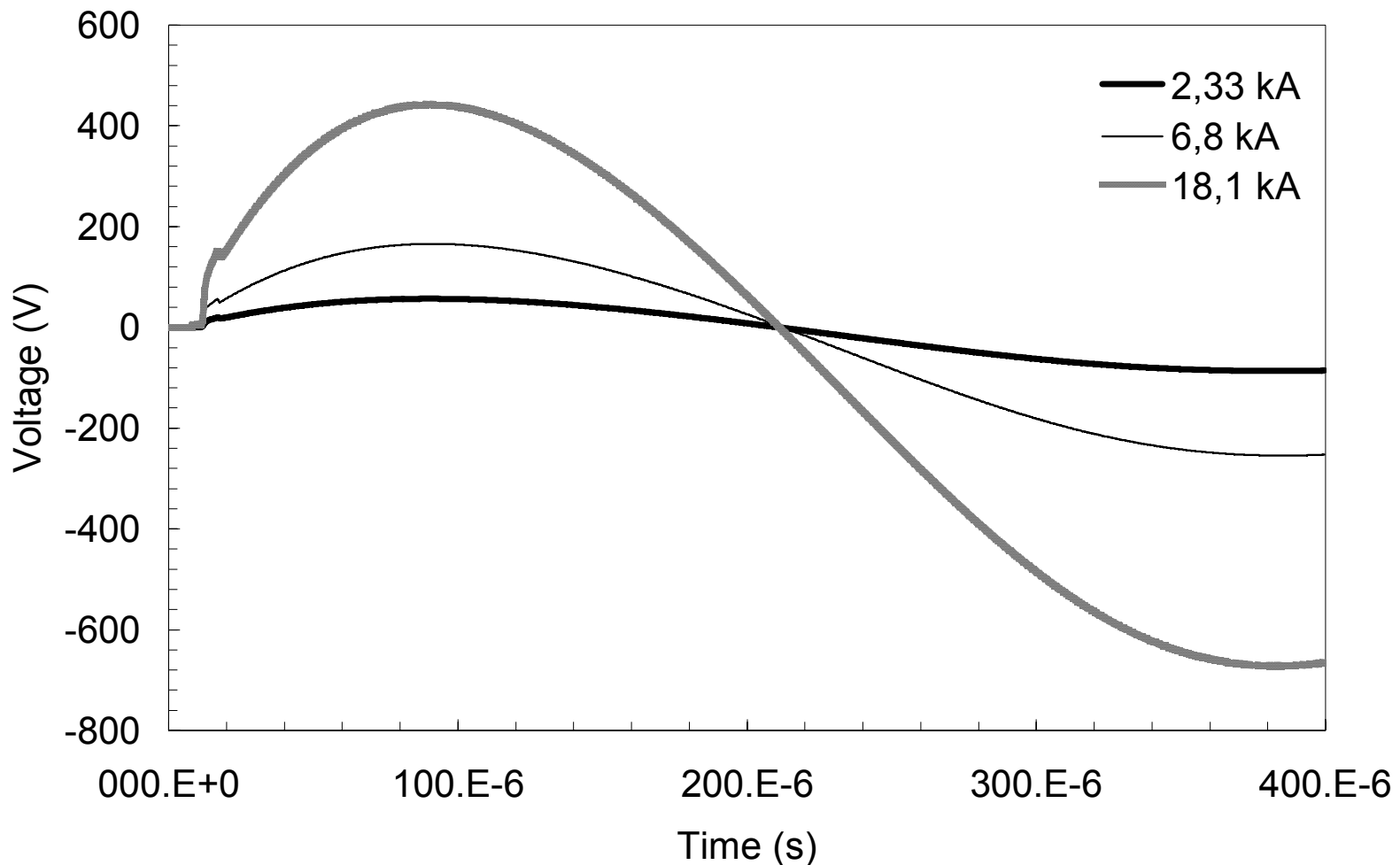


$\text{Tr}_{5\%} = 0.7 \mu\text{s}$

# Sensitivity analysis of CD induced voltages: current waveform

## Sensitivity analysis against current amplitude

(time rise 1.9  $\mu\text{s}$ , time to half value 50  $\mu\text{s}$ , speed  $10^7$  m/s, same previous geometry, voltages in the average point of the line)



# Outline of presentation

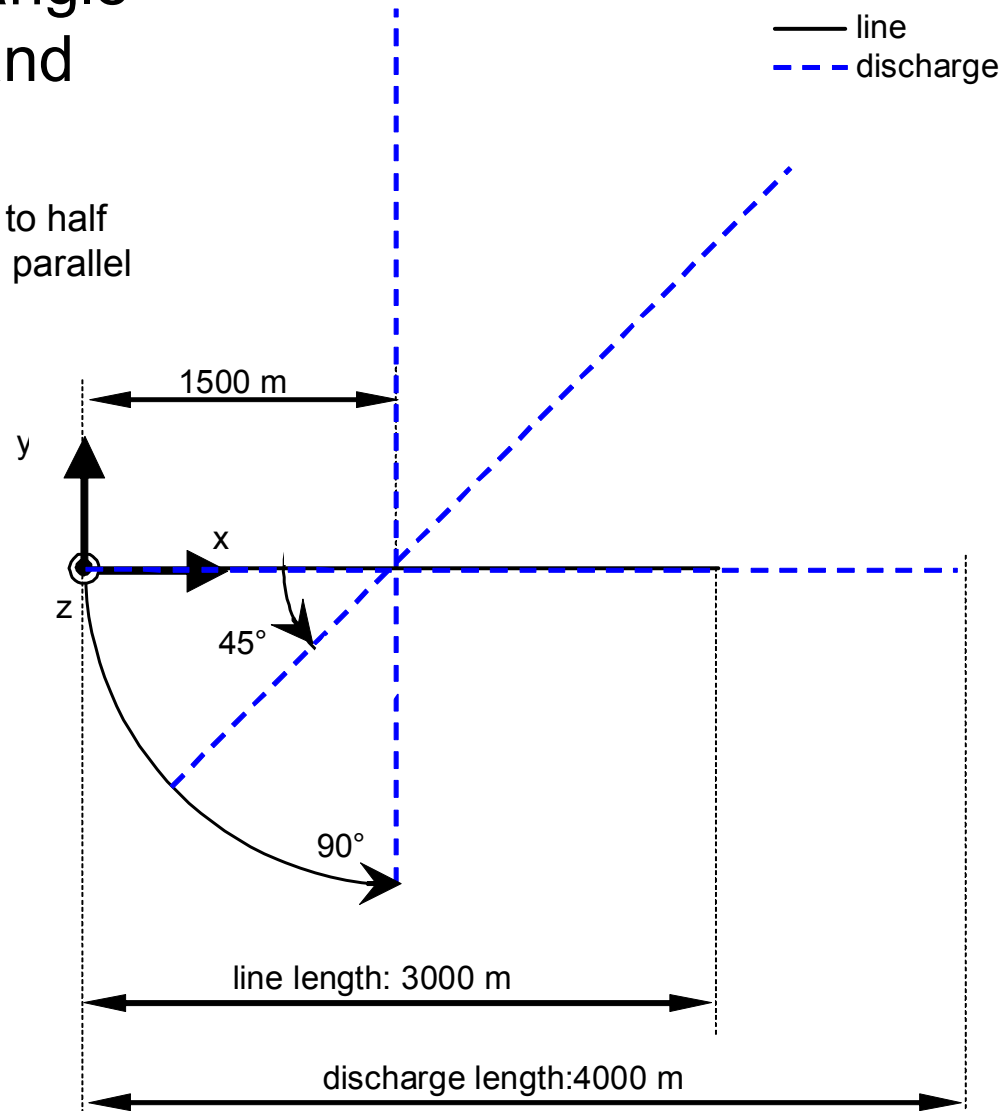
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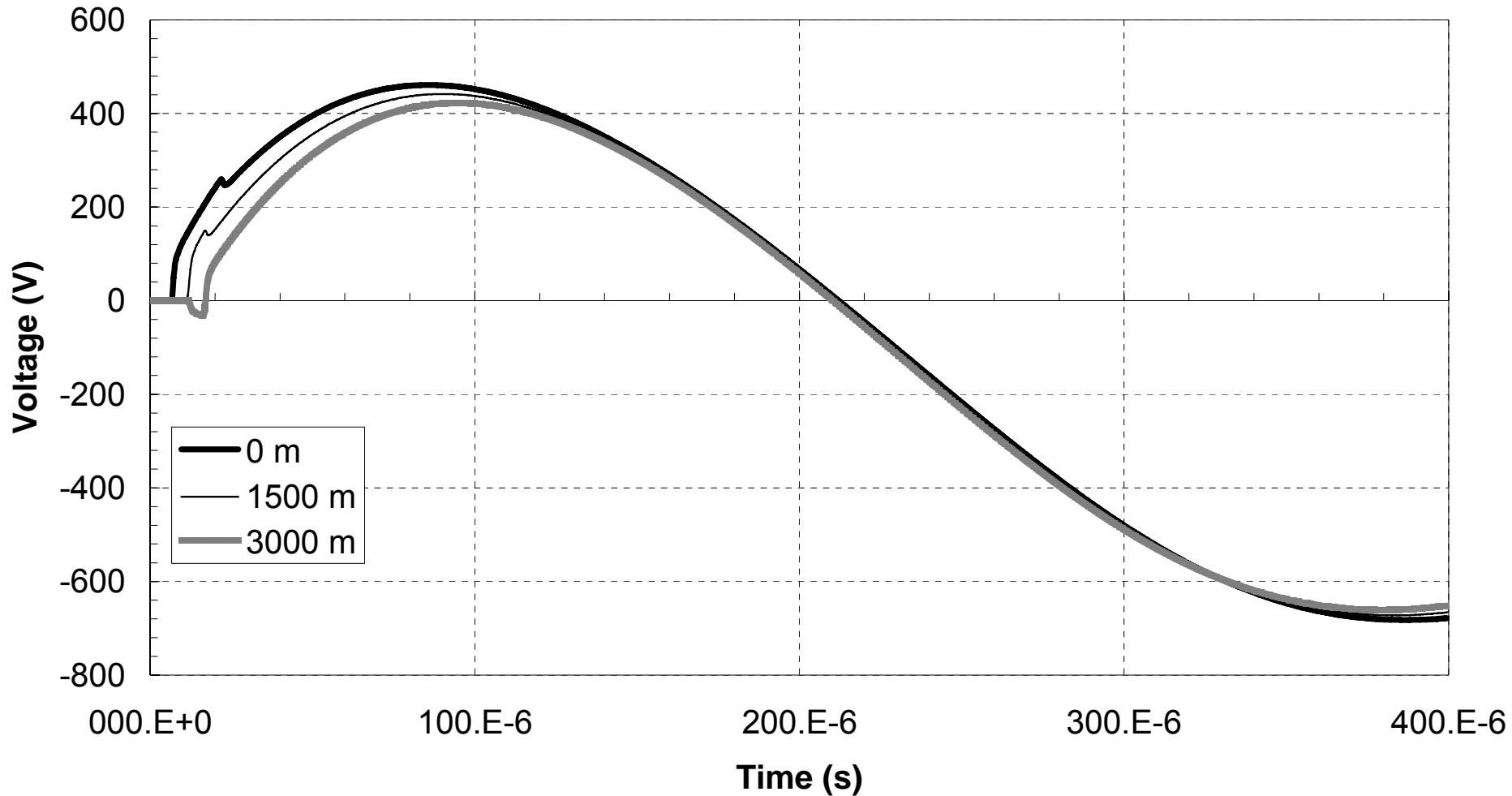
# Sensitivity analysis of CD induced voltages: CD geometry

## Sensitivity analysis against angle between projections of line and discharge

(current amplitude 18.1 kA, time rise 1.9  $\mu$ s, time to half value 50  $\mu$ s, speed  $10^7$  m/s, line and discharge in parallel planes)

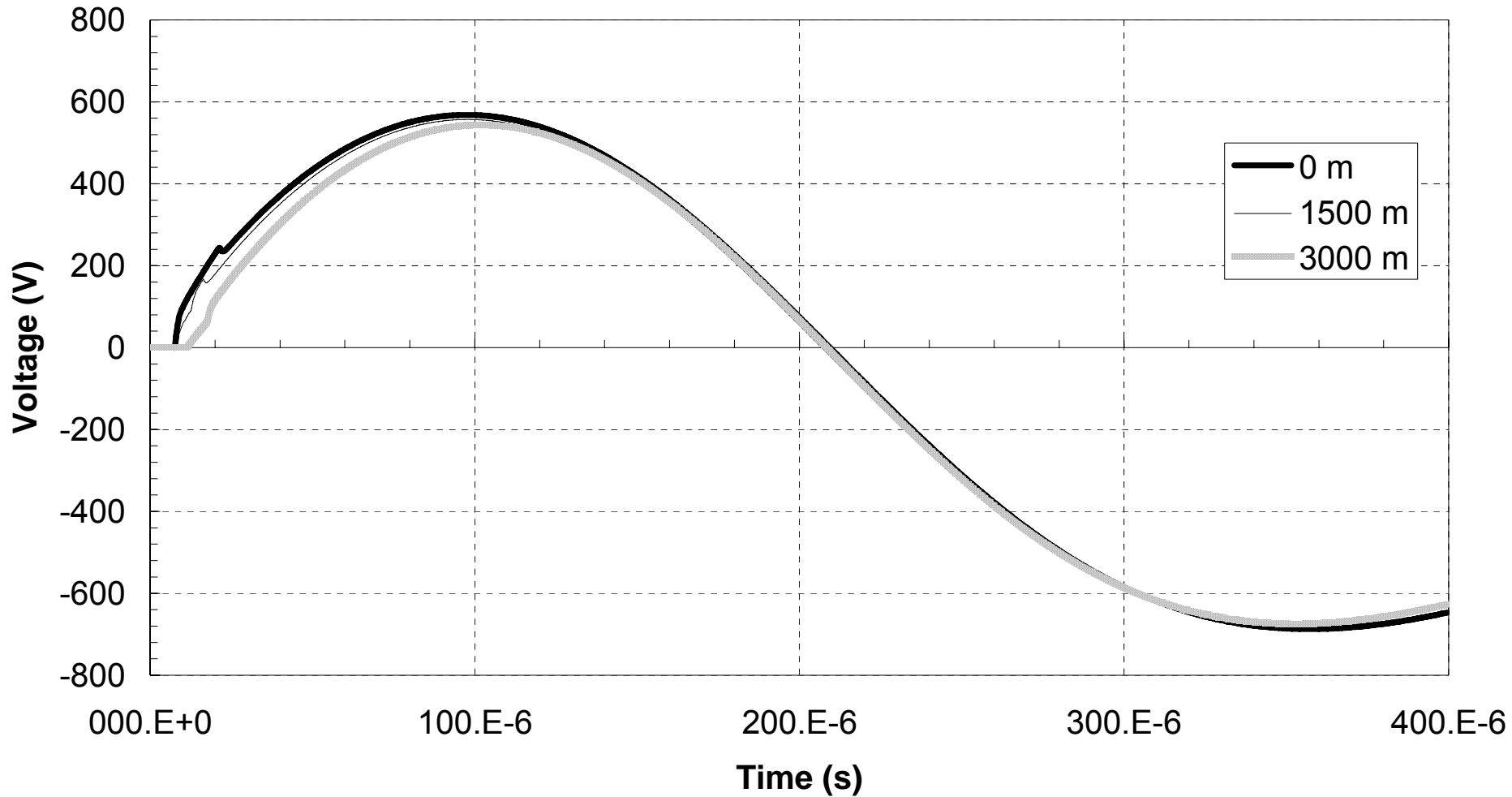


# Sensitivity analysis of CD induced voltages: CD geometry



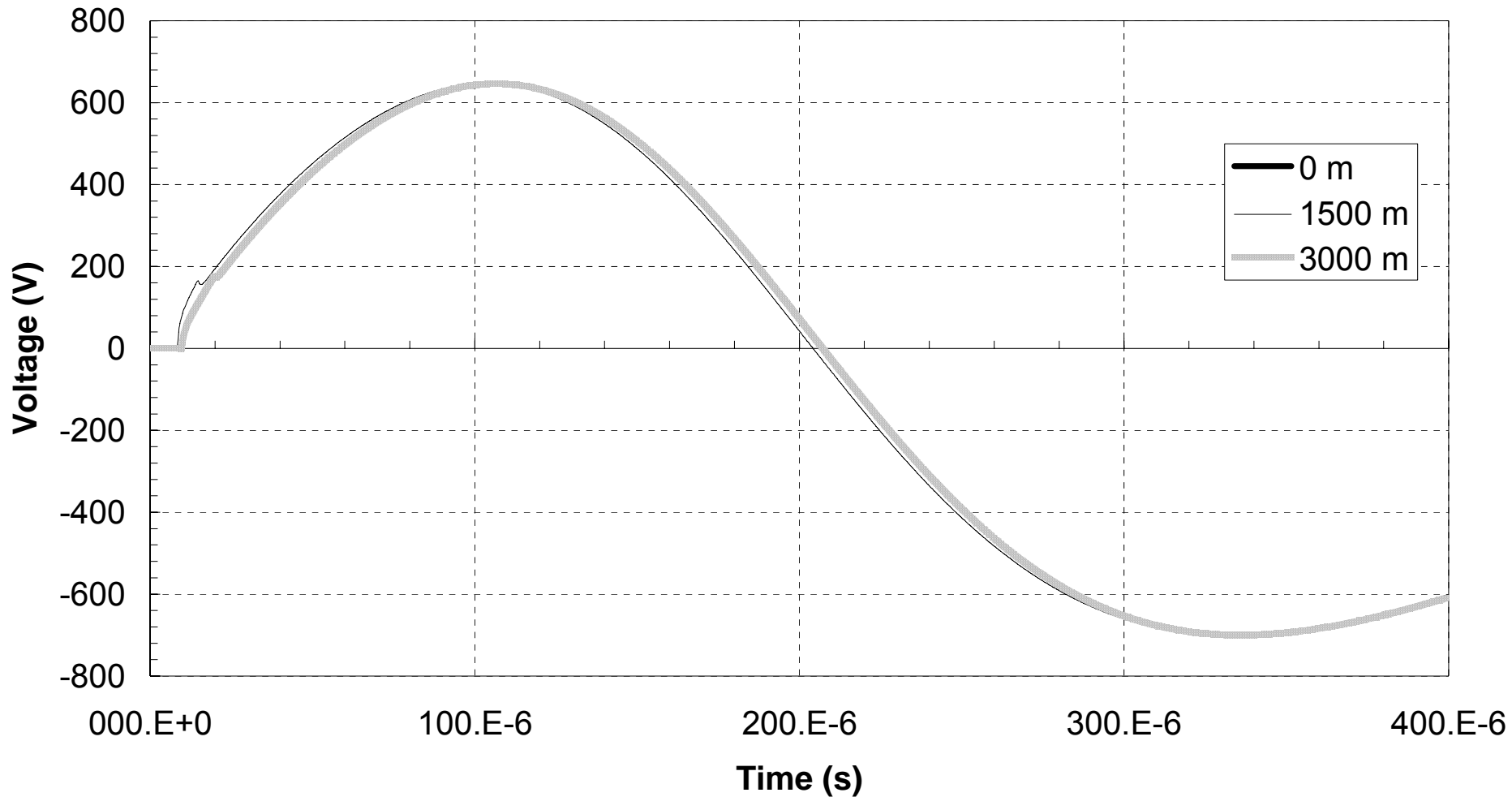
Induced voltages with discharge at 0°

# Sensitivity analysis of CD induced voltages: CD geometry



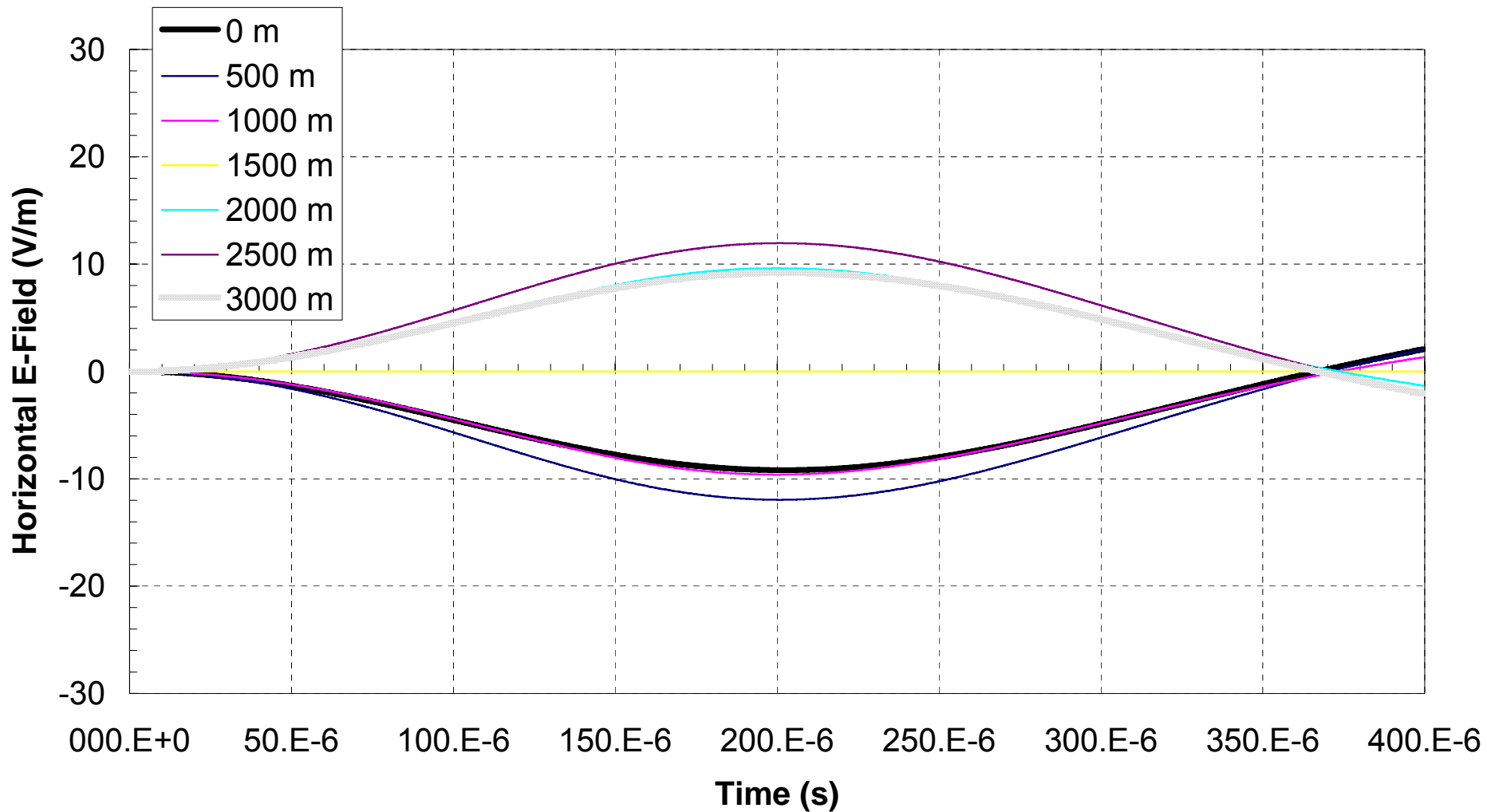
Induced voltages with discharge at 45°

# Sensitivity analysis of CD induced voltages: CD geometry



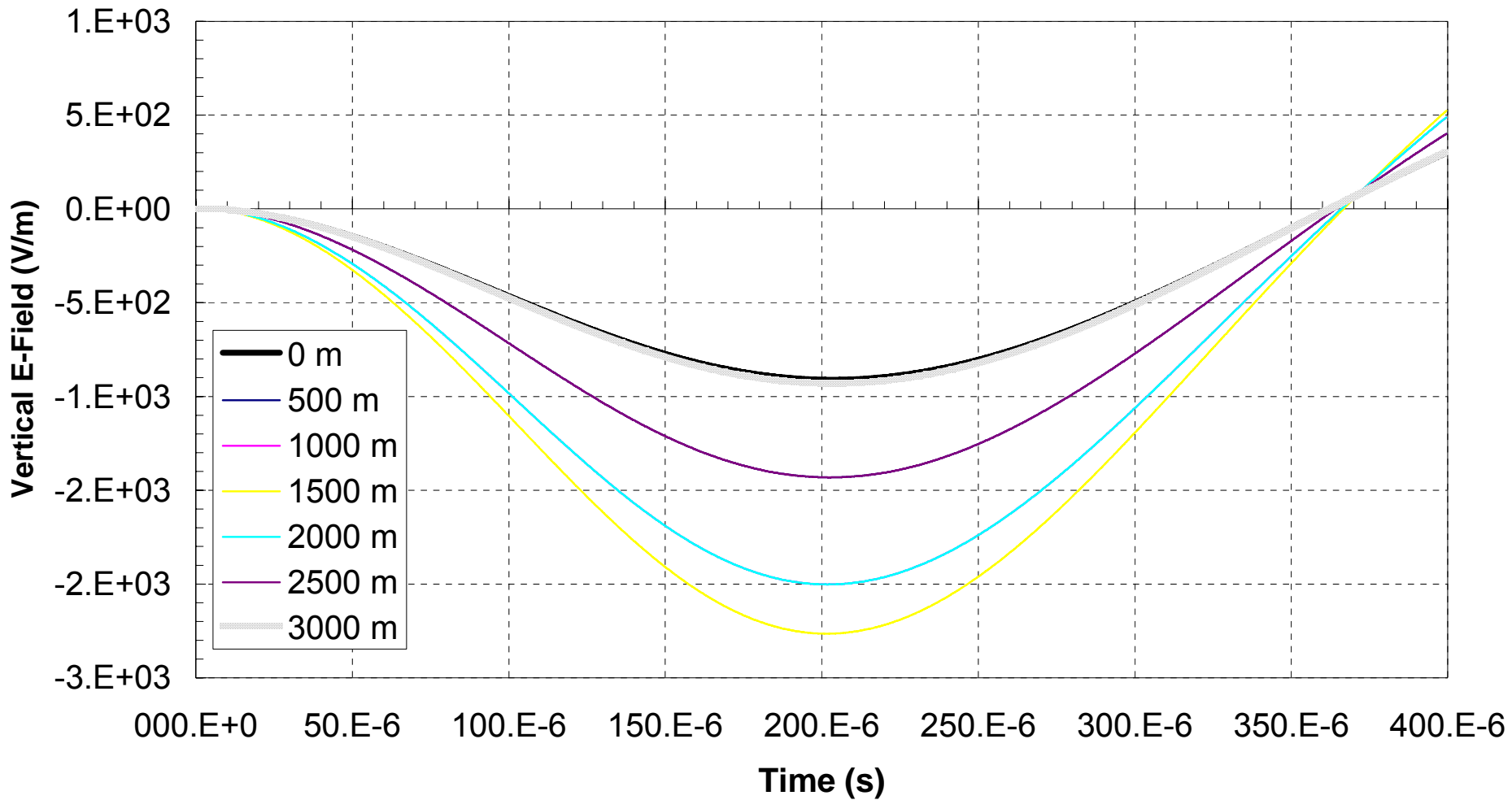
Induced voltages with discharge at 90°

# Sensitivity analysis of CD induced voltages: CD geometry



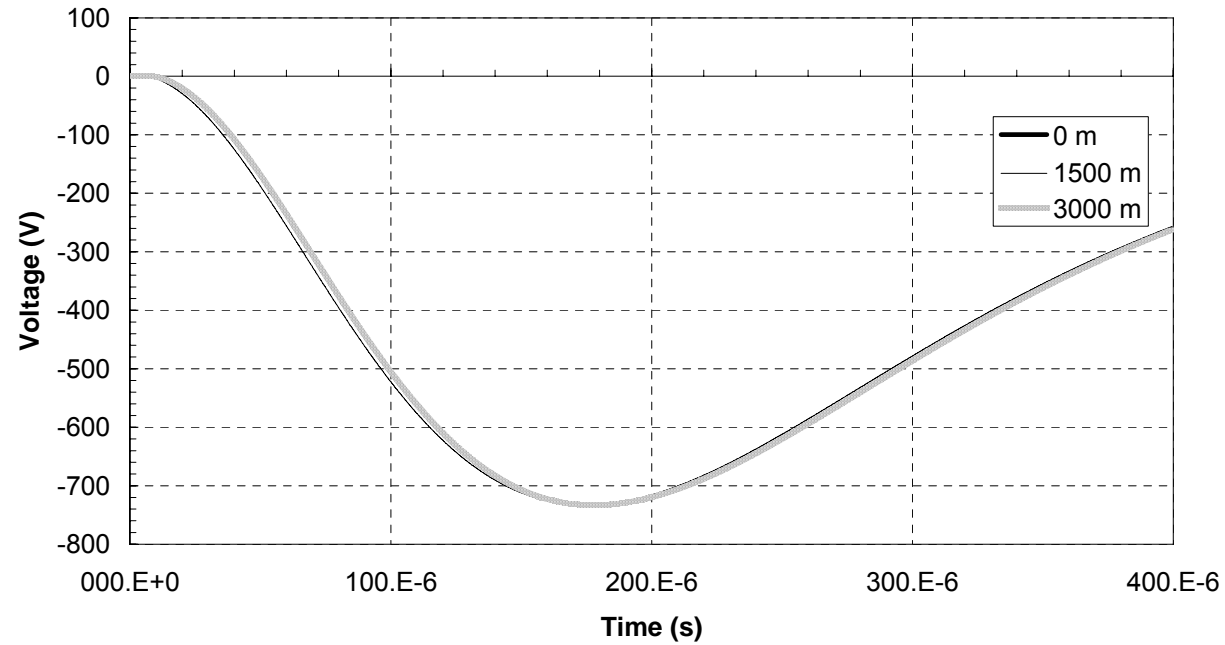
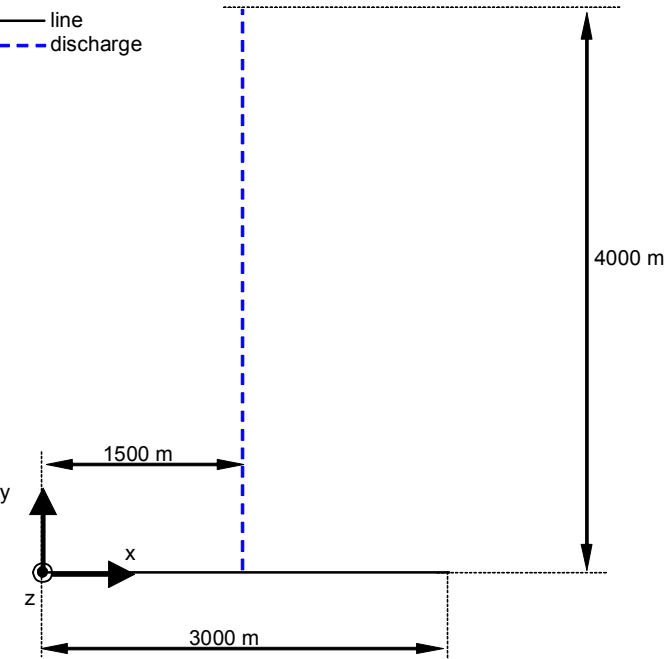
Horizontal Electric field with discharge at 90°

# Sensitivity analysis of CD induced voltages: CD geometry



Vertical Electric field with discharge at 90°

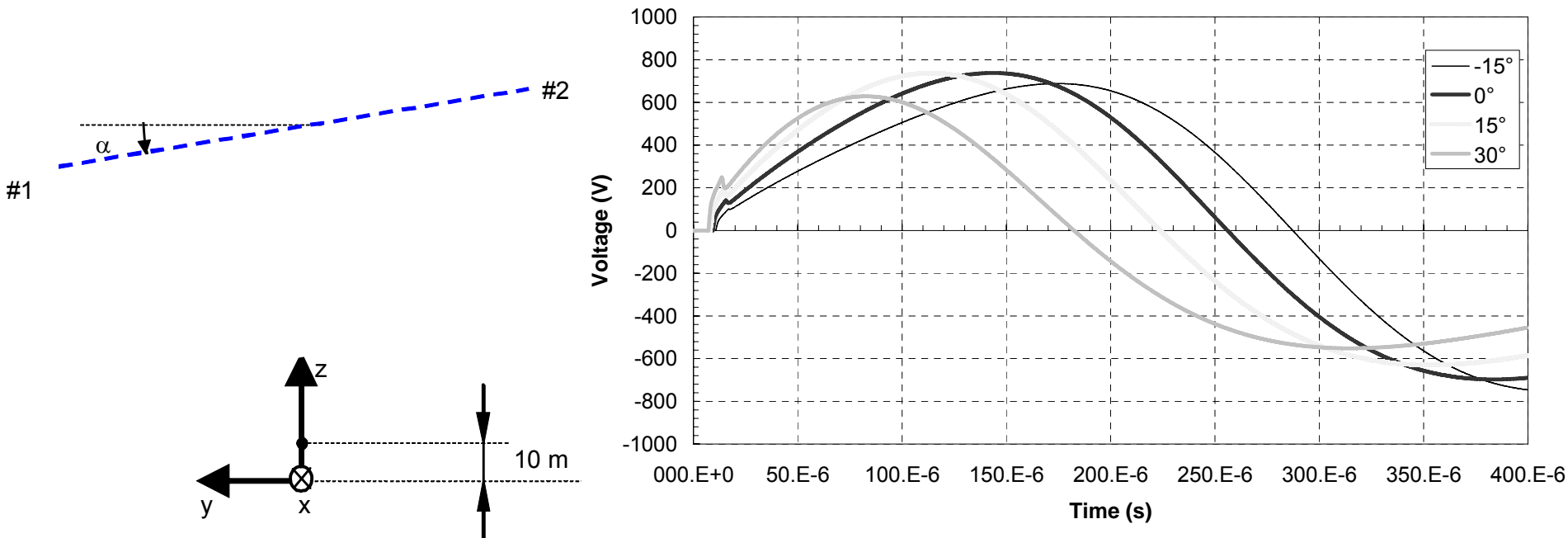
# Sensitivity analysis of CD induced voltages: CD geometry



# Sensitivity analysis of CD induced voltages: CD geometry

## Sensitivity analysis against angle between discharge and the ground

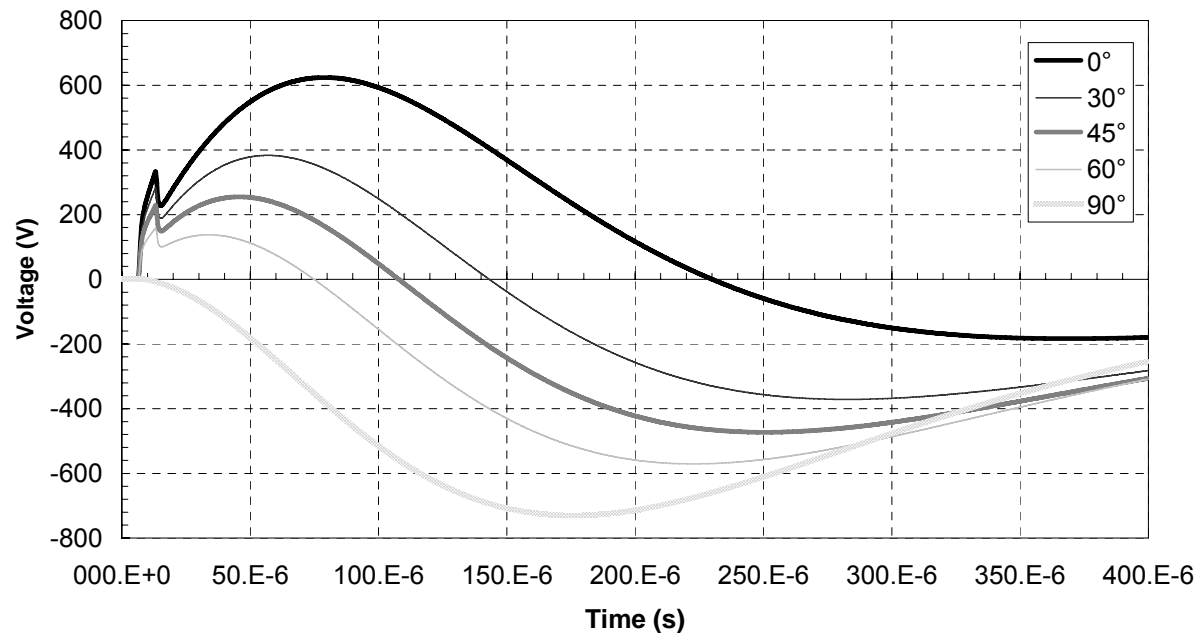
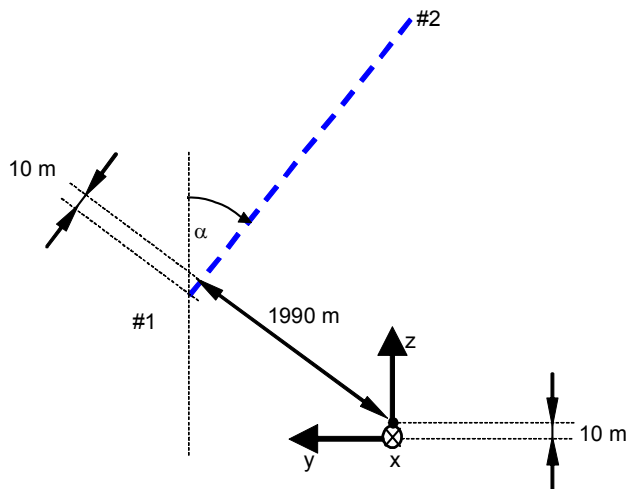
(current amplitude 18.1 kA, time rise 1.9  $\mu\text{s}$ , time to half value 50  $\mu\text{s}$ , speed  $10^7$  m/s, line and discharge at  $90^\circ$  and at a distance of 1990 m)



# Sensitivity analysis of CD induced voltages: CD geometry

Sensitivity analysis against angle between discharge and the ground, so that to  $0^\circ$  corresponds a CG

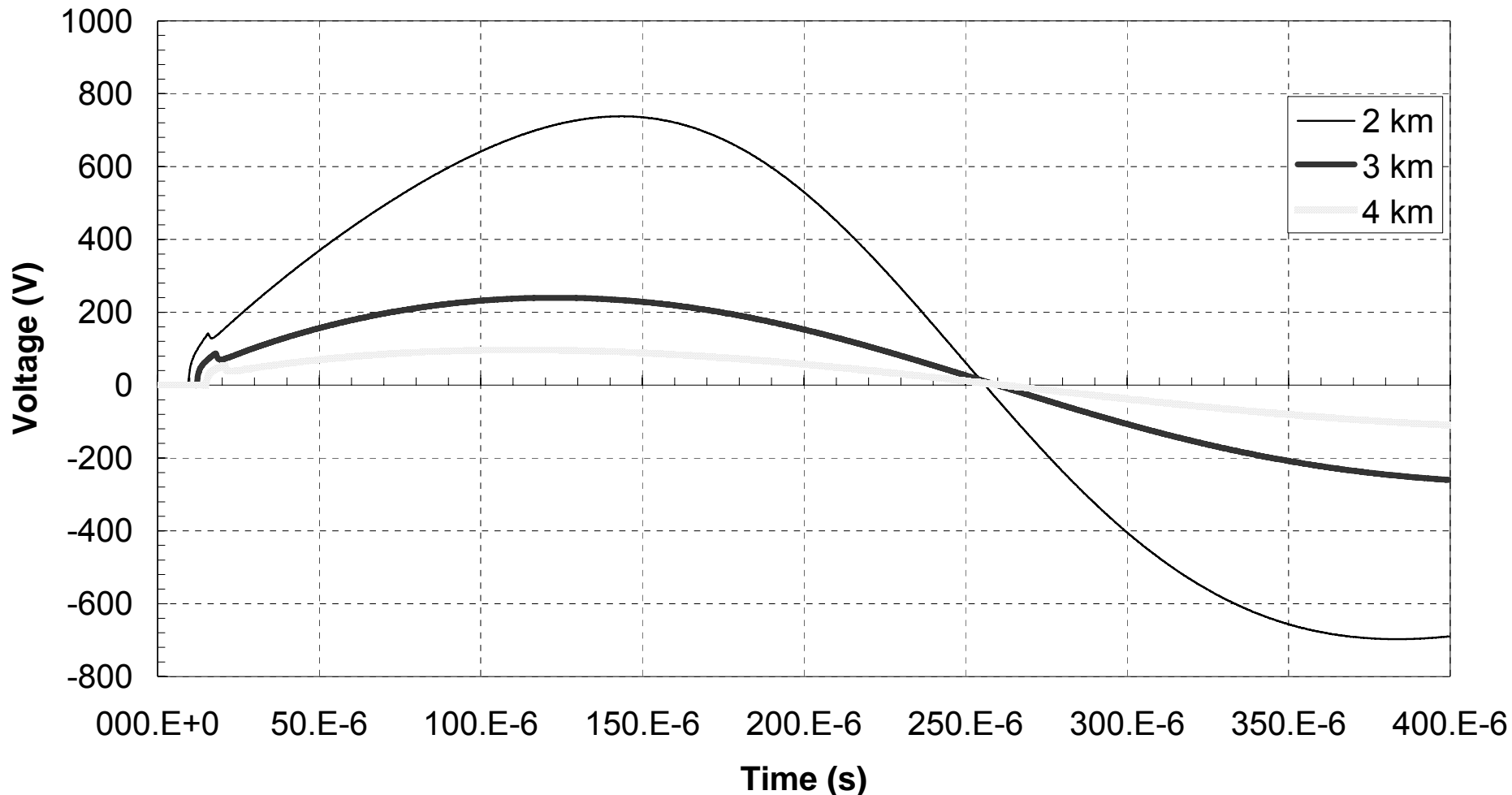
(current amplitude 18.1 kA, time rise 1.9  $\mu\text{s}$ , time to half value 50  $\mu\text{s}$ , speed  $10^7$  m/s)



# Sensitivity analysis of CD induced voltages: CD geometry

## Sensitivity analysis against height of the CD

(current amplitude 18.1 kA, time rise 1.9  $\mu$ s, time to half value 50  $\mu$ s, speed 10<sup>7</sup> m/s, discharge orthogonal and symmetrical to the line)



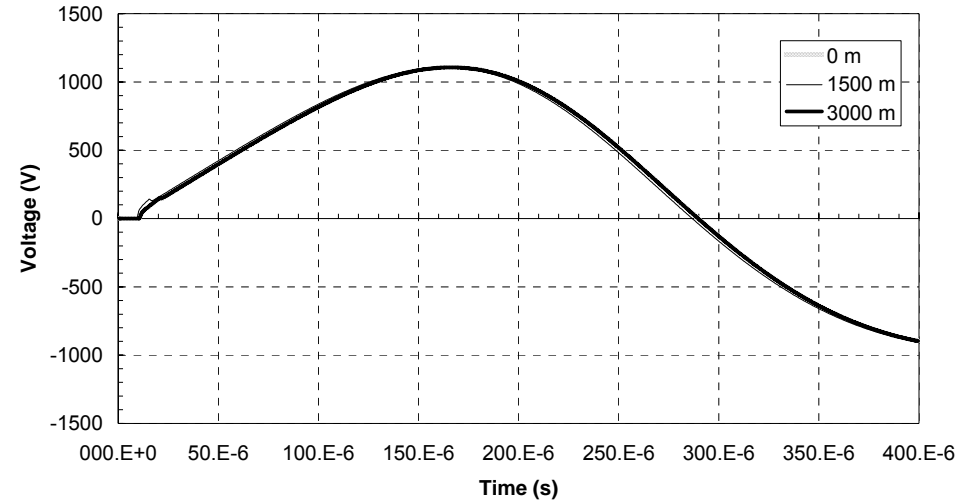
# Outline of presentation

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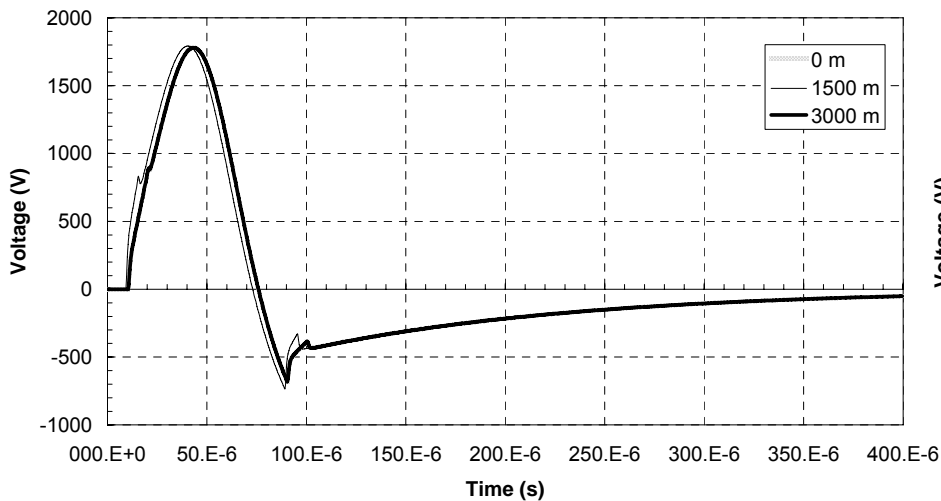
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# Sensitivity analysis of CD induced voltages: speed of wavefront

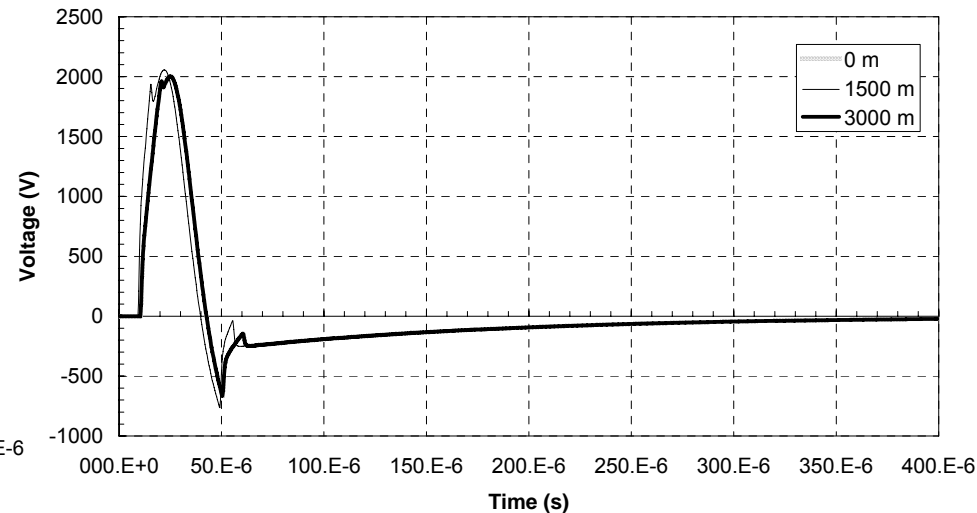
(current amplitude 18.1 kA, time rise 1.9  $\mu$ s, time to half value 100  $\mu$ s, speed  $10^7$  m/s, discharge orthogonal and symmetrical to the line, at 2000 m of height)



$v = 10^7$  m/s

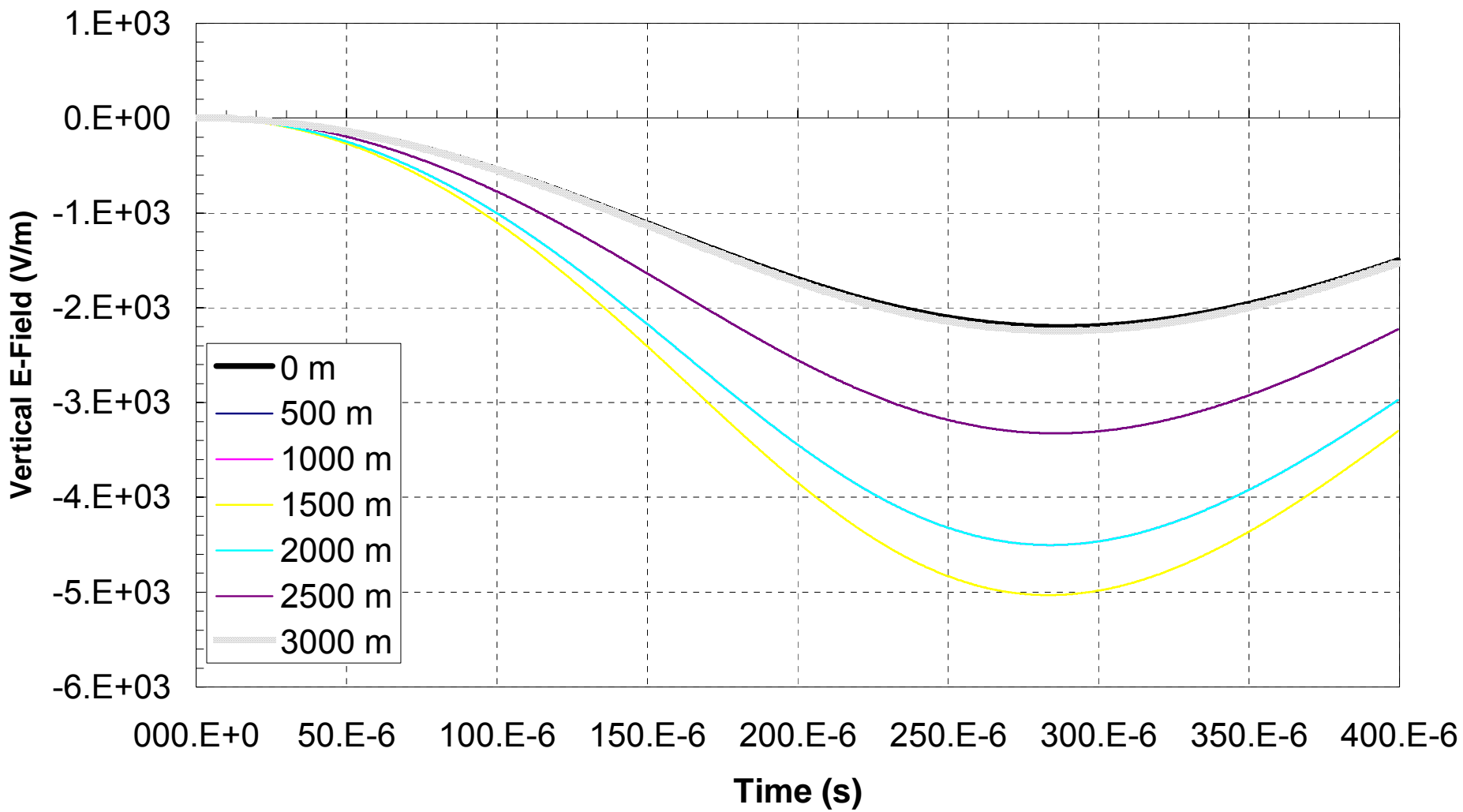


$v = 5 \times 10^7$  m/s



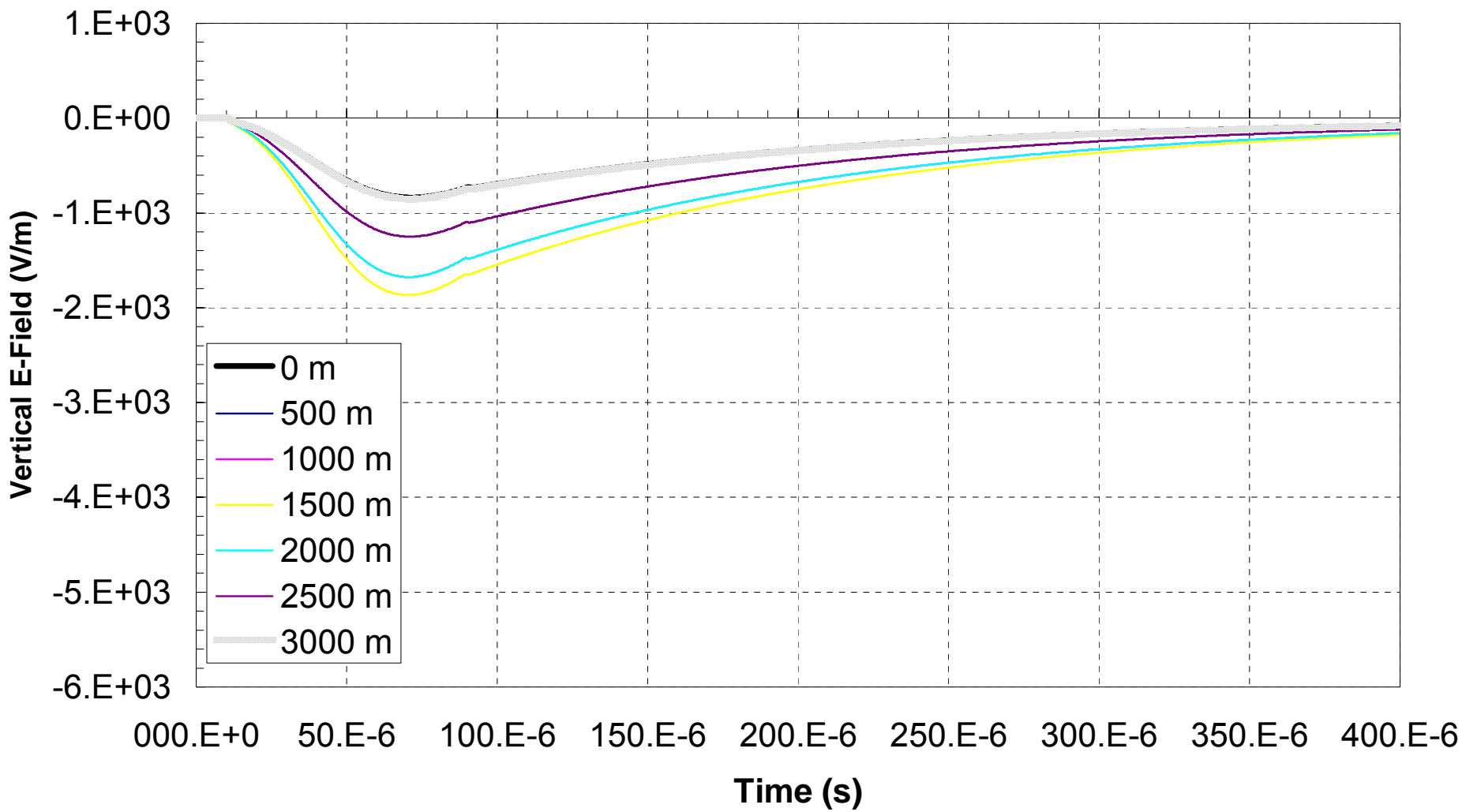
$v = 10^8$  m/s

# Sensitivity analysis of CD induced voltages: speed of wavefront



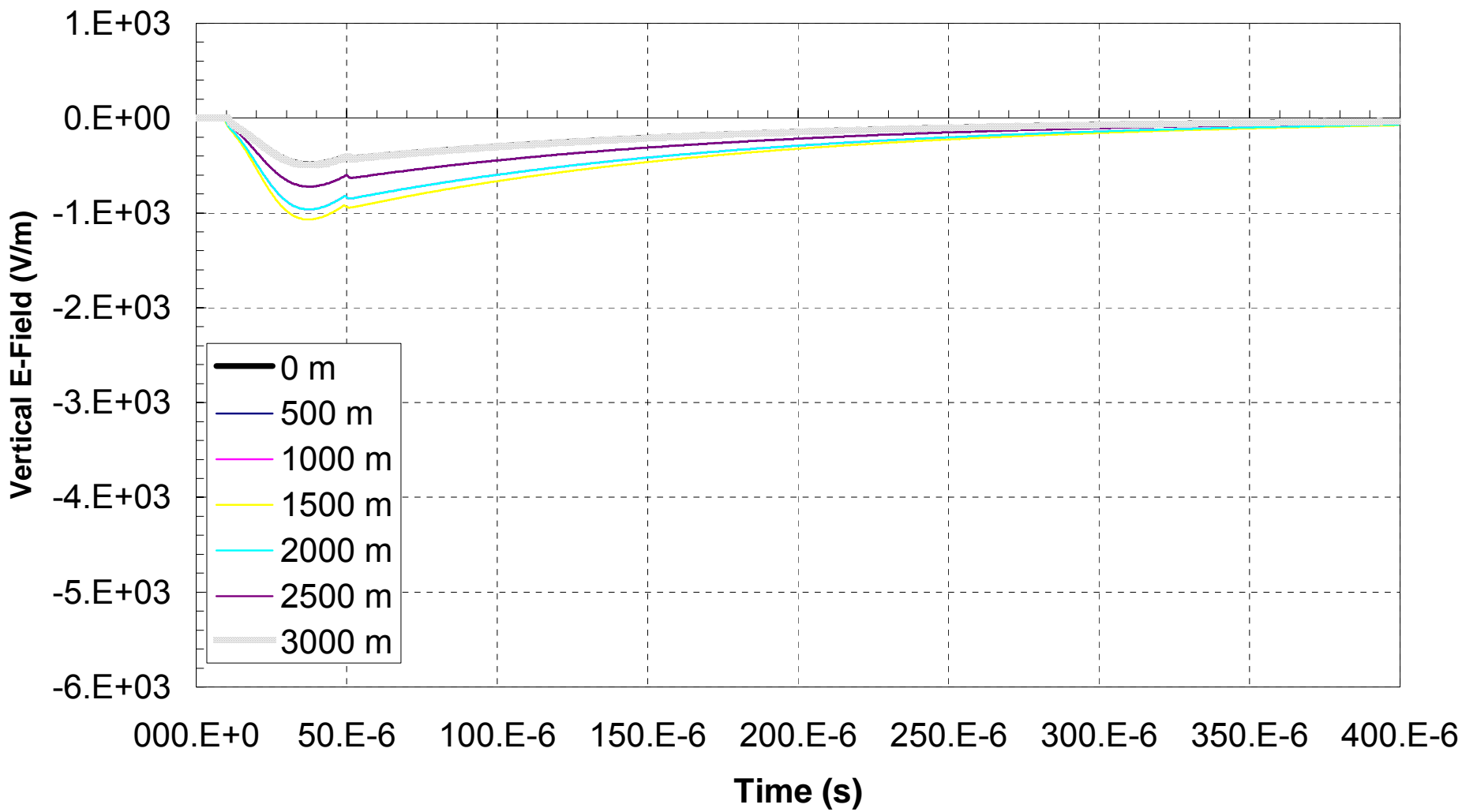
$v = 10^7$  m/s

# Sensitivity analysis of CD induced voltages: speed of wavefront



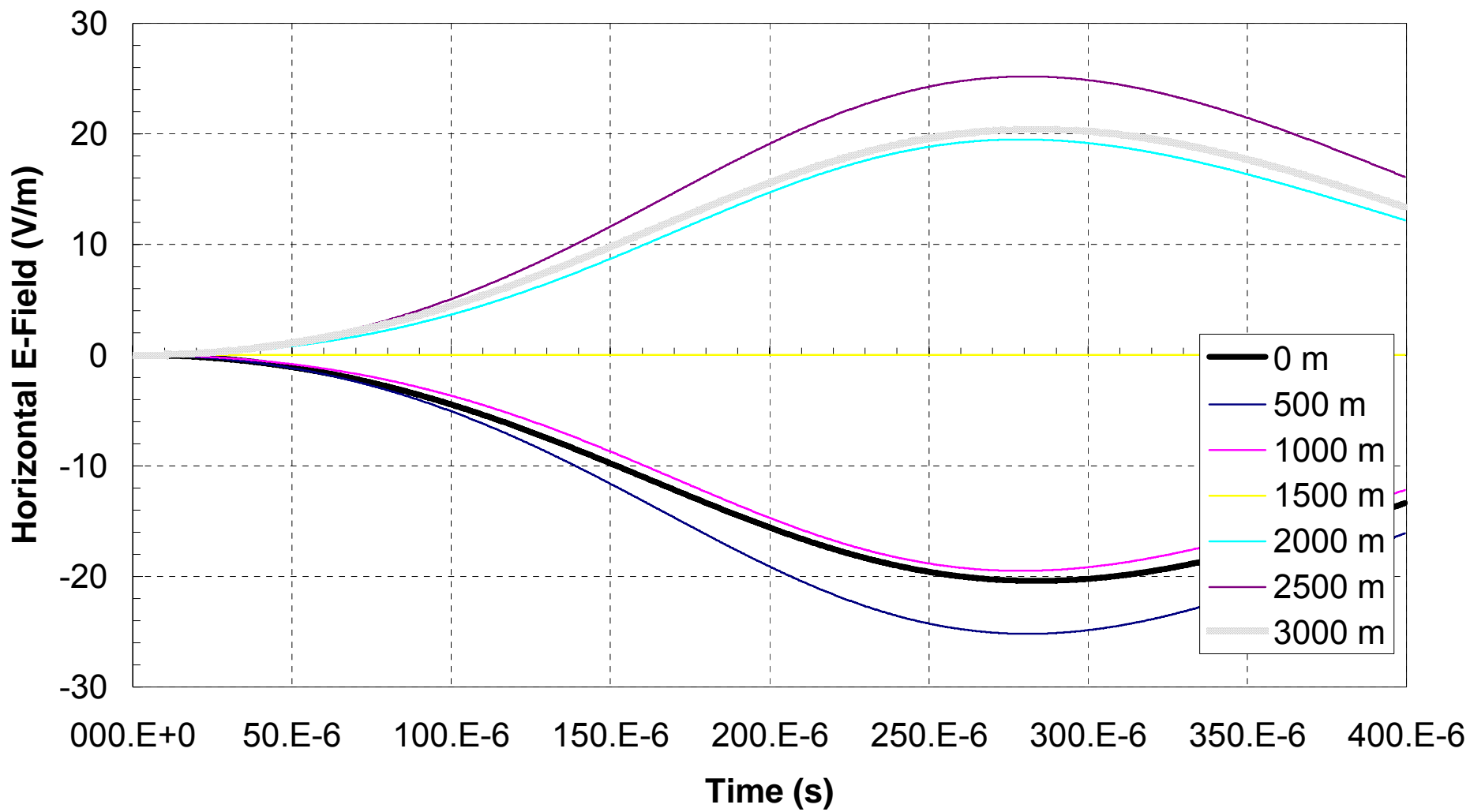
$v = 5 \times 10^7$  m/s

# Sensitivity analysis of CD induced voltages: speed of wavefront



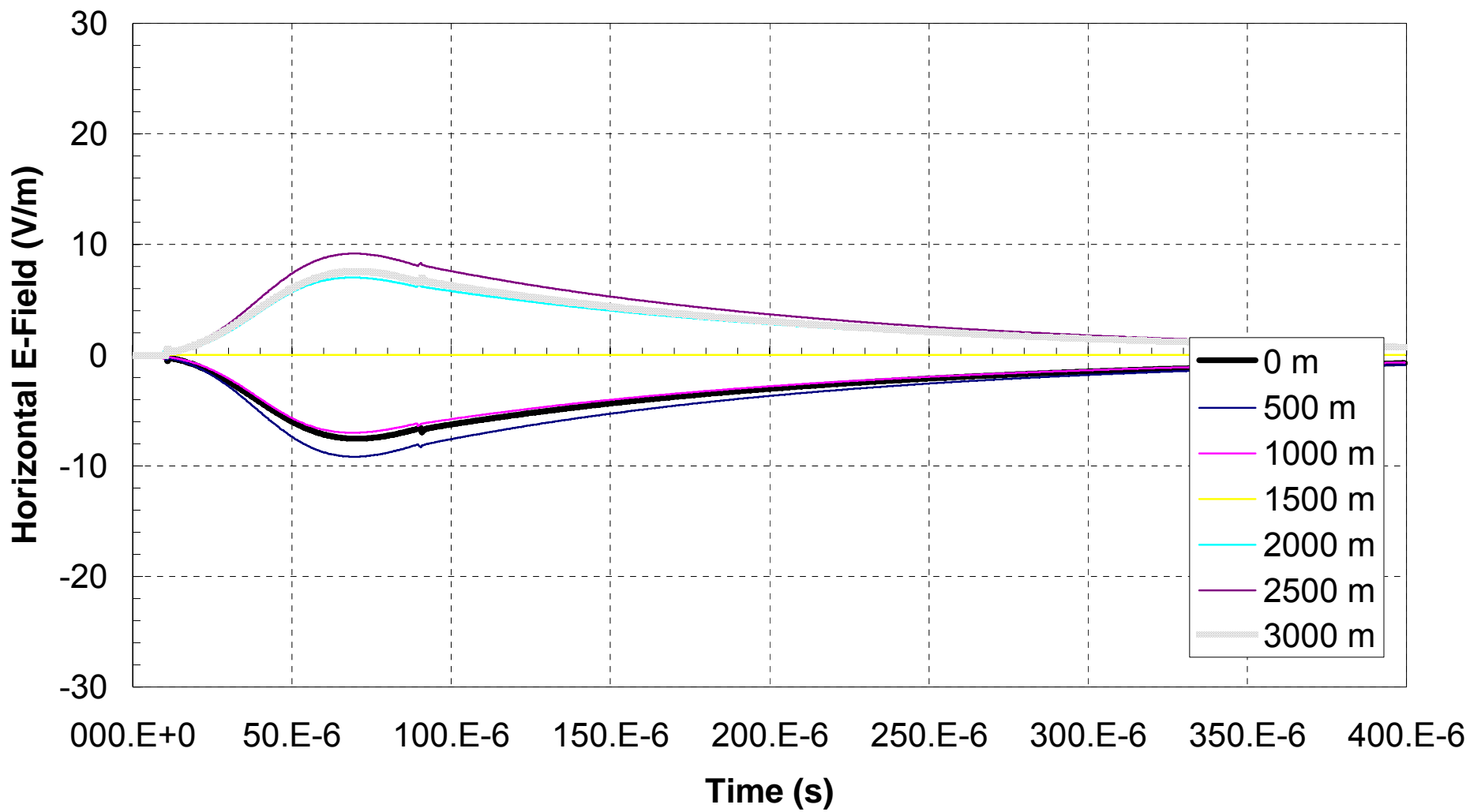
$v = 10^8$  m/s

# Sensitivity analysis of CD induced voltages: speed of wavefront



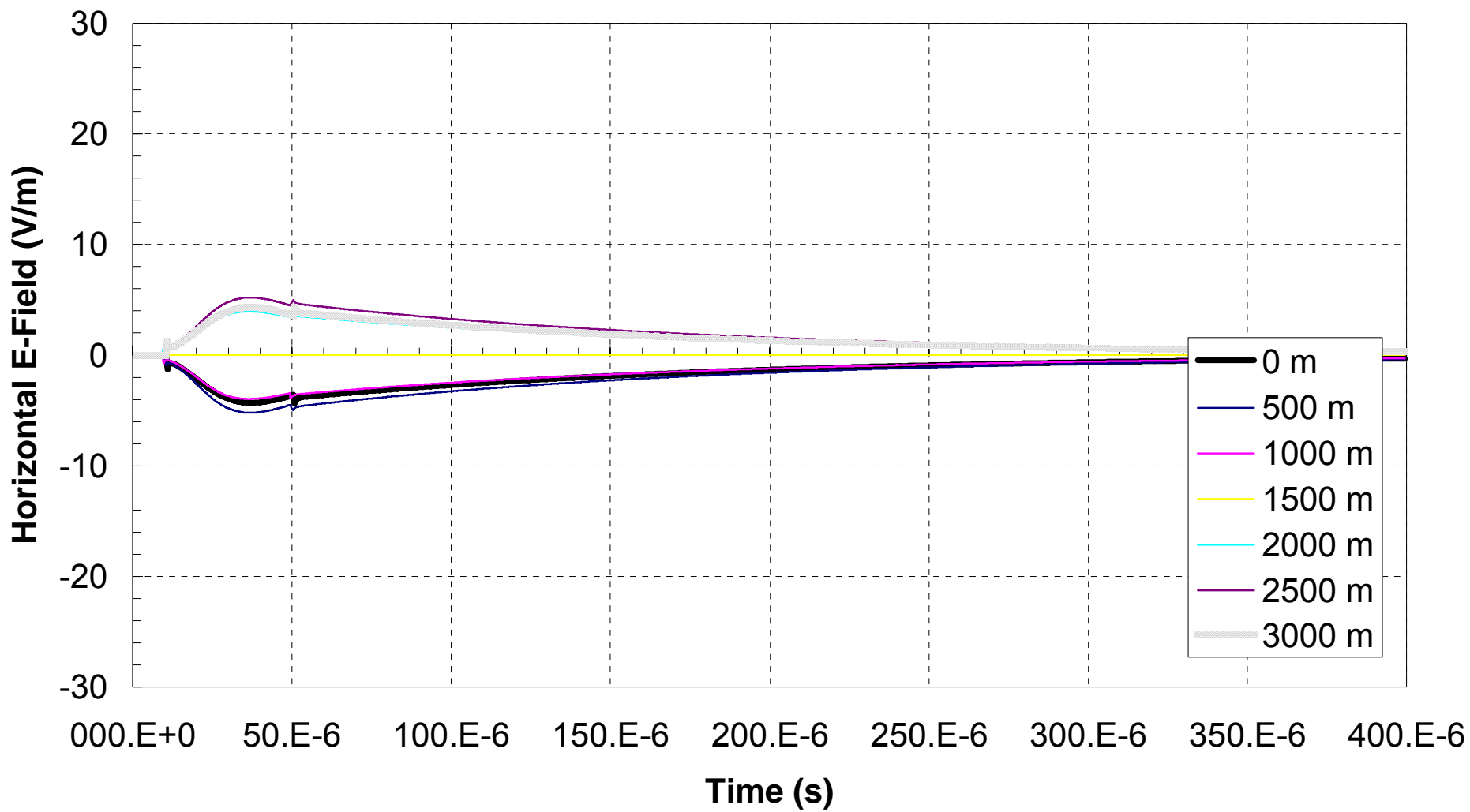
$v = 10^7$  m/s

# Sensitivity analysis of CD induced voltages: speed of wavefront



$v = 5 \times 10^7 \text{ m/s}$

# Sensitivity analysis of CD induced voltages: speed of wavefront



$v = 10^8$  m/s

# Conclusions

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- In order to evaluate the voltages induced in a power line by cloud discharges, a procedure for generally oriented lightning paths has been developed.
- The characteristic of the lightning discharge to which the induced voltages are most sensitive are, under the assumptions made, the current amplitude, the distance between line and discharge and the speed of the wavefront.
- Further work has to be made to obtain more realistic configuration of cloud discharge than those presented in this preliminary study.