Outline of the tutorial

1. Introduction

2. Theoretical basis of the LIOV code
   - Return-Stroke Current Model
   - LEMP model
   - Coupling Model

3. **Application of LIOV**
   - **Sensitivity analysis**
   - Statistical studies

4. Interface with EMTP

5. Conclusions

Sensitivity analysis CARSON?

ground resistivity

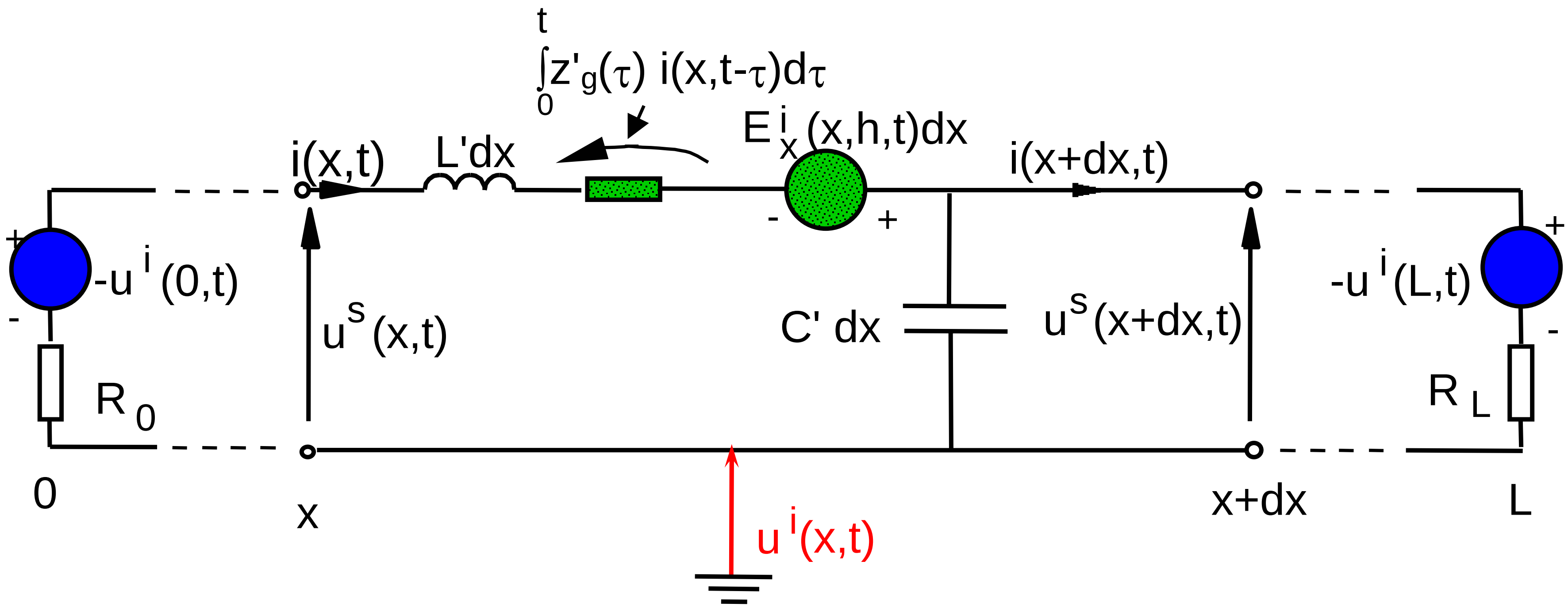
In the determination of lightning-induced voltages, the ground resistivity plays a role

I) **in the calculation of the incident field, and**

II) **in the calculation of the line longitudinal parameters (ground correction term)**

Sensitivity analysis *Cont.*

ground resistivity



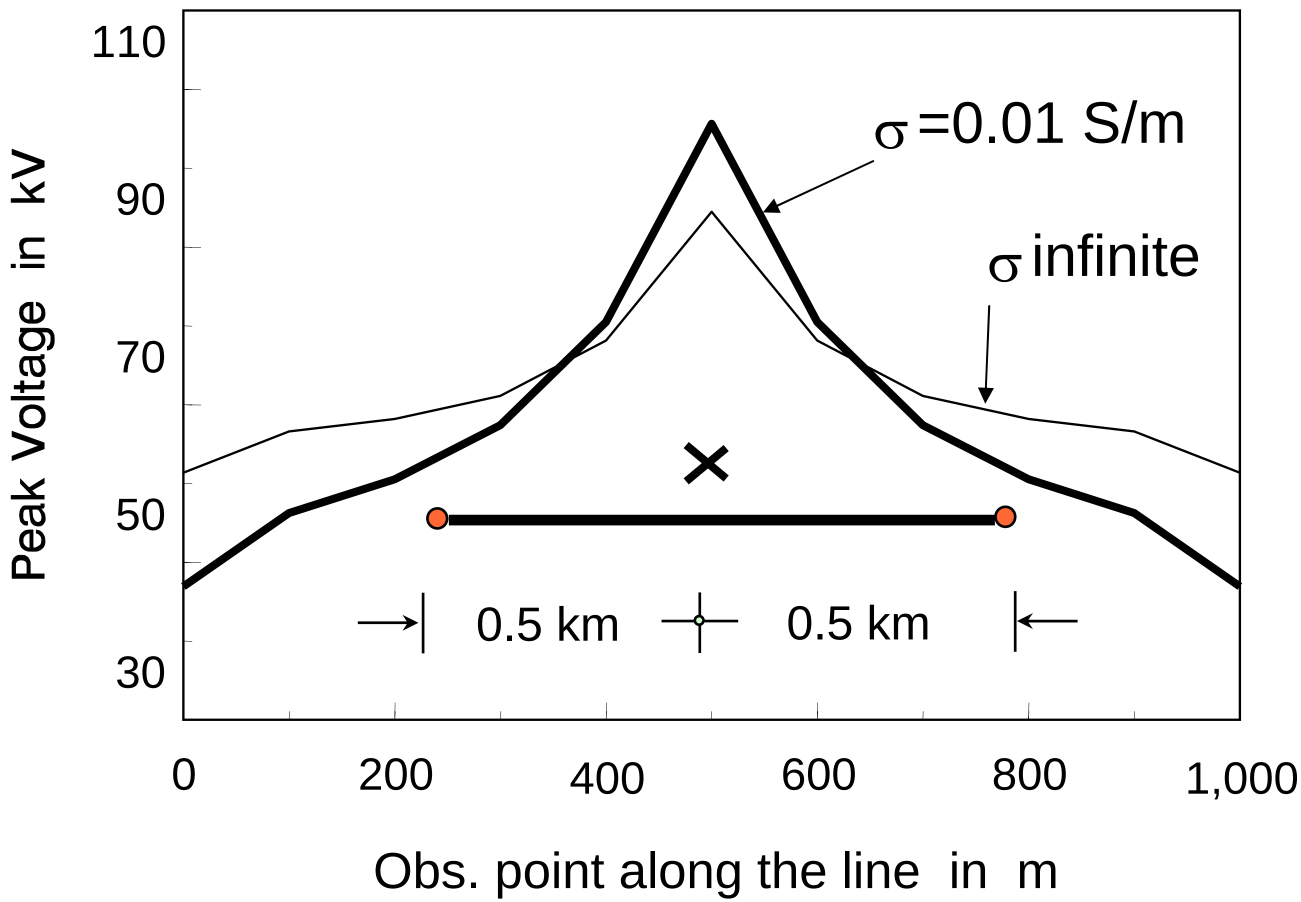
Transmission line Coupling equations by Agrawal et al.

(<u>lossy</u> ground)

Sensitivity analysis TAKEN FROM

Cont.

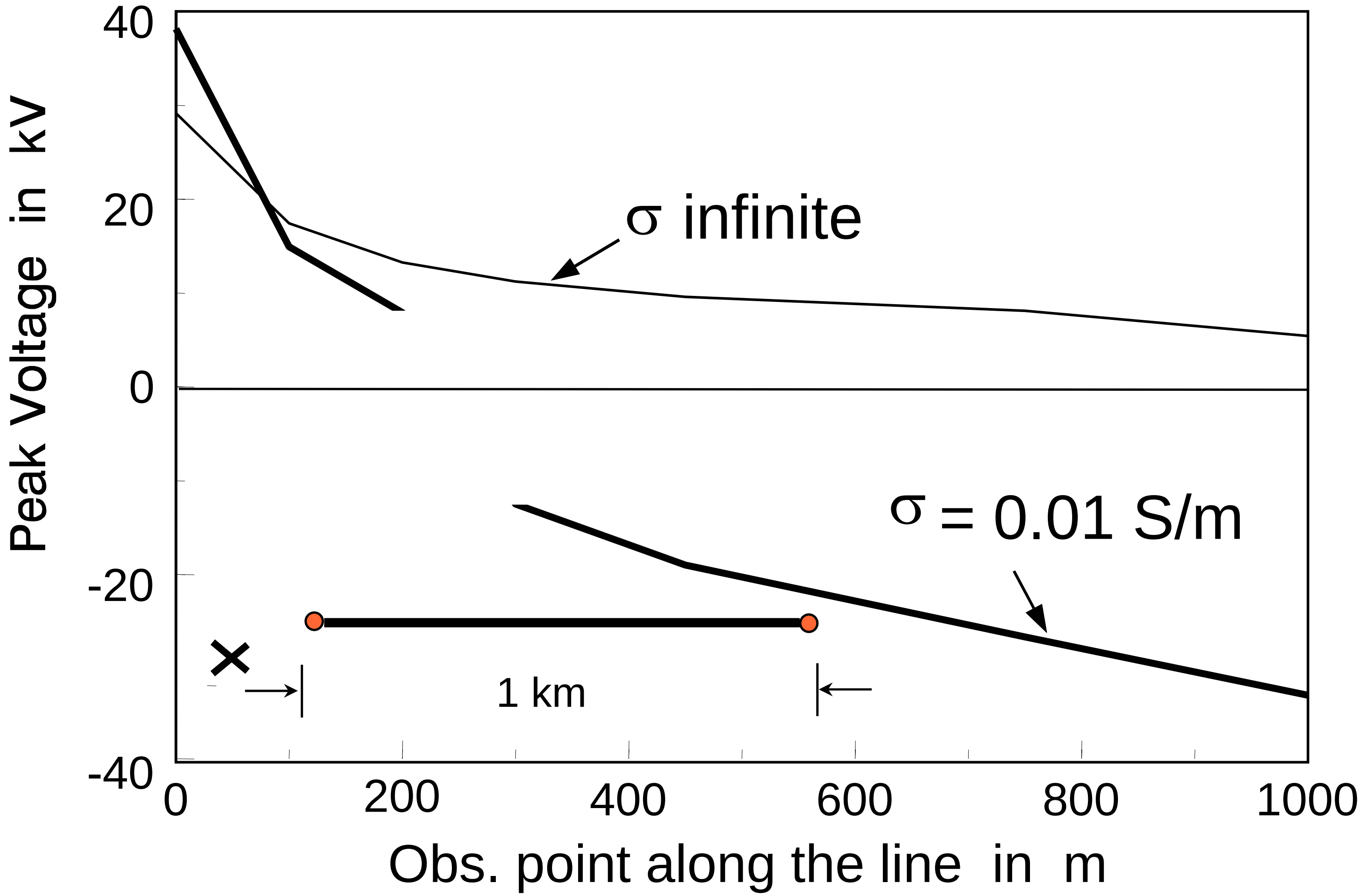
ground resistivity



Sensitivity analysis TAKEM FROM

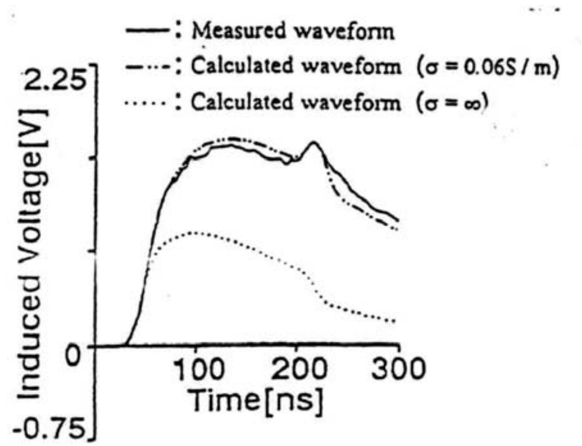
Cont.

ground resistivity

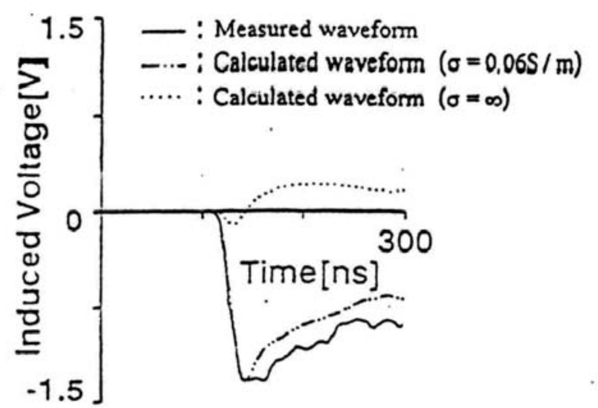


Sensitivity analysis *Cont.*

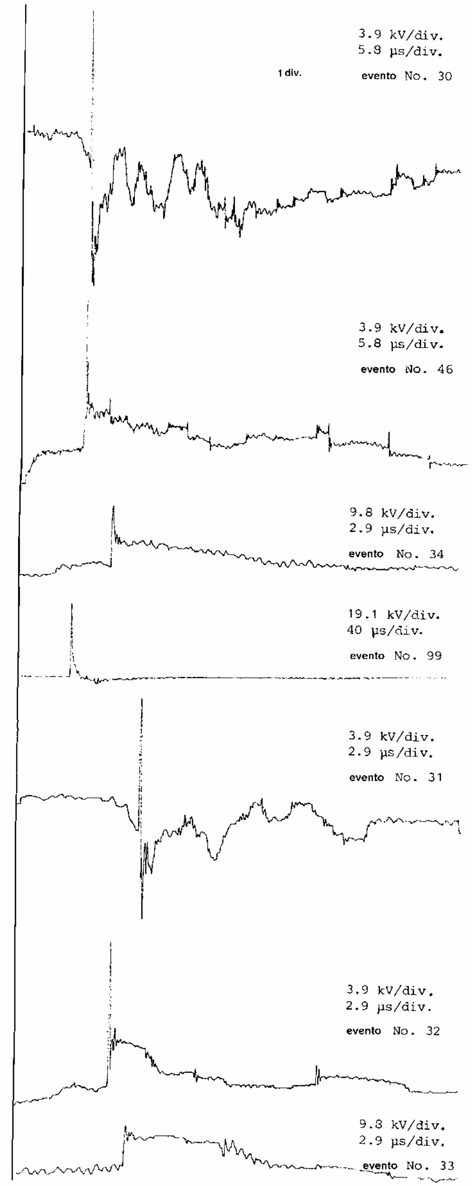
ground resistivity

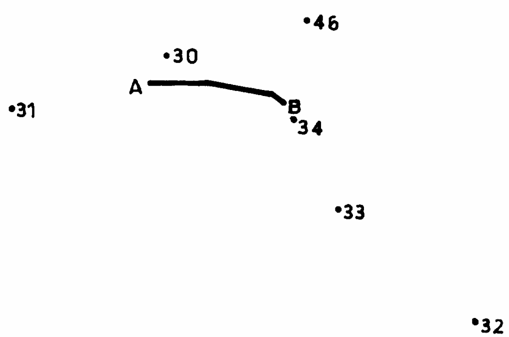


(a) Voltage waveforms at the closer end to the simulated striking point.



(b) Voltage waveforms at the farther end from the simulated striking point.





From Ishii et al. CIGRE Colloquium SC33, Toronto, 1997

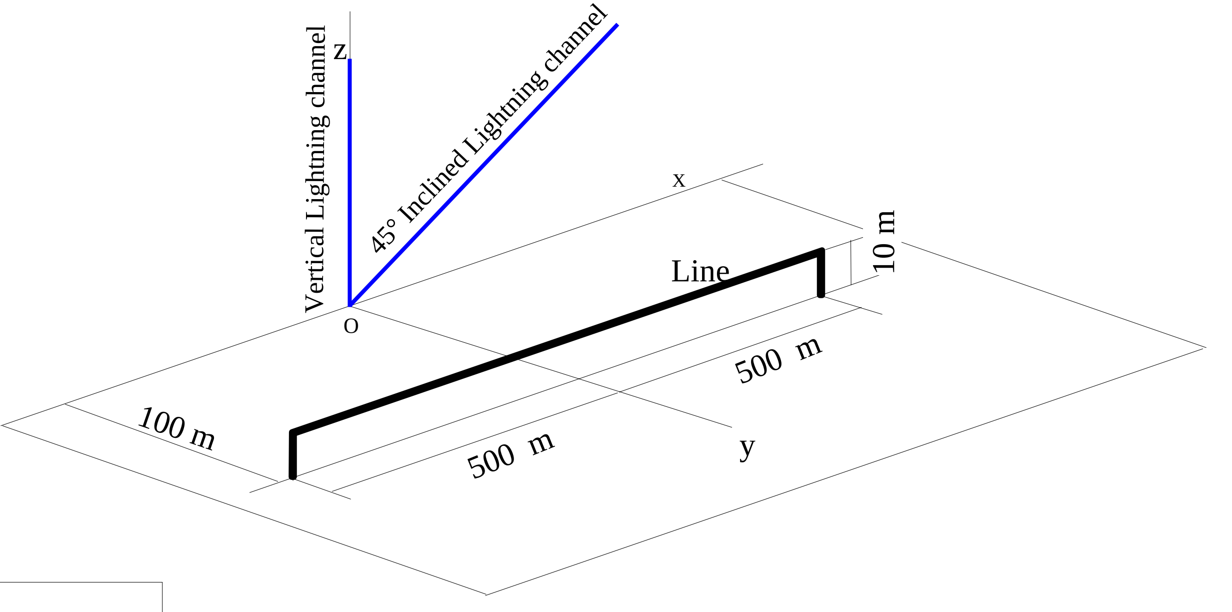
From De La Rosa et al, IEEE Trans. on PWDR, 1988

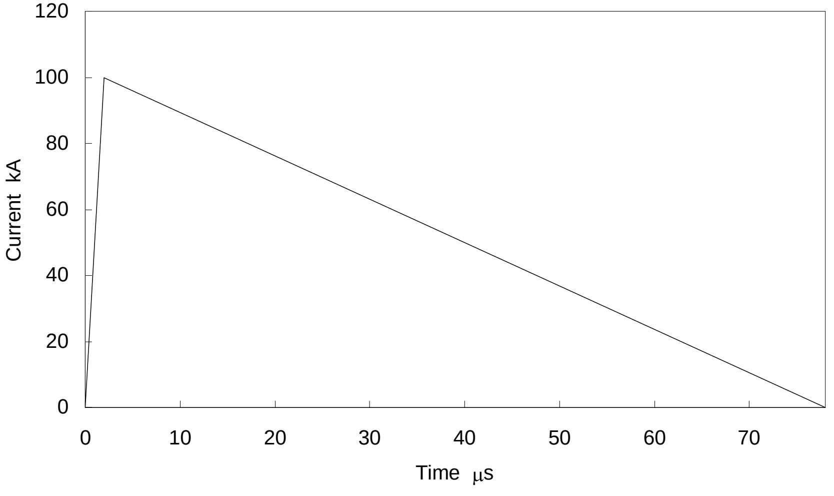
Sensitivity analysis MIGLIORARE

Cont.

Effects of inclined lightning channel

Model geometry

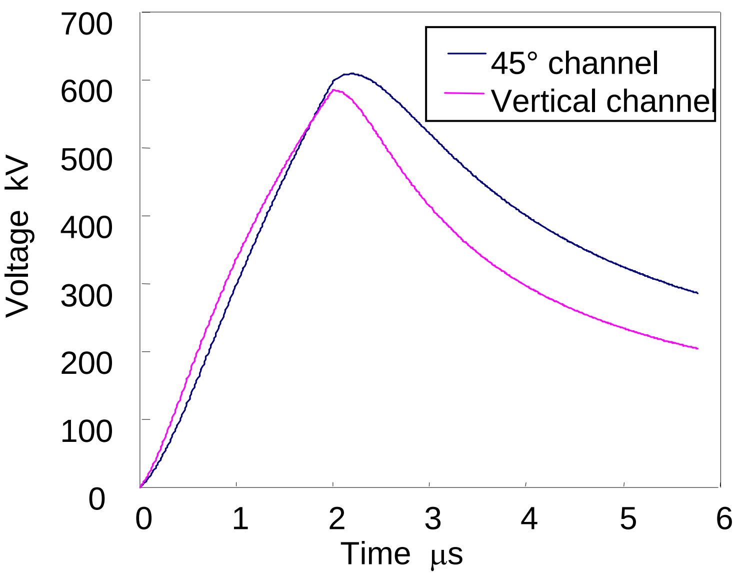


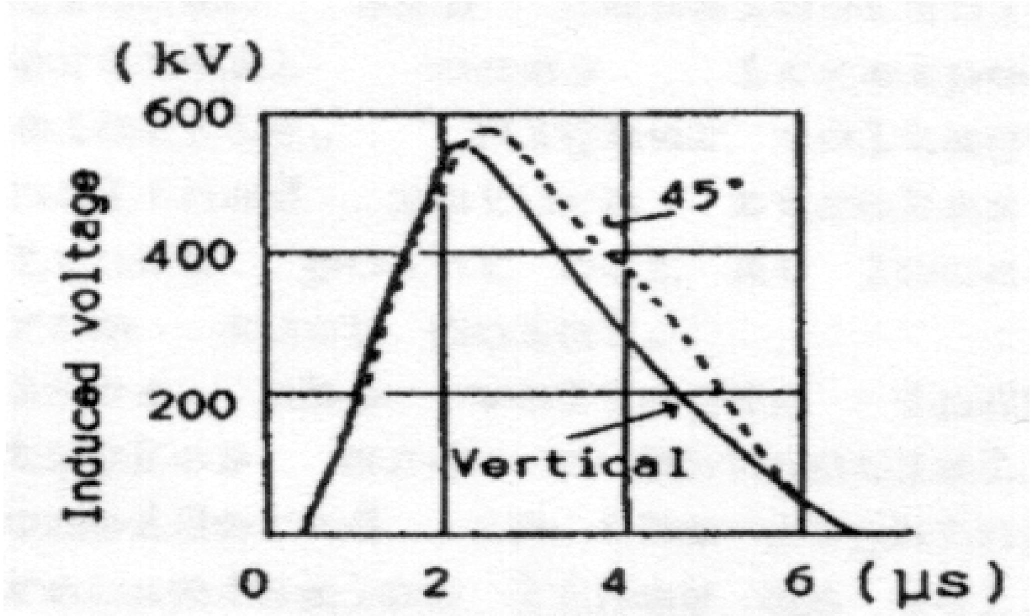


Lightning Current

Sensitivity analysis *Cont.*

Effects of inclined lightning channel





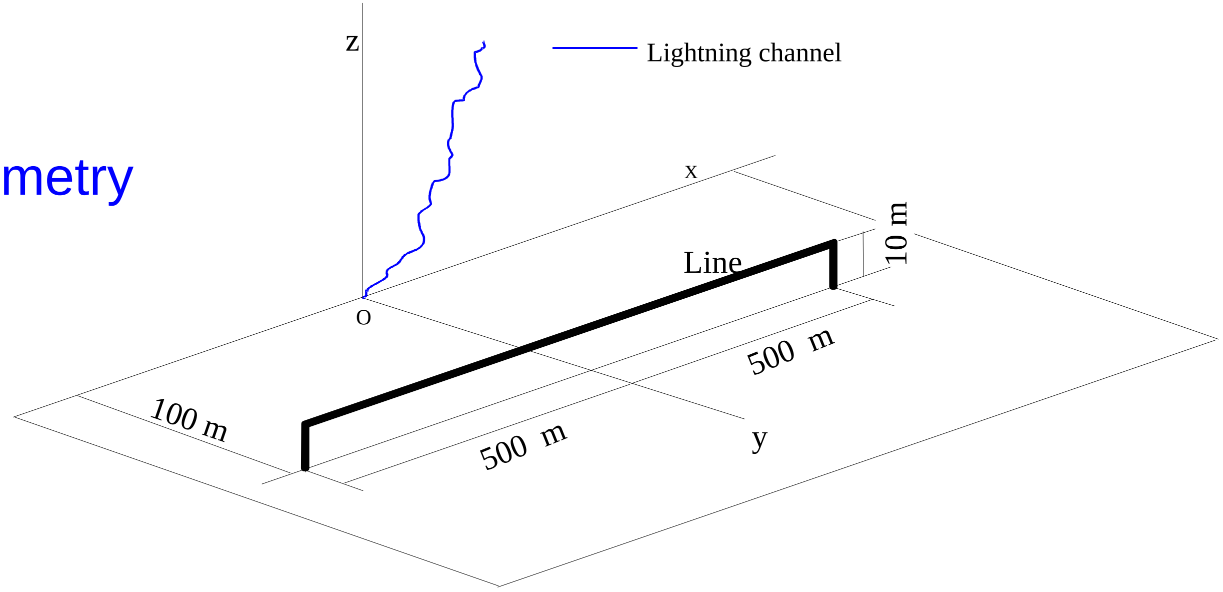
Comparison with [A.Sakakibara-"Calculation of Lightning-Induced Voltages on Overhead Lines Caused by Inclined Lightning Strokes",
IEEE PAS Vol.4 No.1 Jan 1989 pp.683-693]

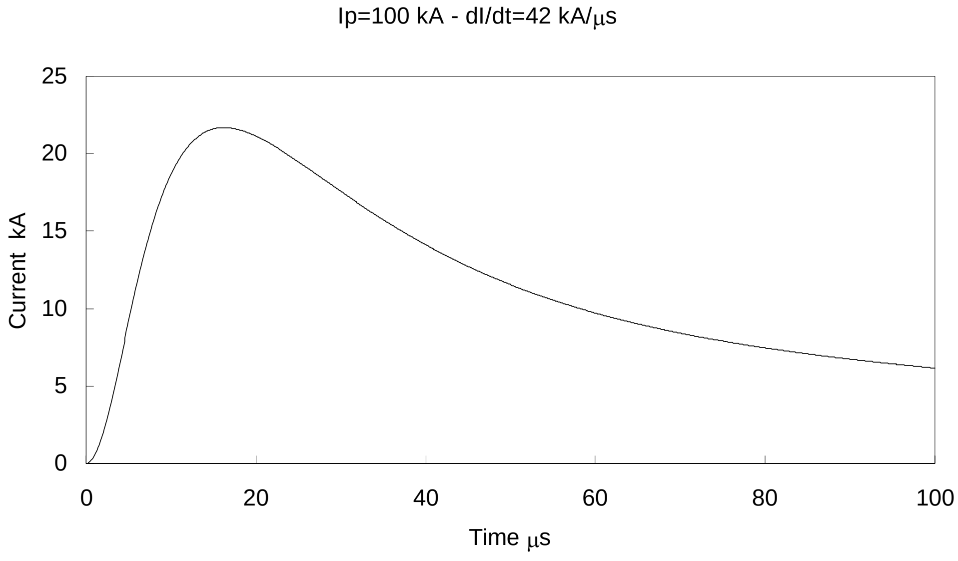
Sensitivity analysis MIGLIOR

Cont.

Effects of tortuosity of lightning channel

Model geometry

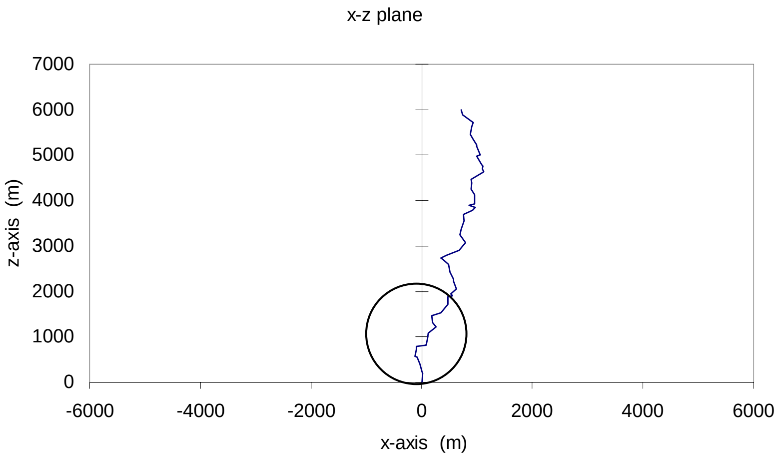


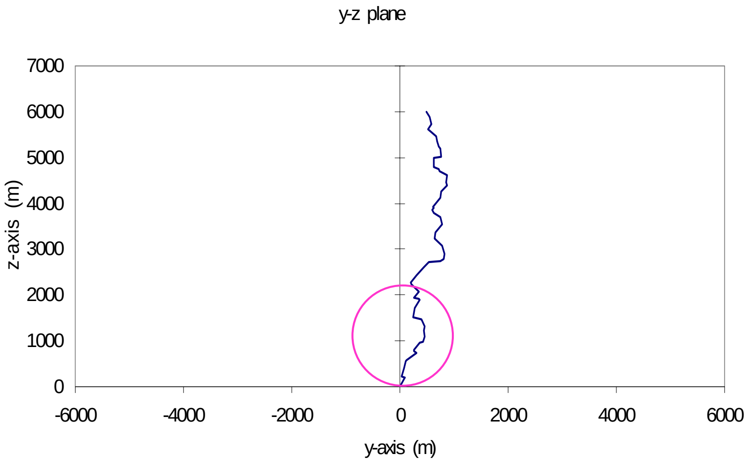


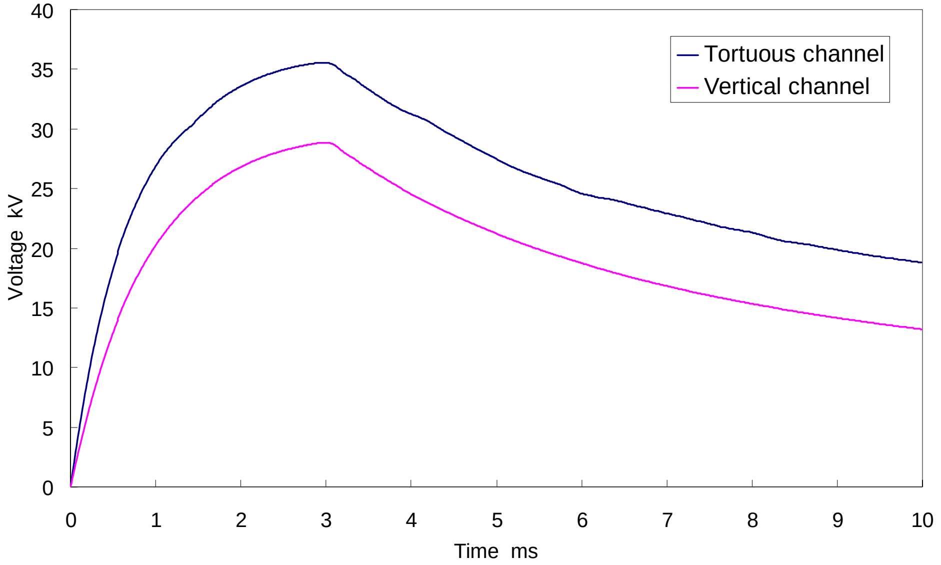
Lightning Current

Sensitivity analysis MIGLIOR
Cont.

Effects of tortuosity of lightning channel



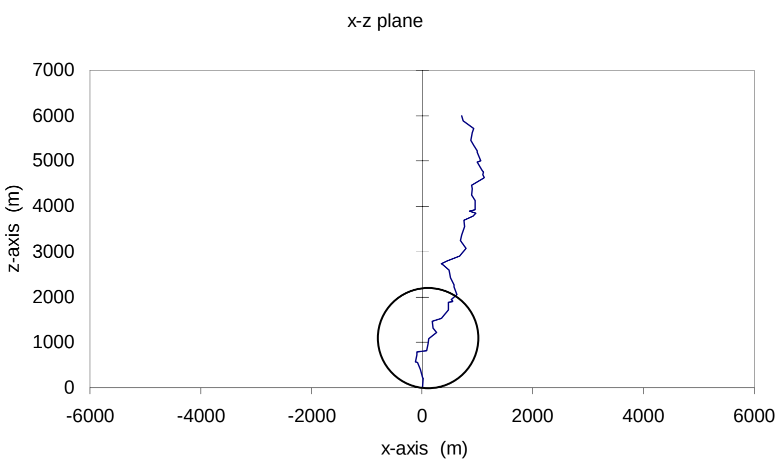


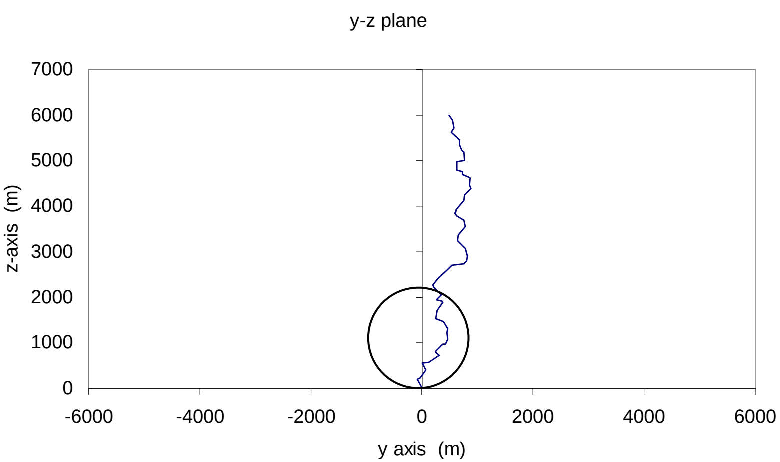


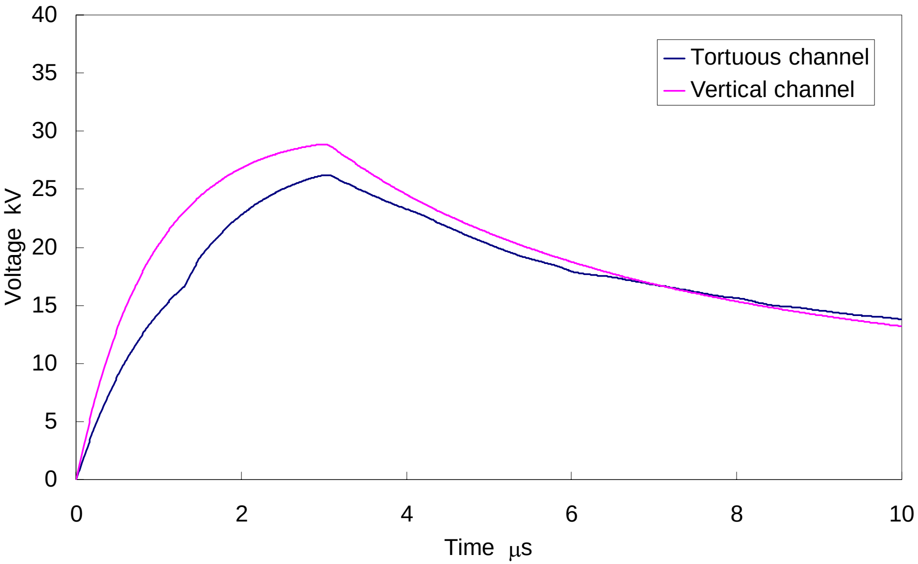
Sensitivity analysis MIGLIOR

Cont.

Effects of tortuosity of lightning channel

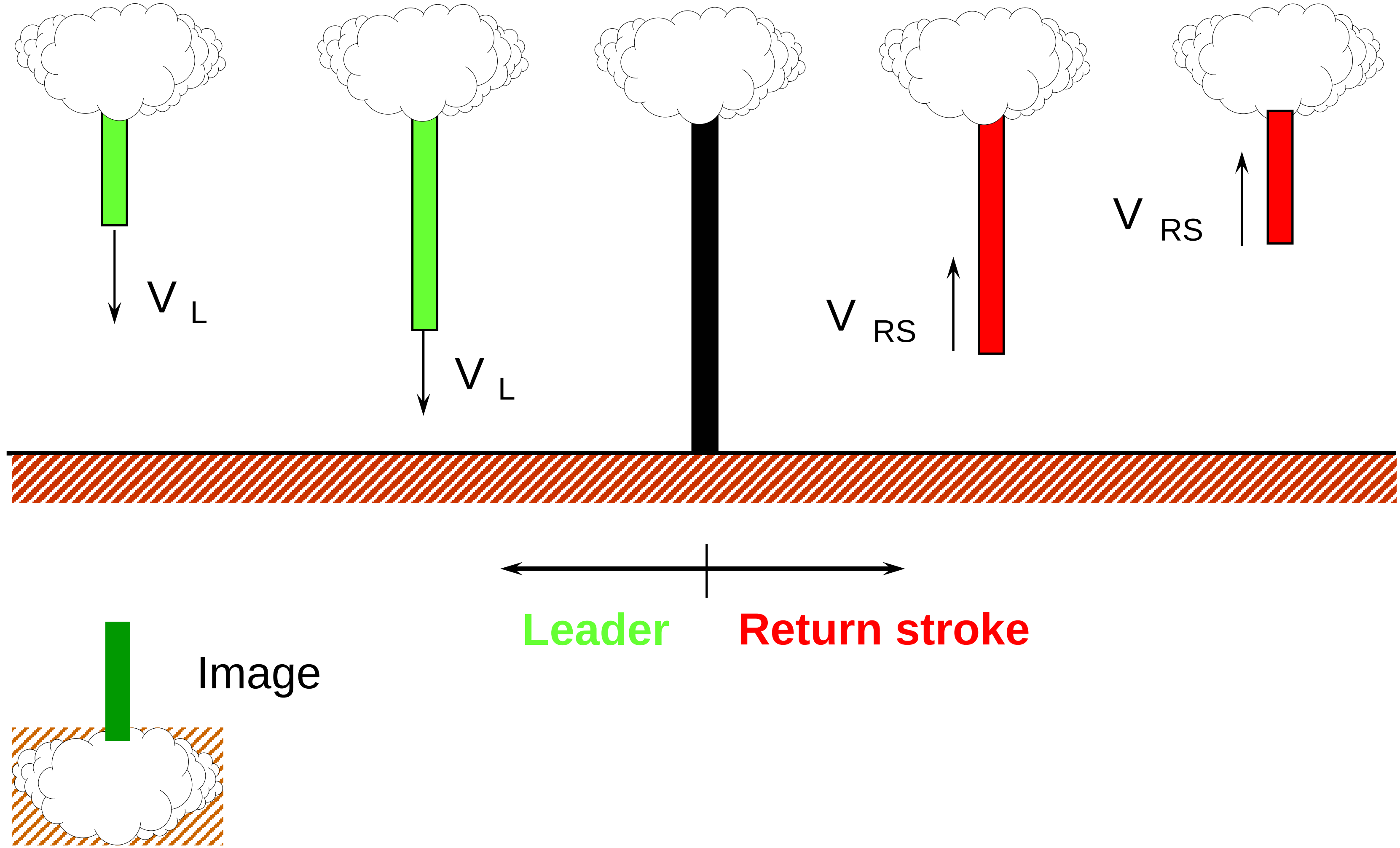






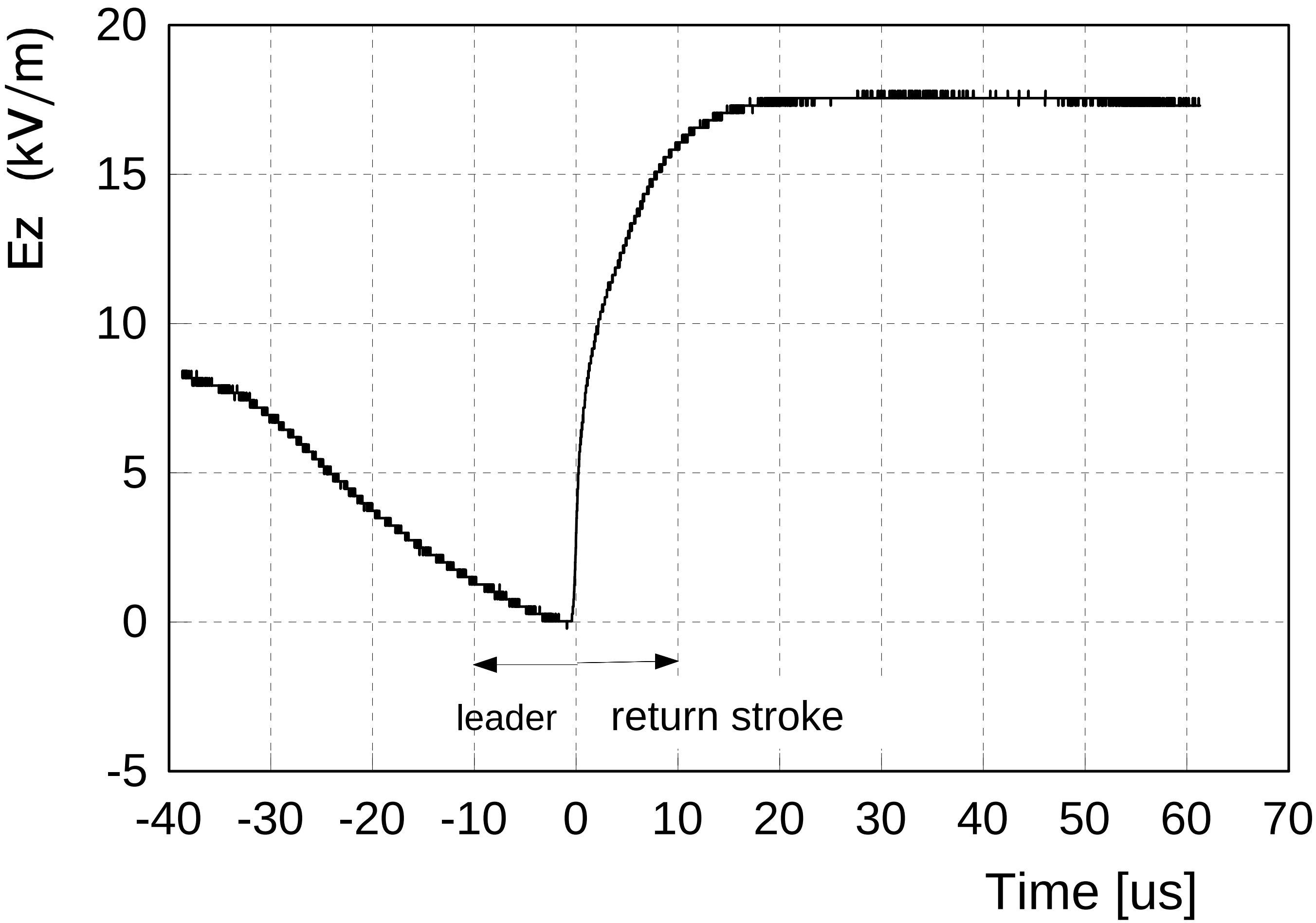
Sensitivity analysis *Cont.*

Leader induction effects



Sensitivity analysis *Cont.*

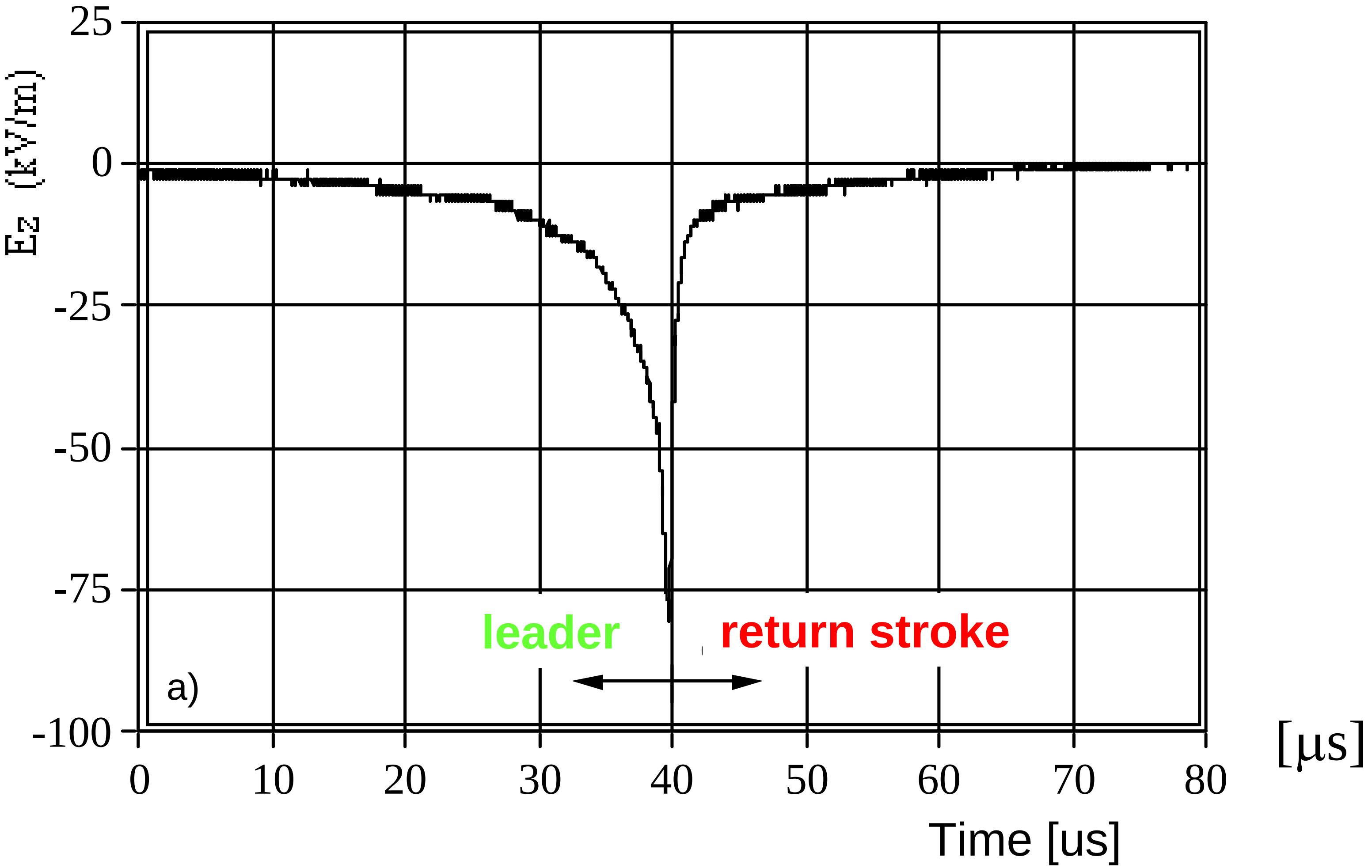
Leader induction effects



Leader and return-stroke E field 70 m from triggered lightning

Sensitivity analysis *Cont.*

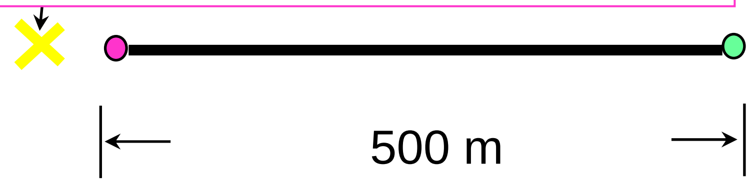
Leader induction effects

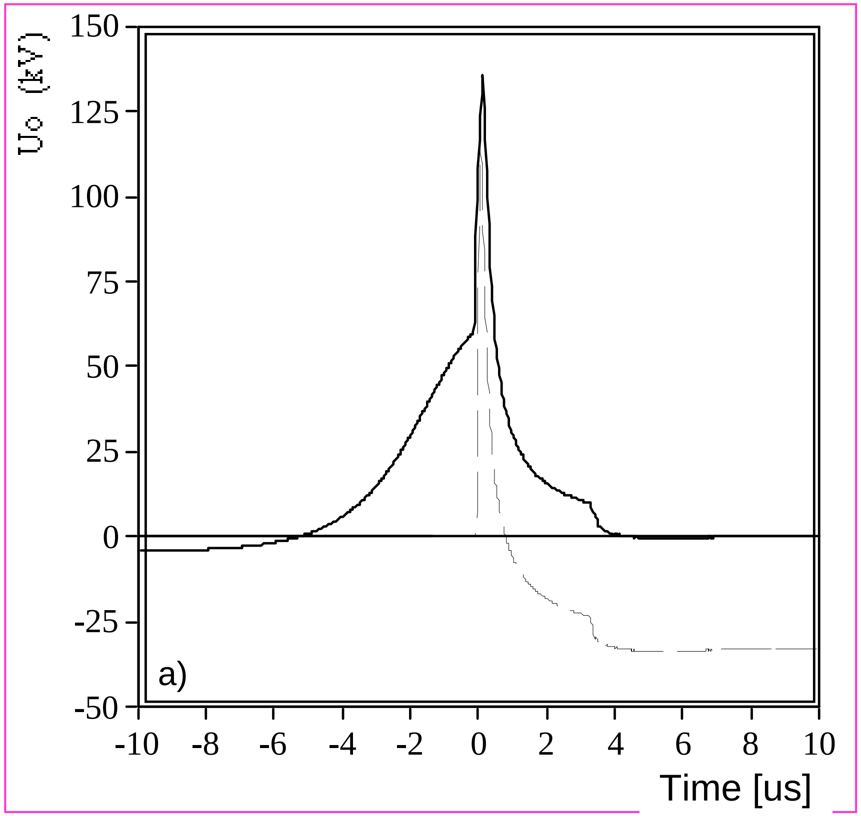


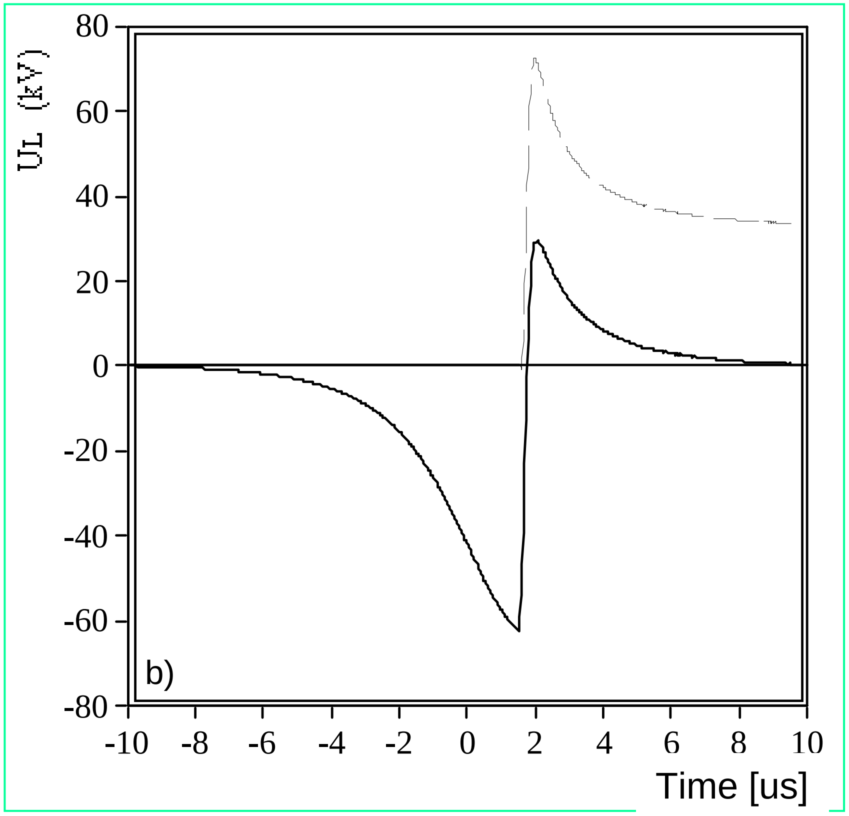
Leader and return-stroke E field 30 m from triggered lightning

Sensitivity analysis *Cont.*

Leader induction effects



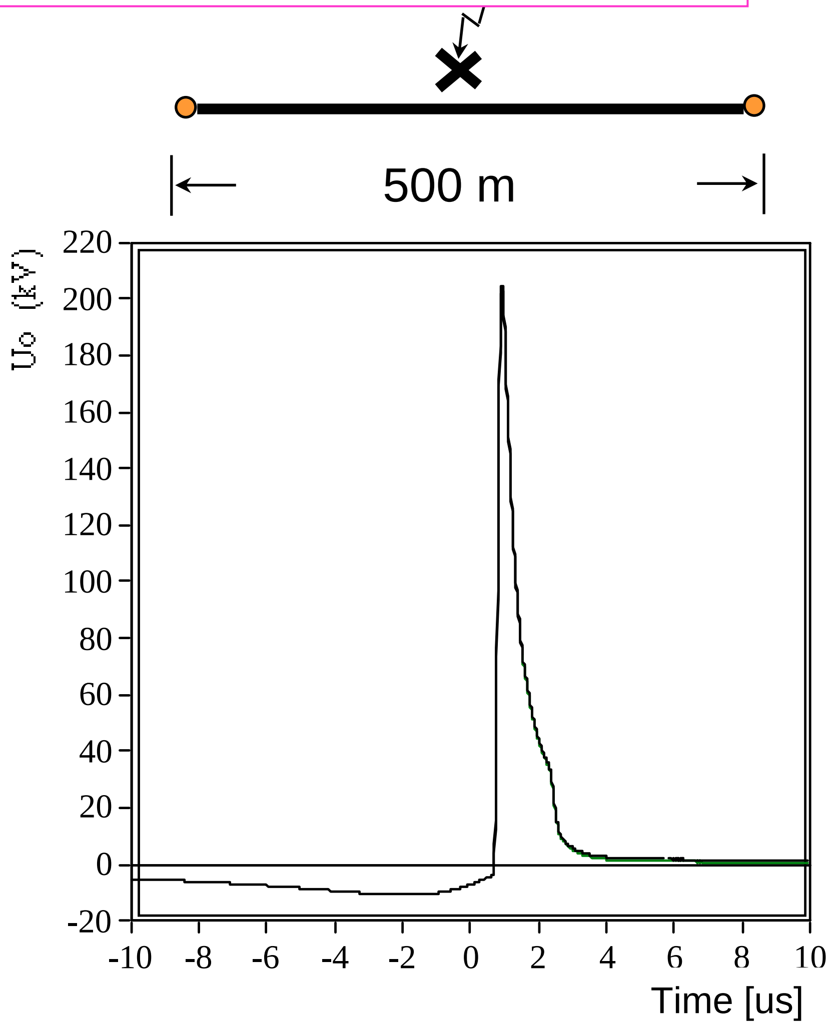




(Solid line: *leader* + return stroke Dashed line: return stroke)

Sensitivity analysis *Cont.*

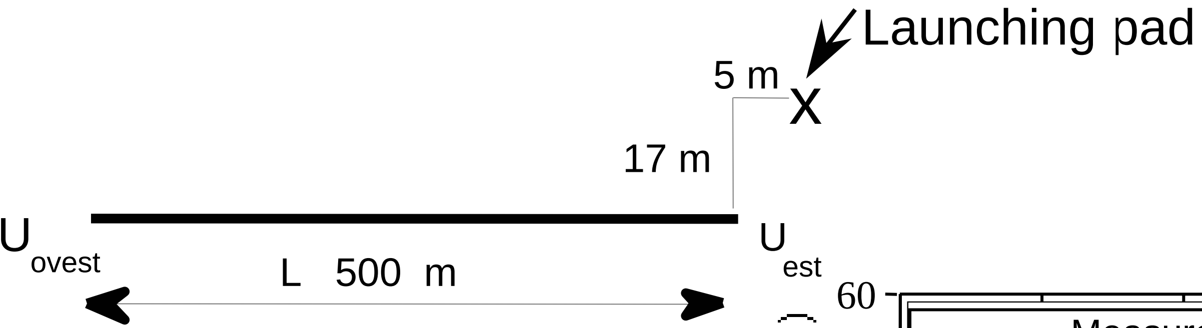
Leader induction effects

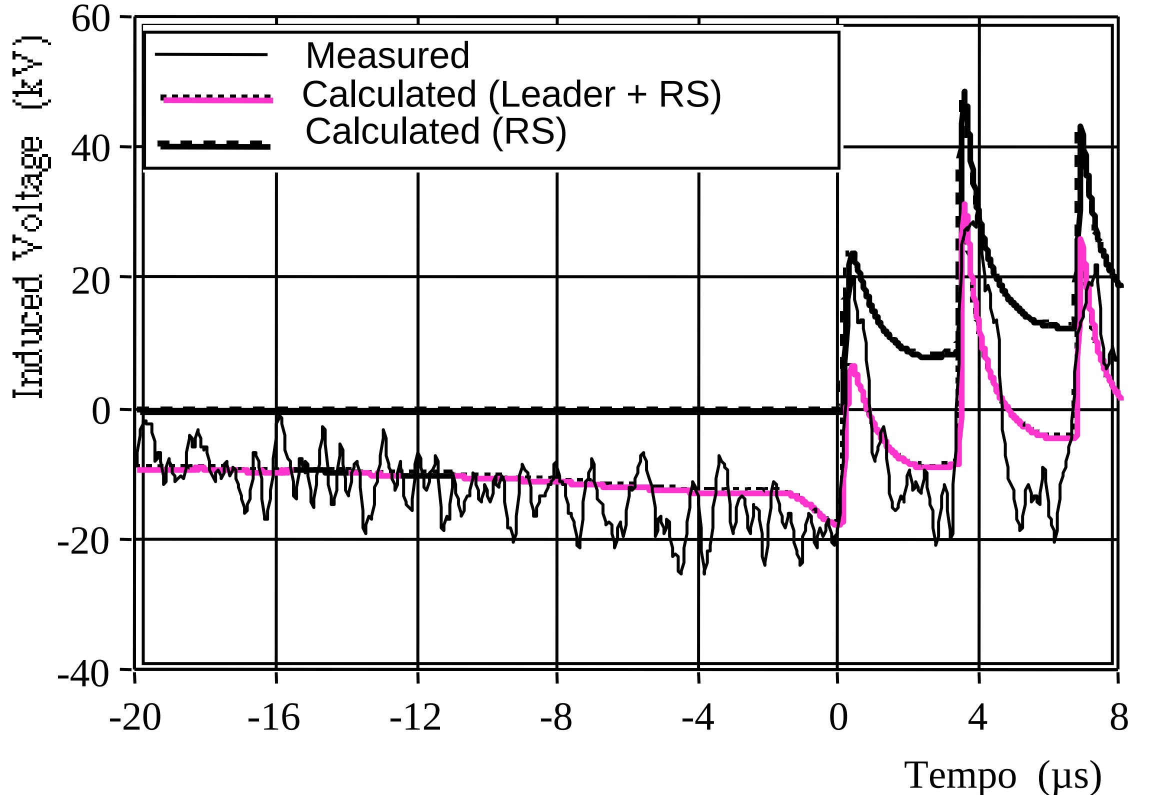


(Solid line: *leader* + return stroke Dashed line: return stroke)

Sensitivity analysis *Cont.*

Leader induction effects



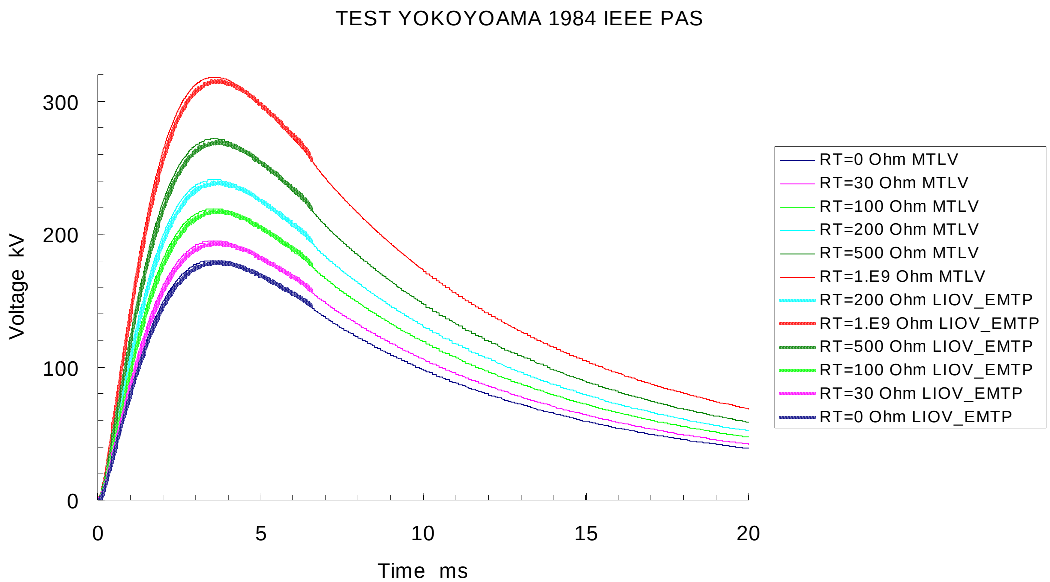


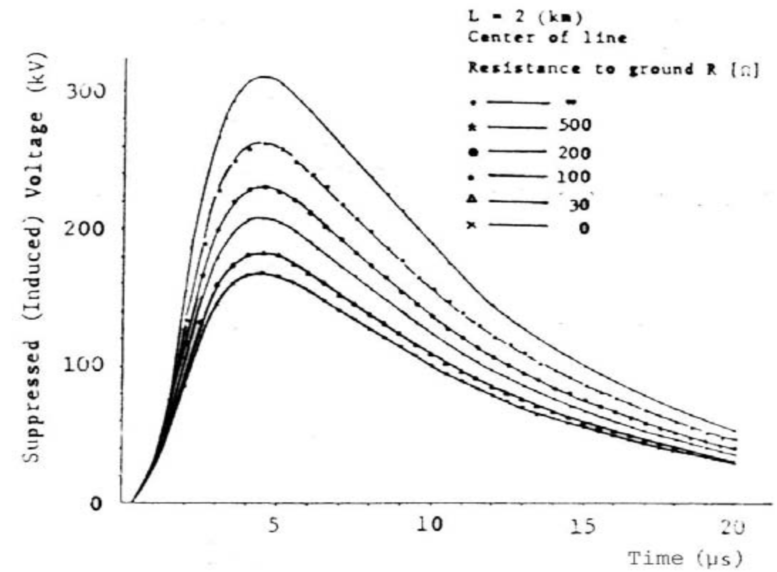
NASA, Kennedy Space Cei
1986

[*Rubinstein*, 1991]
[*Rubinstein et al*, 1994]

Sensitivity analysis MIGLIOR
Cont.

Grounding at a generic point of a multiconductor line





Effect of grounding resistance of a shielding wire (multi-conductors line)

Comparison with [S.Yokoyama - “Calculation of Lightning-Induced Voltages on Overhead Multiconductor Systems”, IEEE PAS Vol.103 No.1 Jan 1984 pp.100-108]

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2. Theoretical basis of the LIOV code

   Return-Stroke Current Model

   LEMP model

   Coupling Model

3. Application of LIOV

   Sensitivity analysis

   Statistical studies

4. Interface with EMTP

5. Conclusions

Statistical studies

The LIOV code has been recently provided with a numerical routine for fast cpmputation of the em field

This has been used in a statistical program based on the Monte Carlo method [Borghetti and Nucci, ICLP, Birmimgham, 1998] for the evaluation of the lightning performances of distribution lines;

Output: number of events that exceed, for a certain ground flash density, a given value

Statistical studies *Cont'd*

Previous studies:

- ideal ground (Rusck, Chowdhuri, De La Rosa, Jankov-Grzybowski)
- lossy ground (Hermosillo and Cooray): one observation point along the line

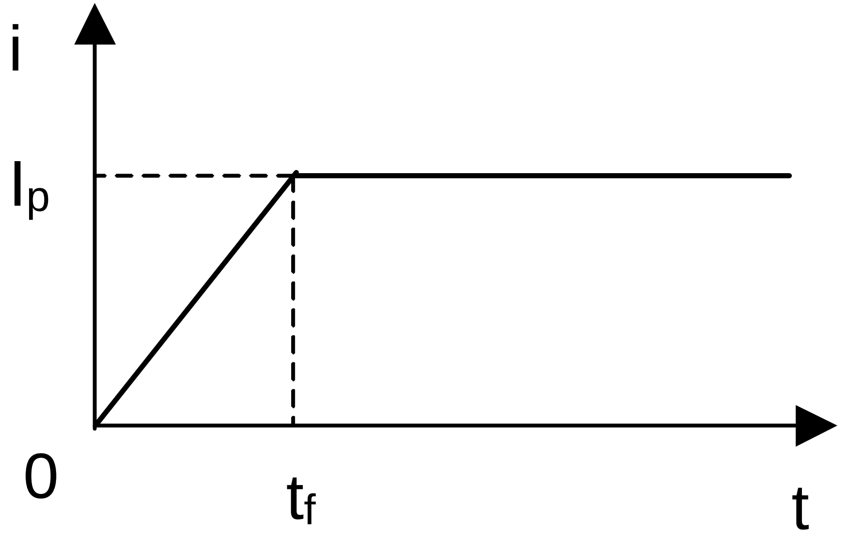
With the statistical package of the LIOV program:

- lossy ground
- all points along the line
- correlation factor between lightning current peak and rise time
- different lateral distance expressions
- correlation between return-stroke velocity and current
- periodical grounding of shielding wire

Statistical studies *Cont'd*

Lightning current waveshape and parameters

I_p	peak value
t_f	front time

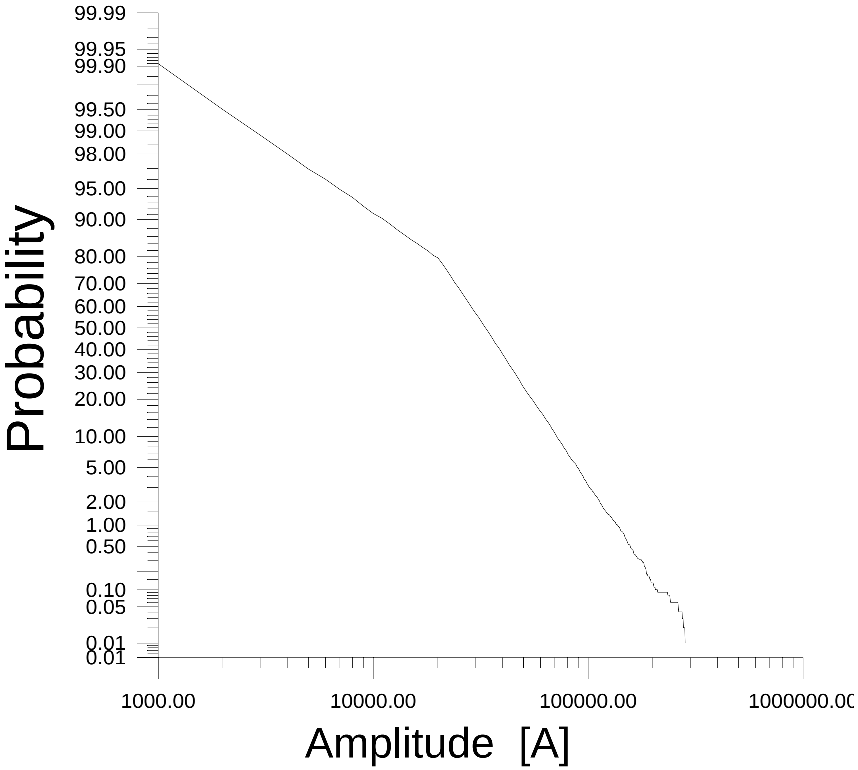


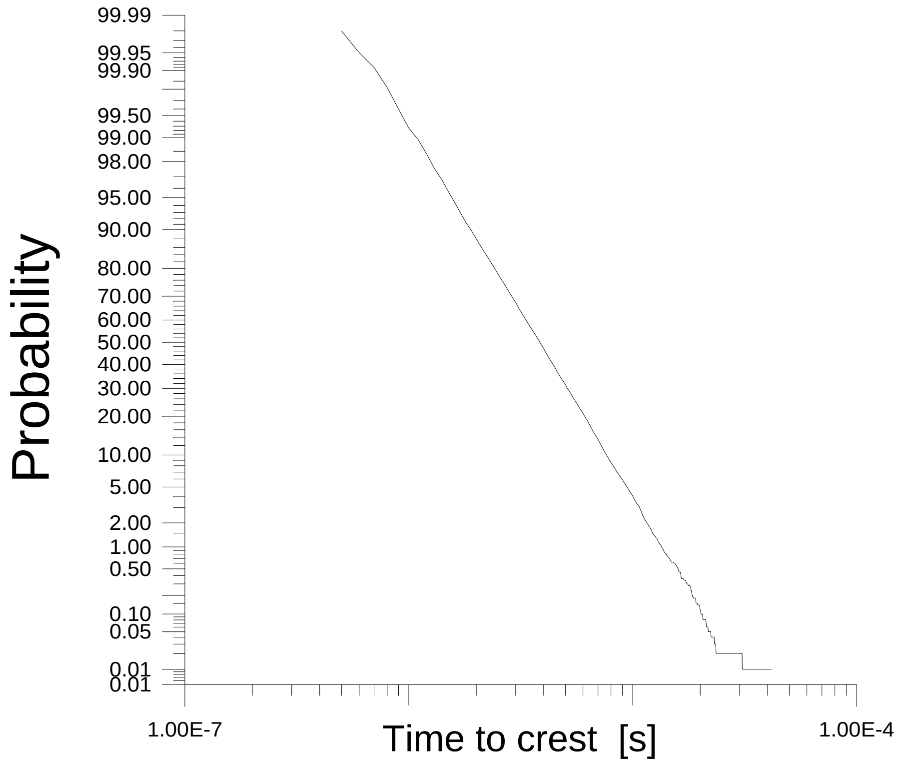
Lightning Current Statistical Parameters

$I_p \leq 20$kA
$\underline{I}_p = 61.1$ kA
$\delta_{\ln I_p} = 1.33$

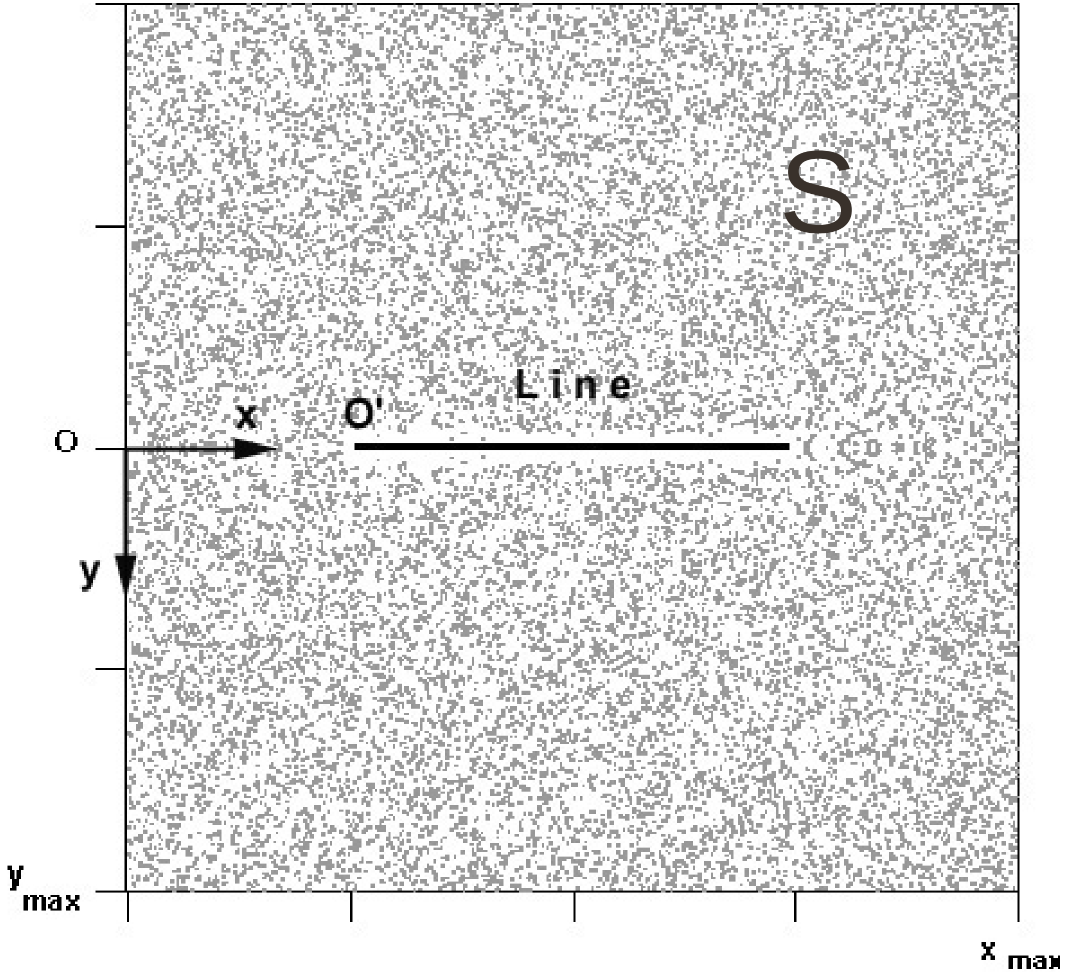
$I_p > 20$ kA
$\underline{I}_p = 33.3$ kA
$\delta_{\ln I_p} = 0.605$

$\underline{t}_f = 3.83\ \mu s$
$\delta_{\ln t_f} = 0.553$





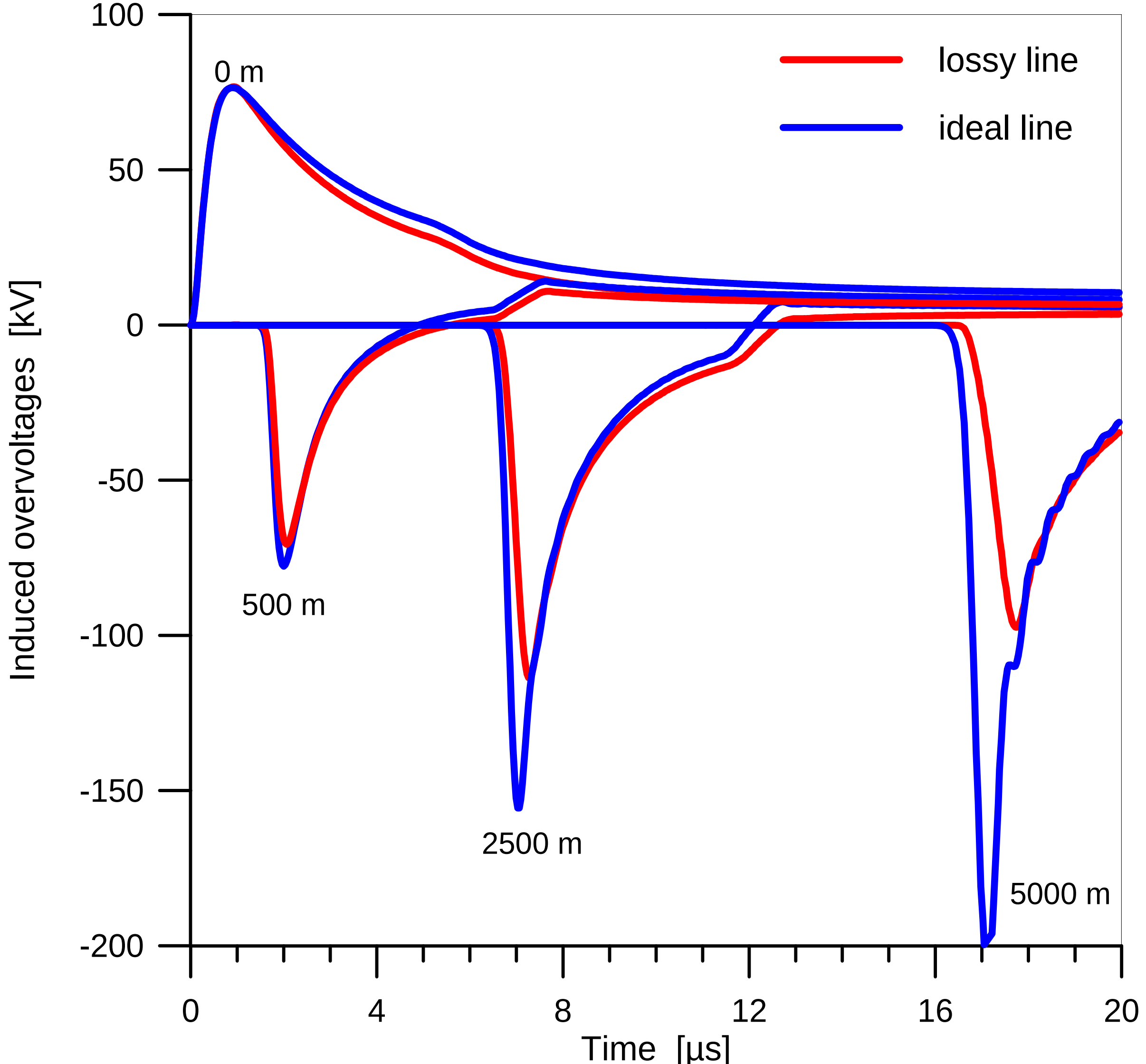
Statistical studies *Cont'd*

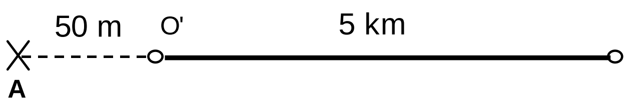


Indirect Stroke Area Top view

Statistical studies TAKEN FROM

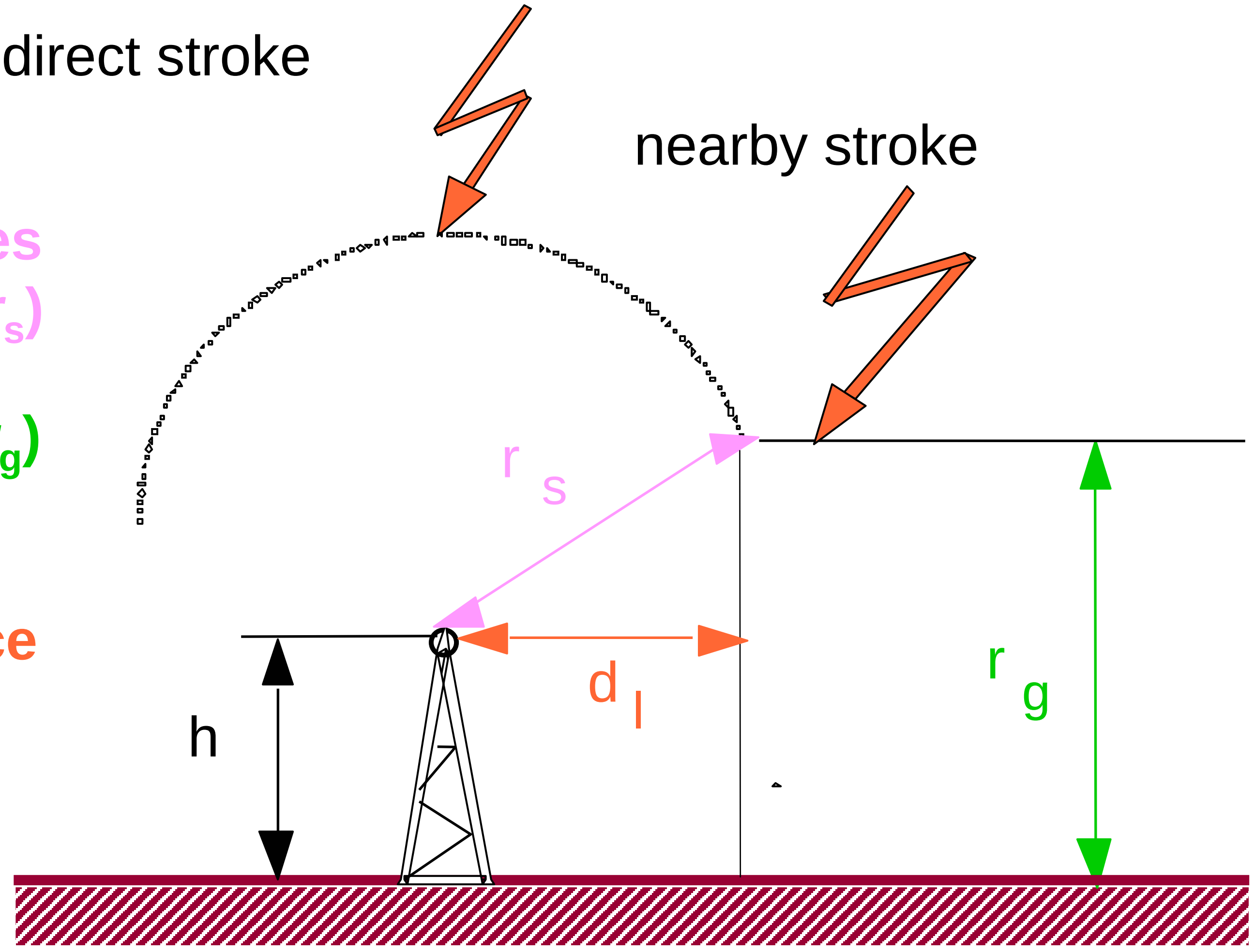
Cont'd





Some additional comments

Statistical studies *Cont'd*



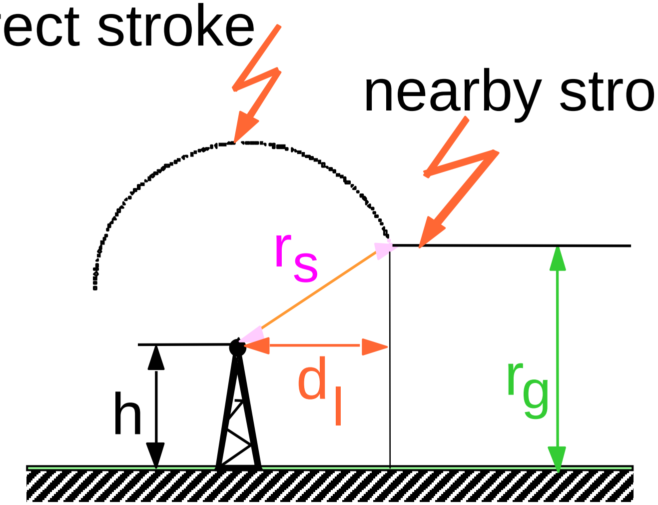
Striking distances to a conductor (r_s)

and to ground (r_g)

and lateral attractive distance (d_l) of a line

Statistical studies BERNARDI

Cont'd



Striking distances to a conductor (r_s) and to ground (r_g) and lateral attractive distance (d_l) of a line

$$r = A \cdot I^b$$

(*) $r = c + A \cdot I^b$

	r_s			r_g		no. d. s.
	c	A	b	A	b	
Armstrong and Whitehead		6.7	0.8	6.0	0.8	393
IEEE WG		8.0	0.65	8.0	0.65	213
Eriksson		$0.67\ h^{0.6}$	0.74	na	na	224
Rizk		$1.57\ h^{0.45}$	0.69	na	na	309
CESI (*)	$3\ h^{0.6}$	0.028 h	1	na	na	135

Statistical studies *Cont'd*

Application of the Monte Carlo Method

1 Inputs
return stroke velocity
line and ground data

2 Random generation of events ($\mathbf{I_p}$; $\mathbf{t_f}$: x ; y) 10 000

3 Induced overvoltages calculation

4 Counting of the **n** events generating overvoltages greater than a given value

5 Plot a graph:
No. of events/(100 km x year) vs BIL
where **No. of events / (100 kmx year) =**
(n/10000) • $\mathbf{n_f}$ • 2S • 100/L (with n_f =ground flash density)

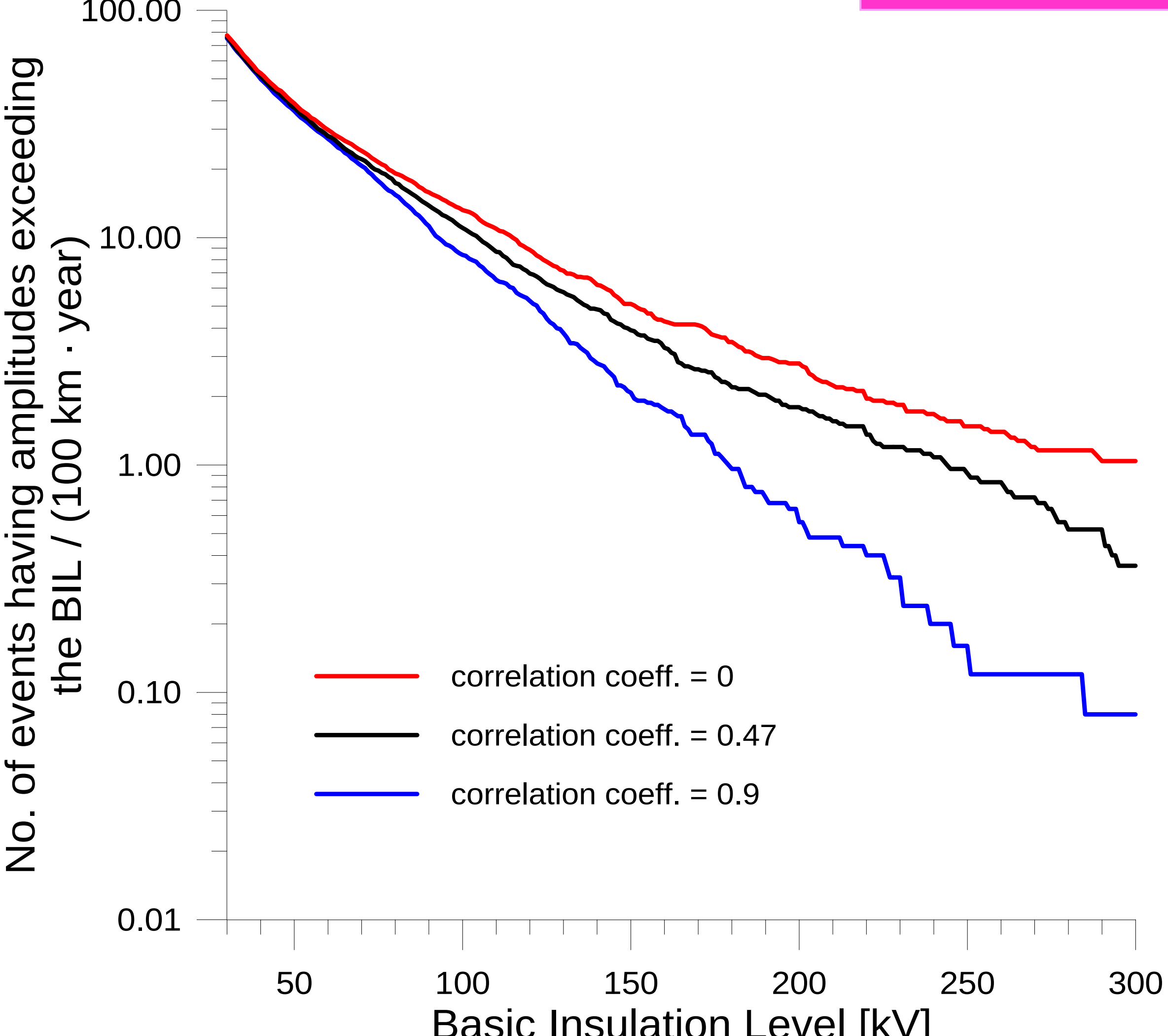
Statistical studies TAKEMìN FROM

Cont'd

Ideal ground

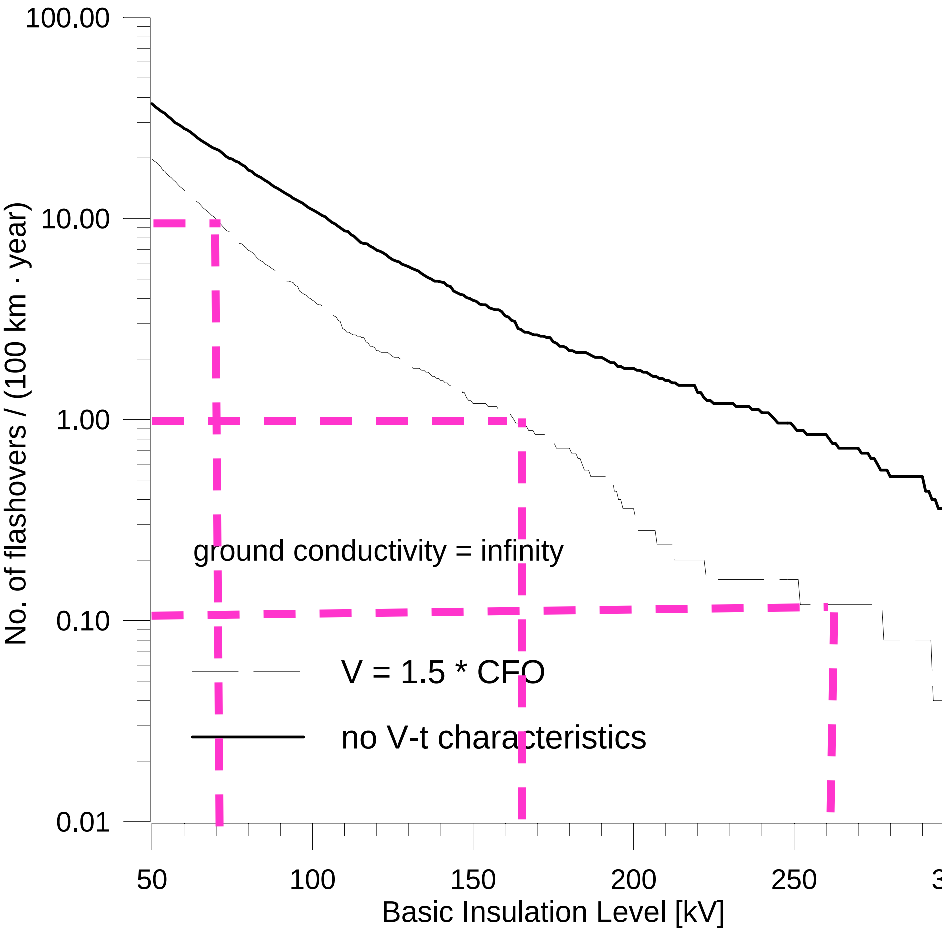
Influence of the Correlation

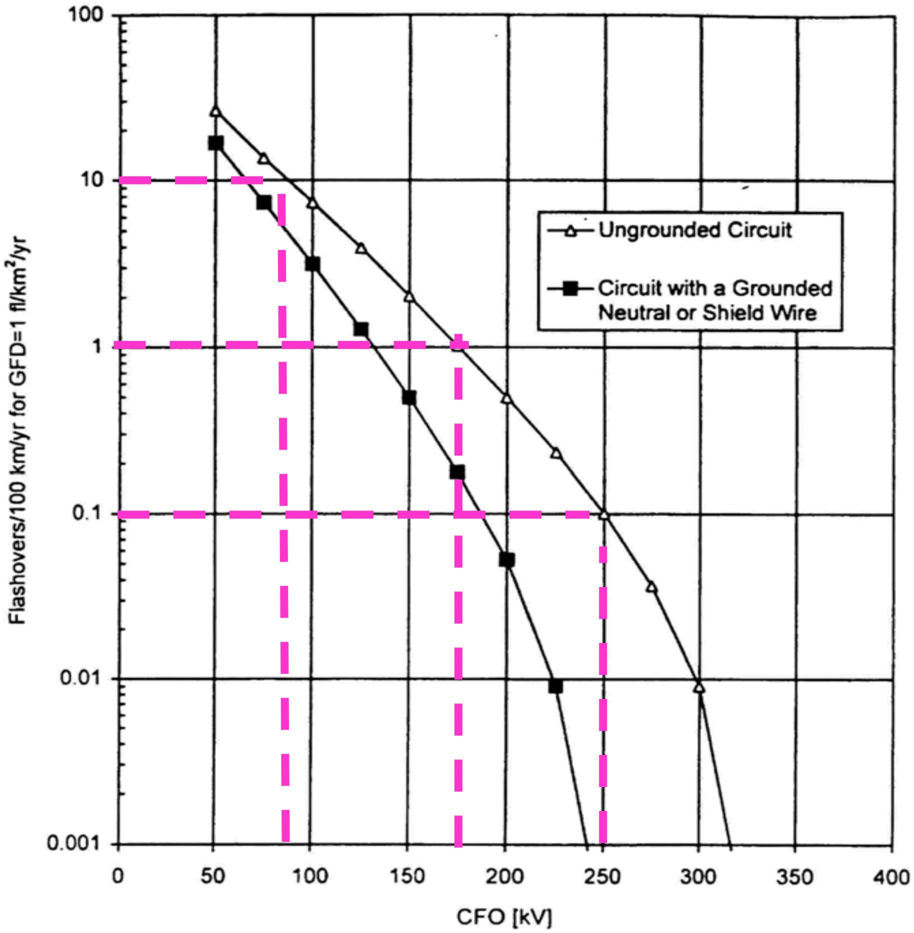
between amplitude (I_p) and front duration (t_f) of the lightning current



Statistical studies CHECK

Cont'd



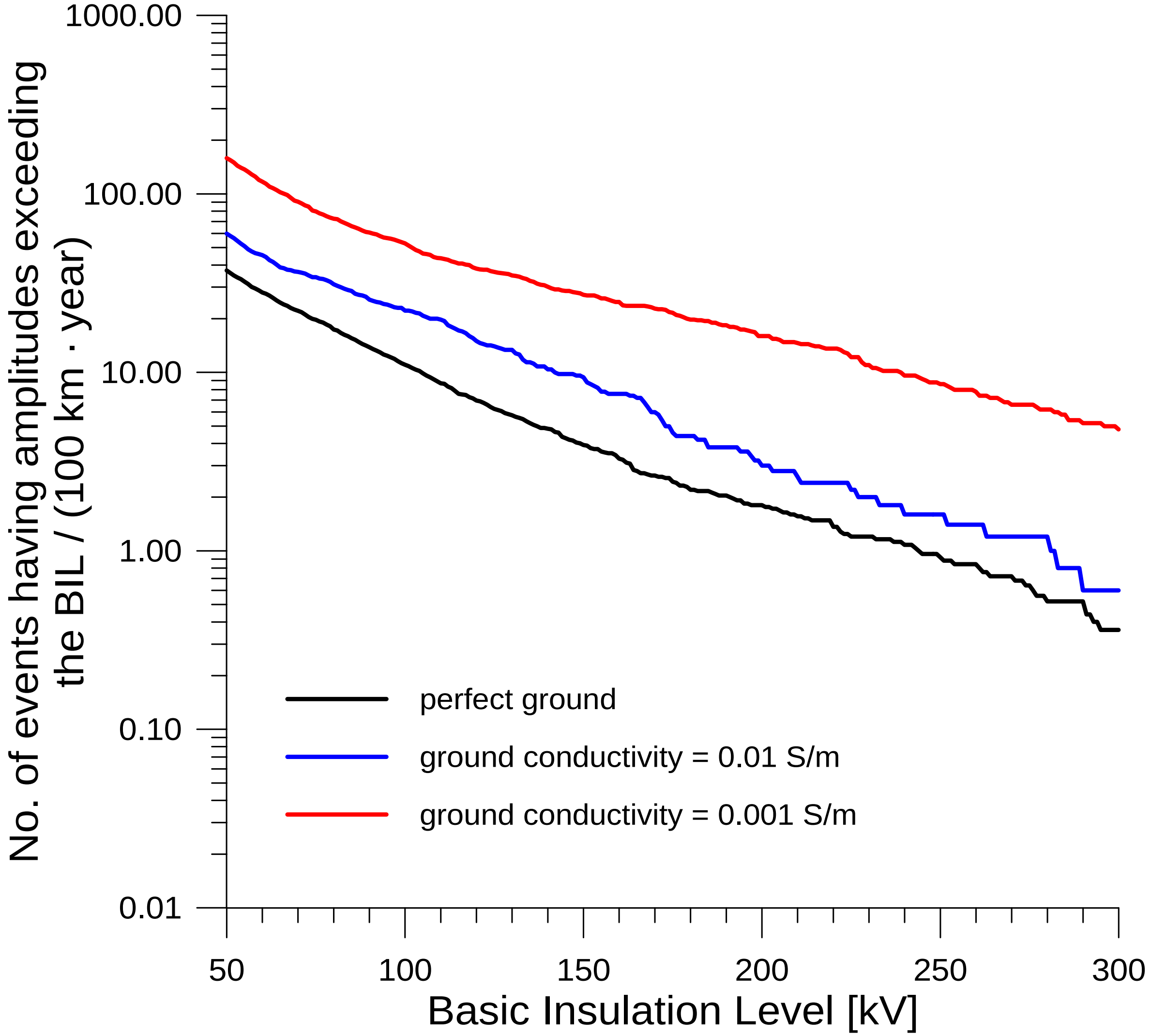


Statistical studies TAKEN

Cont'd

Lossy ground

Influence of the Ground Conductivity (σ_g)

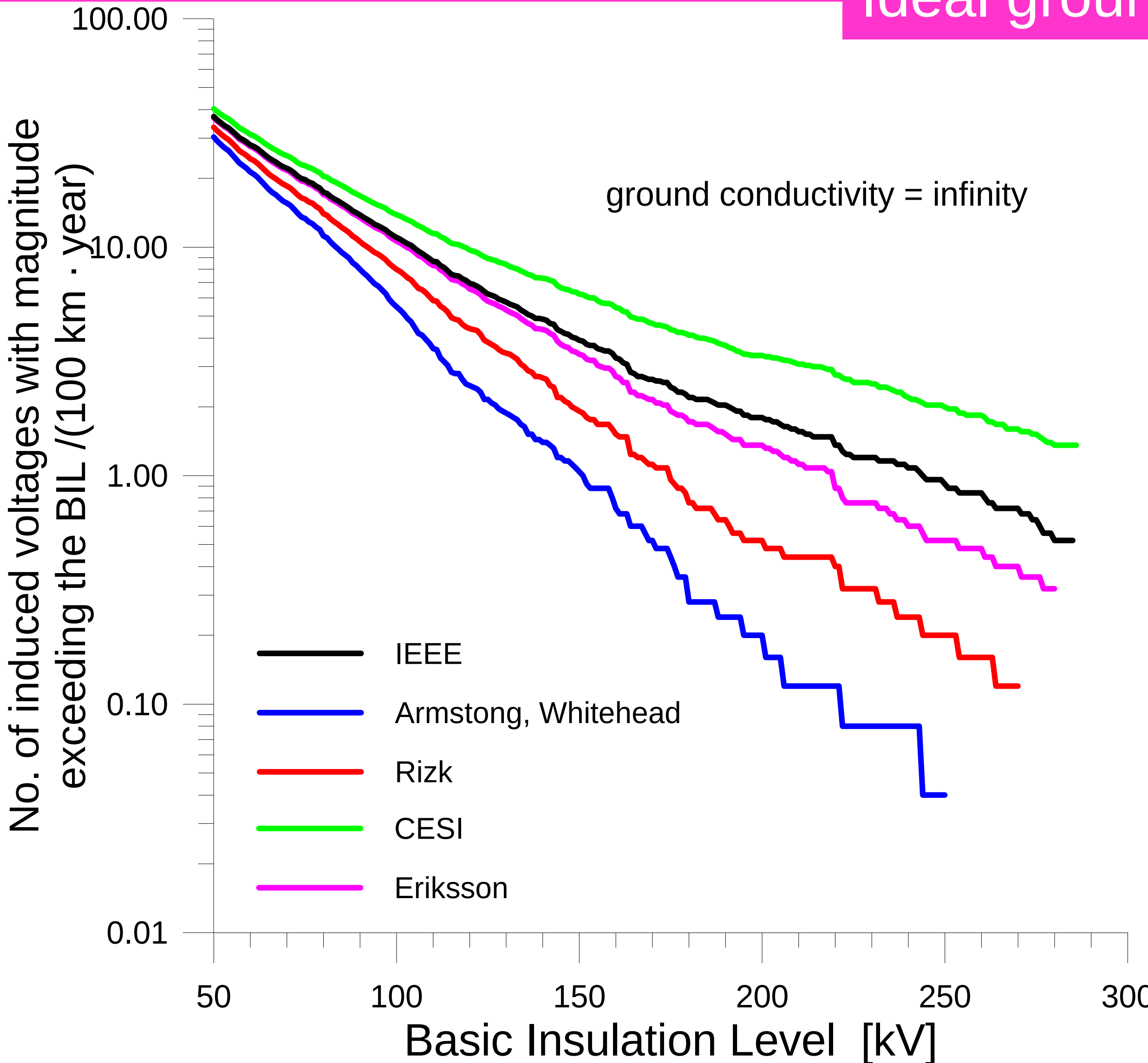


Statistical studies TAKEN

Cont'd

Ideal ground

Influence of the Striking Distance Expression

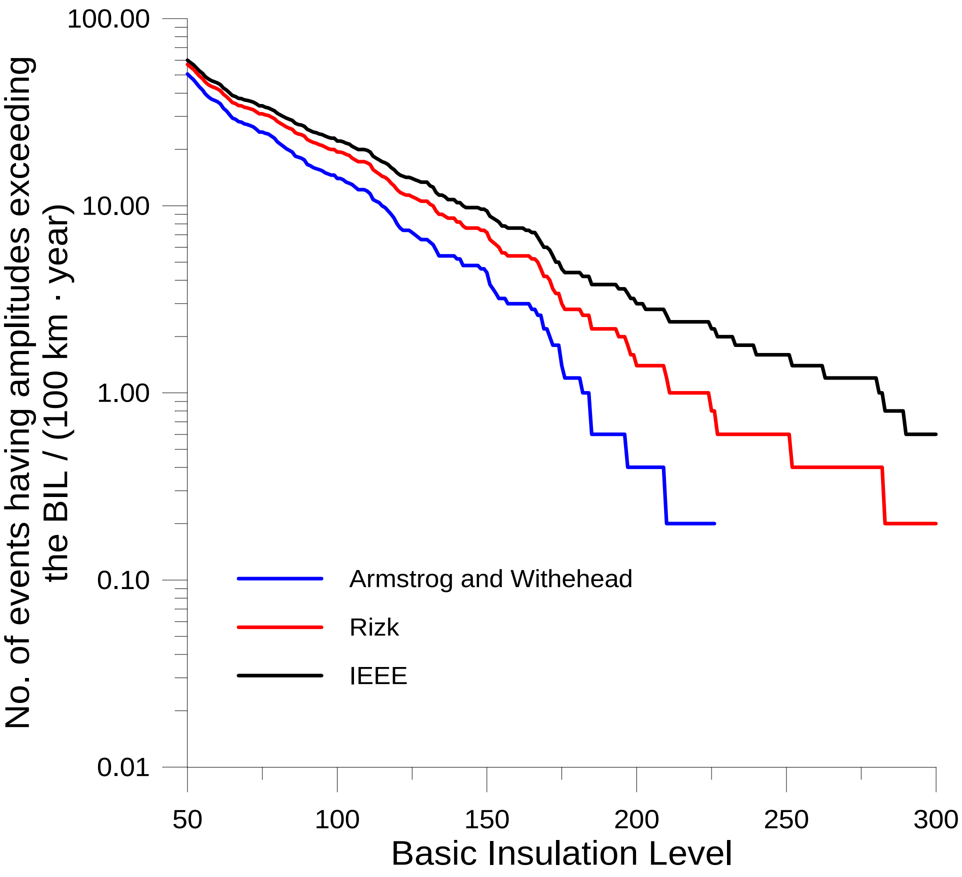


Statistical studies TAKEN

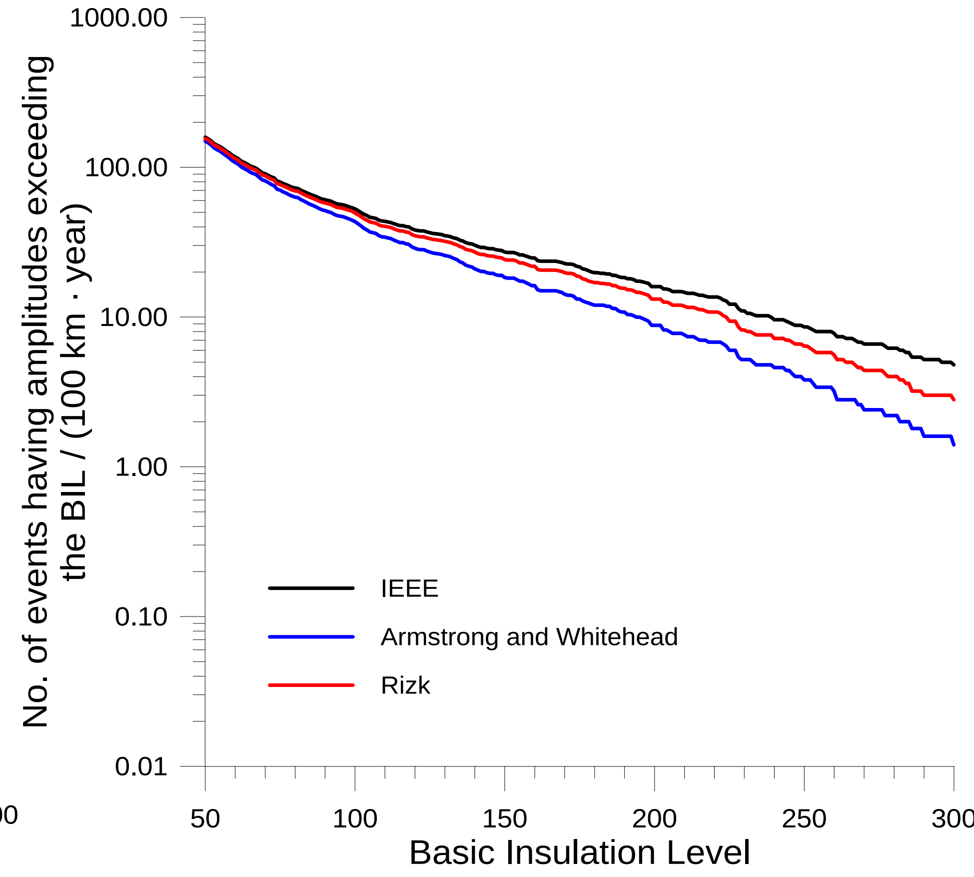
Cont'd

Lossy ground

a) σ_g=0.01 S/m



b) σ_g=0.001 S/m



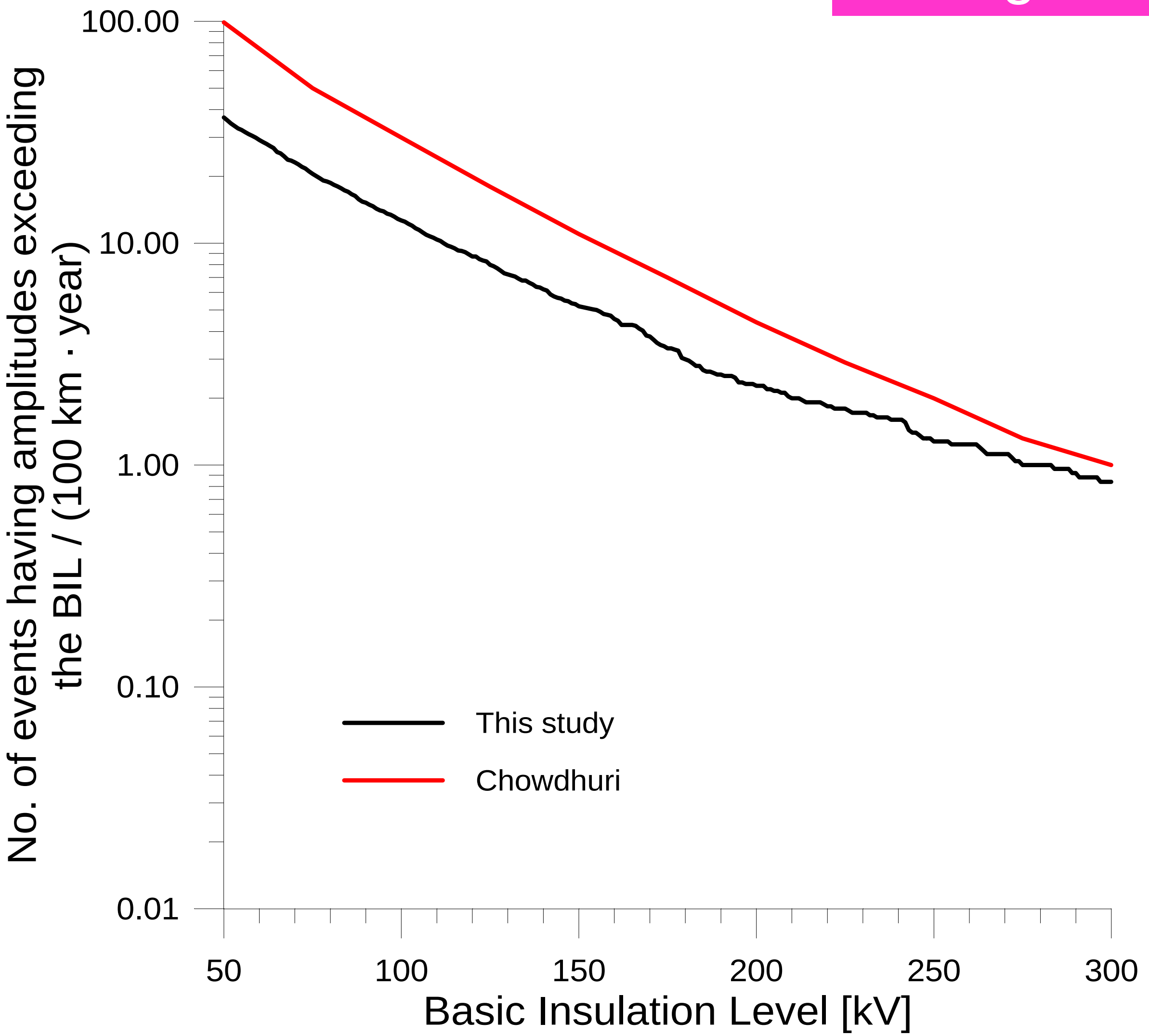
Statistical studies TAKEN

Cont'd

Ideal ground

Comparison with the results presented by Chowdhuri

(1989)

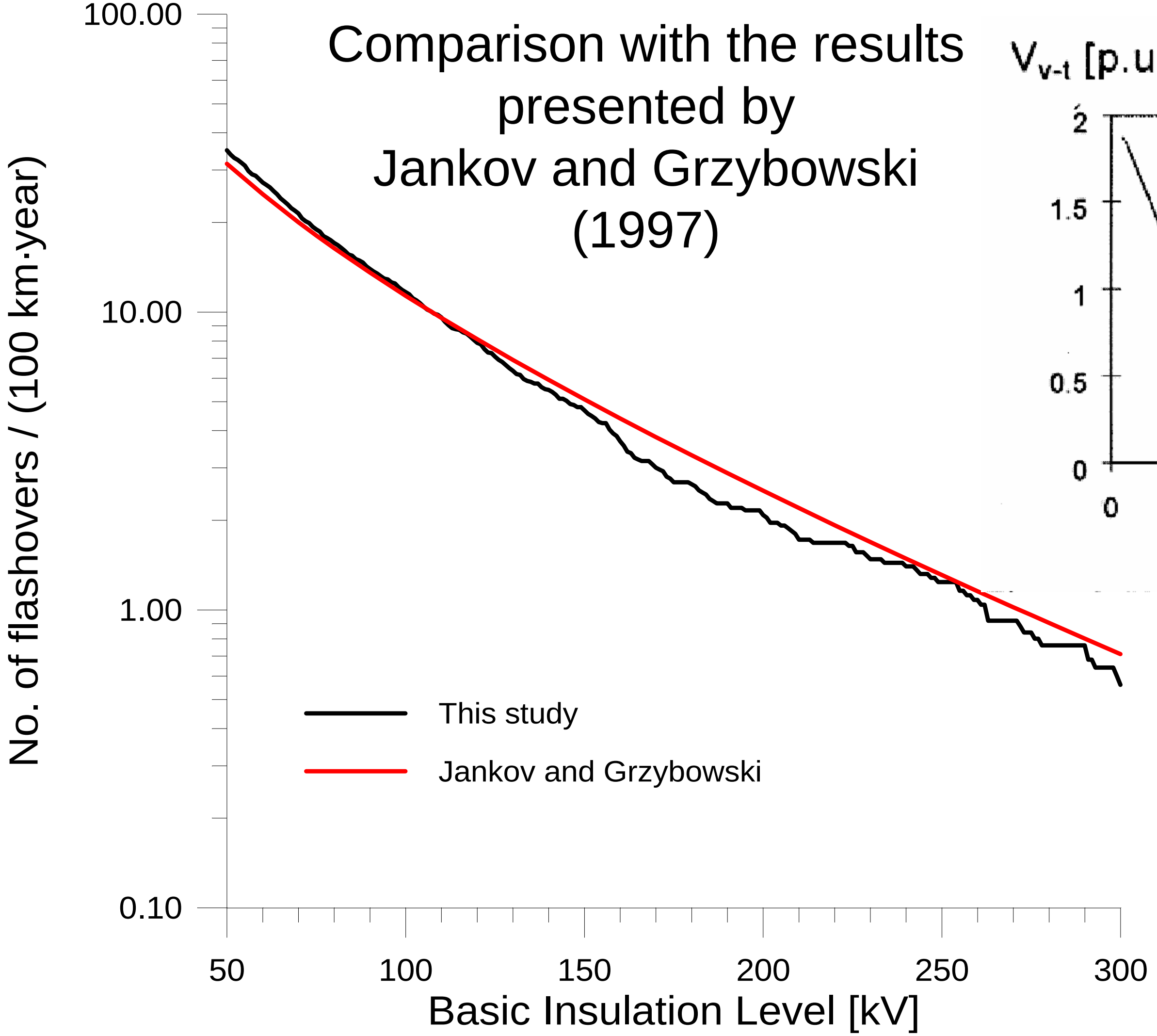


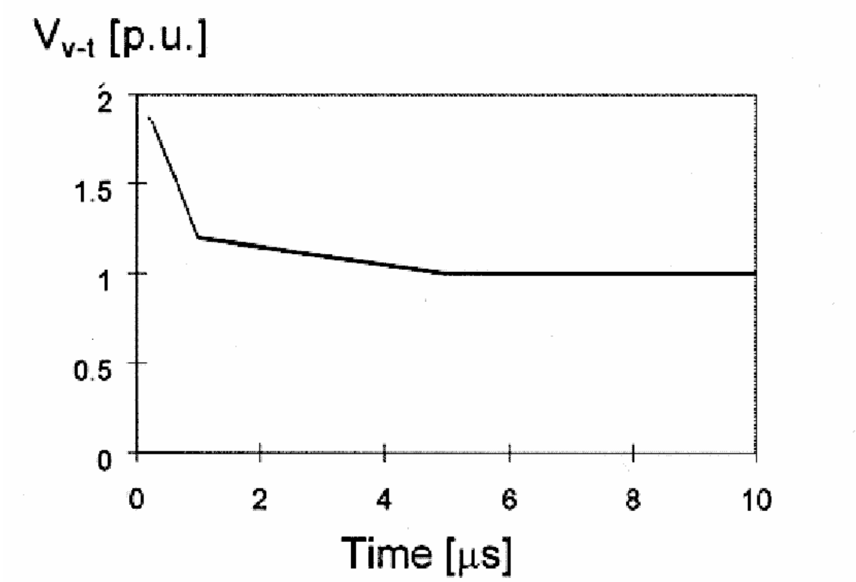
Statistical studies TAKEN

Cont'd

Ideal ground

Comparison with the results presented by Jankov and Grzybowski (1997)





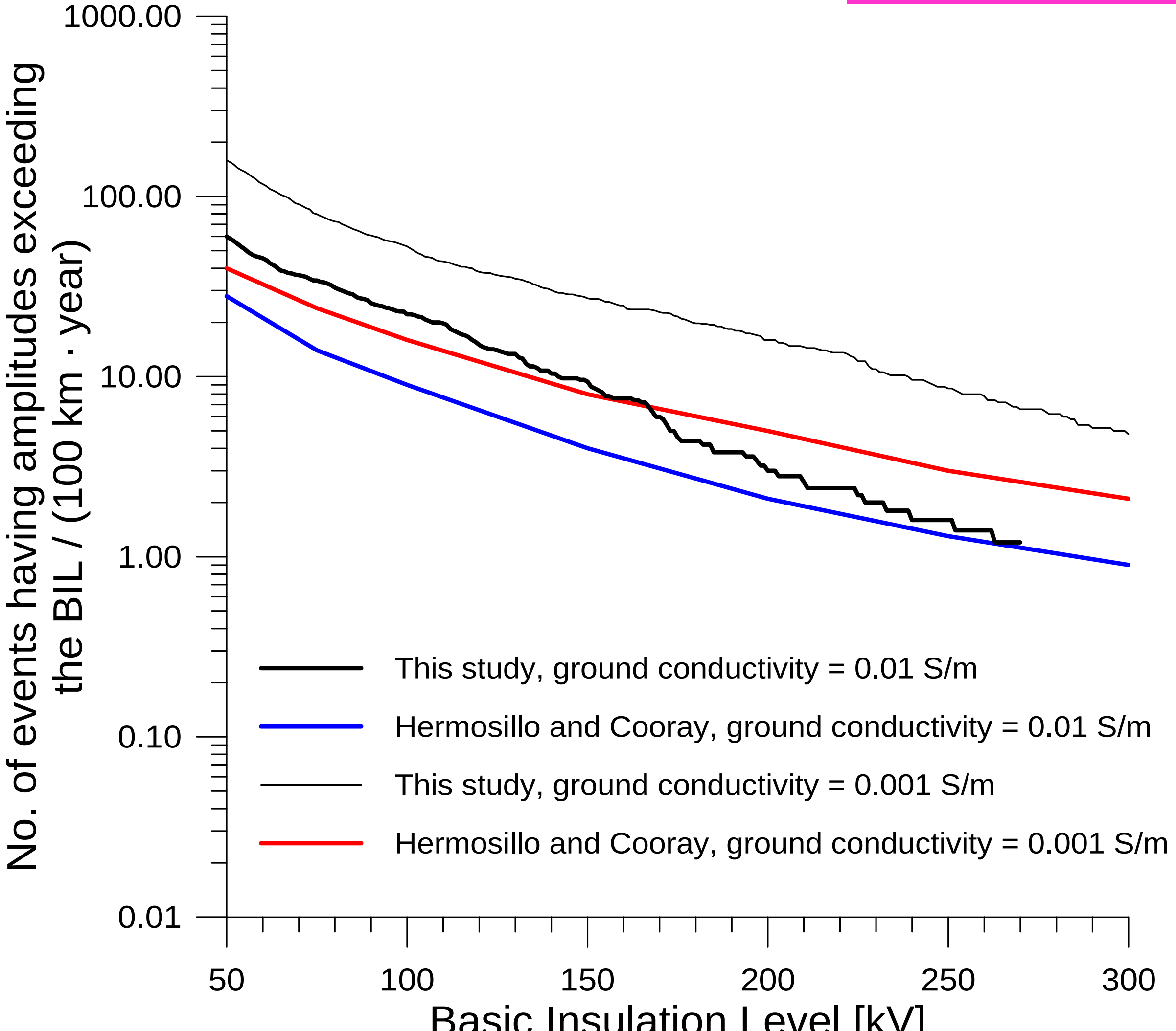
V-t insulators characteristic used by Jankov and Grzybowski

Statistical studies TAKEN

Cont'd

Lossy ground

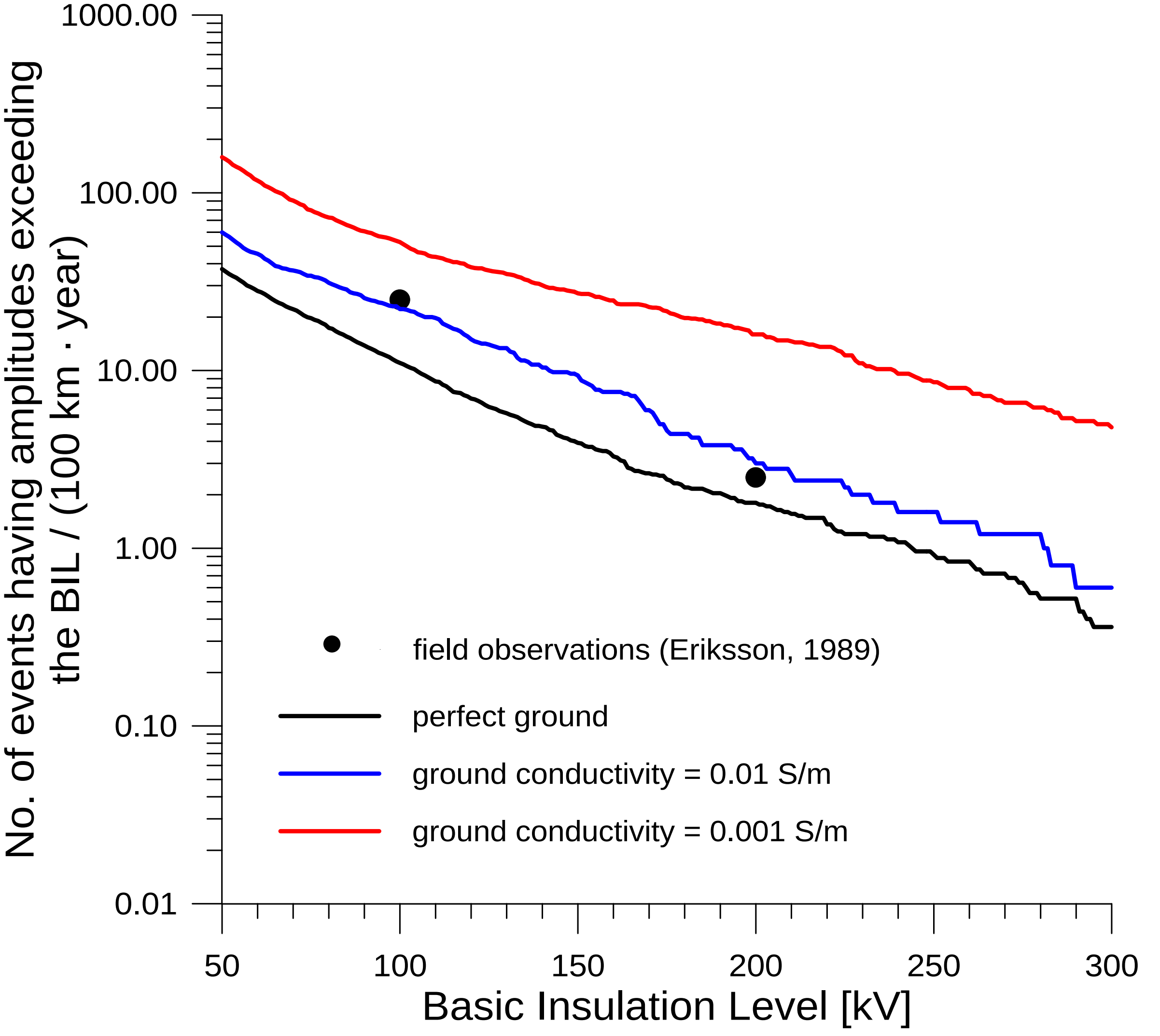
Comparison with the results presented by Hermosillo and Cooray (1995)



Statistical studies TAKEN

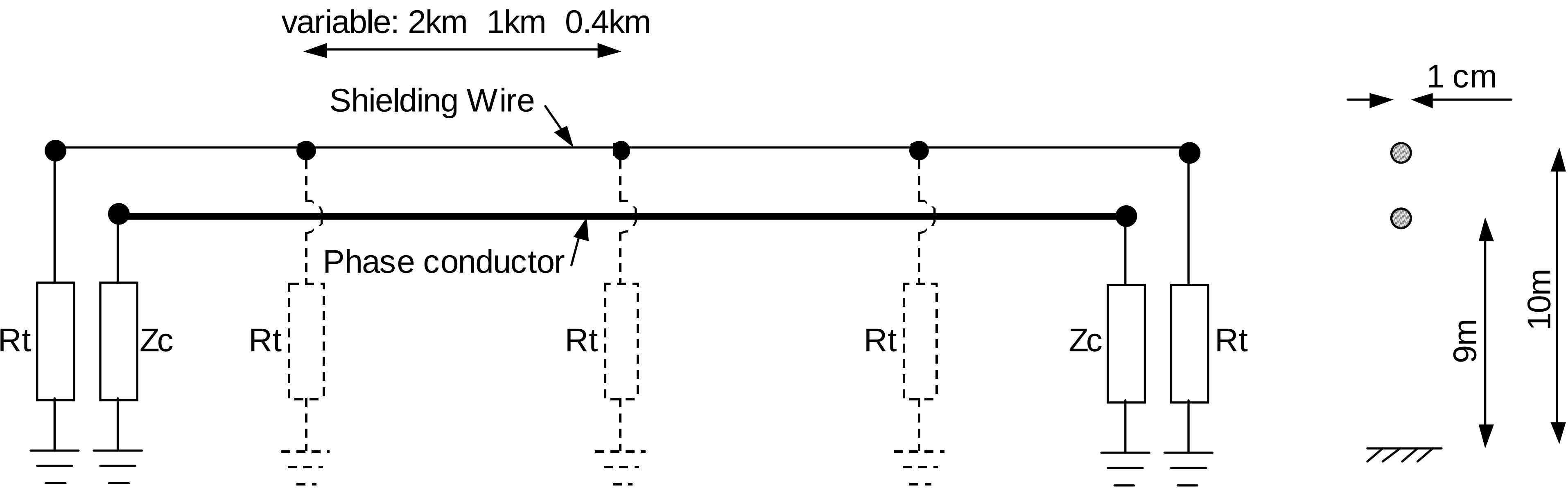
Cont'd

Comparison with the data reported by Eriksson (1989)

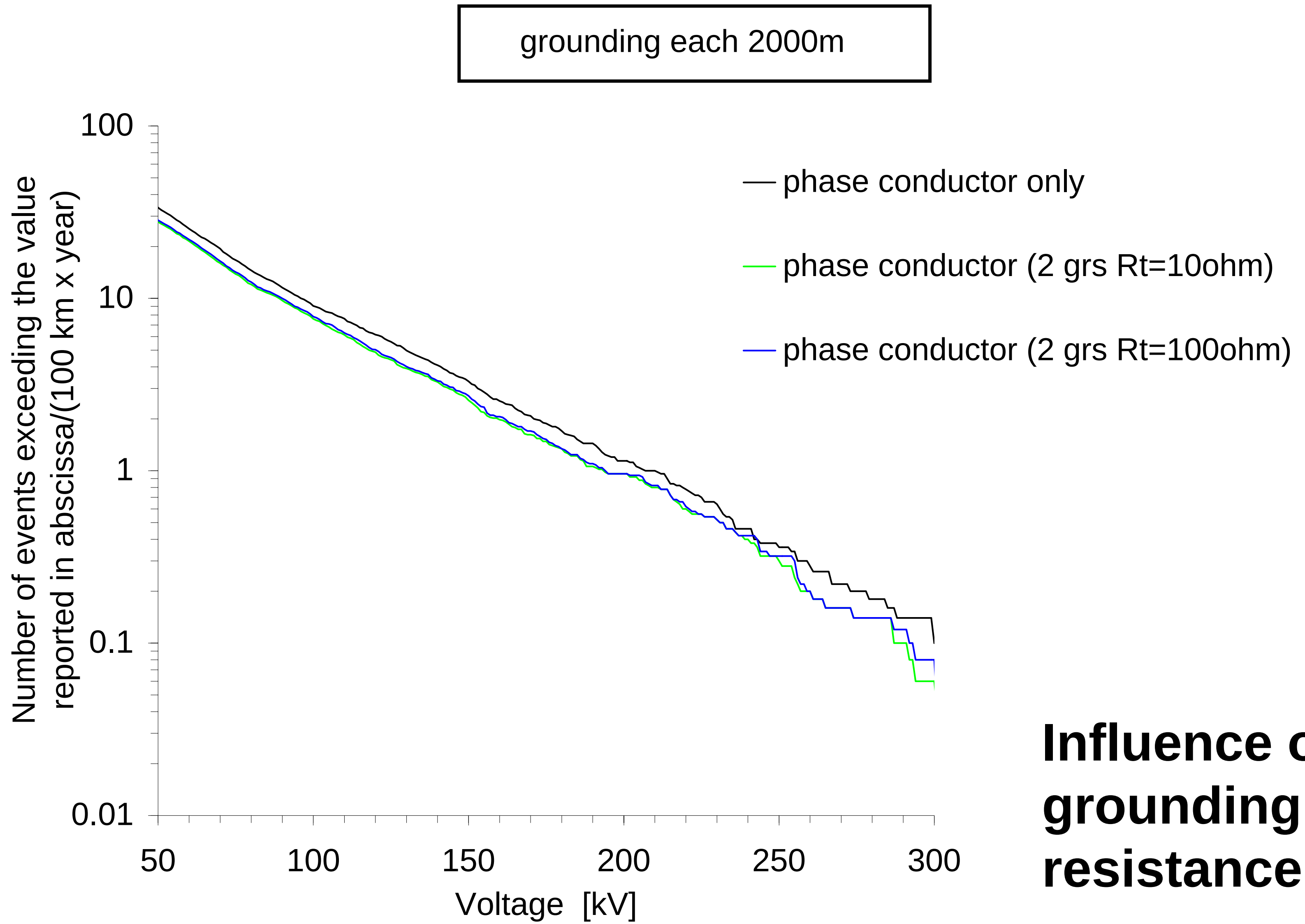


Statistical studies ACKNOW *Cont'd*

Influence of the presence of periodically grounded shielding wires



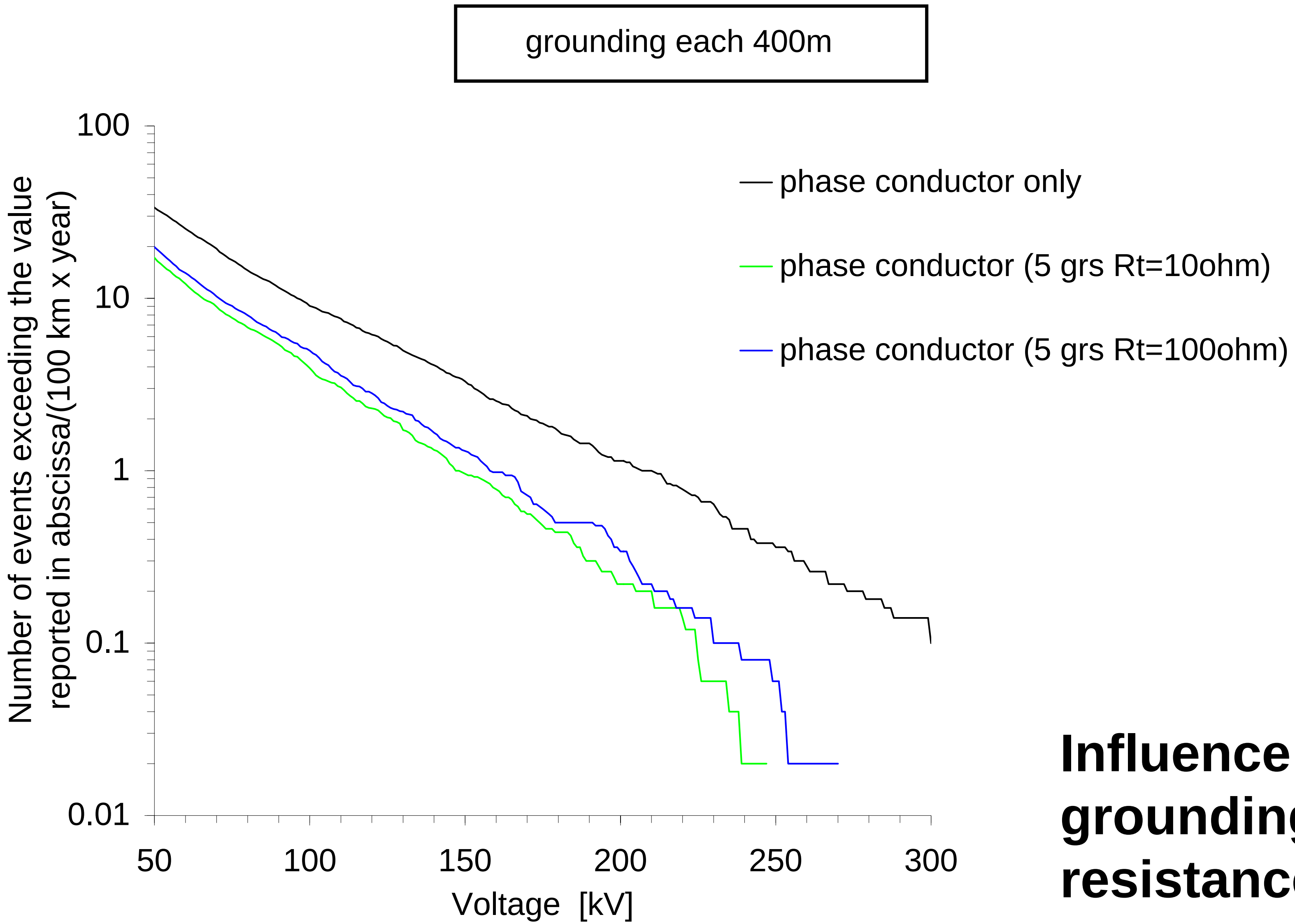
Statistical studies ACKN *Cont'd*



Influence of grounding resistance (Rt)

Statistical studies ACKN

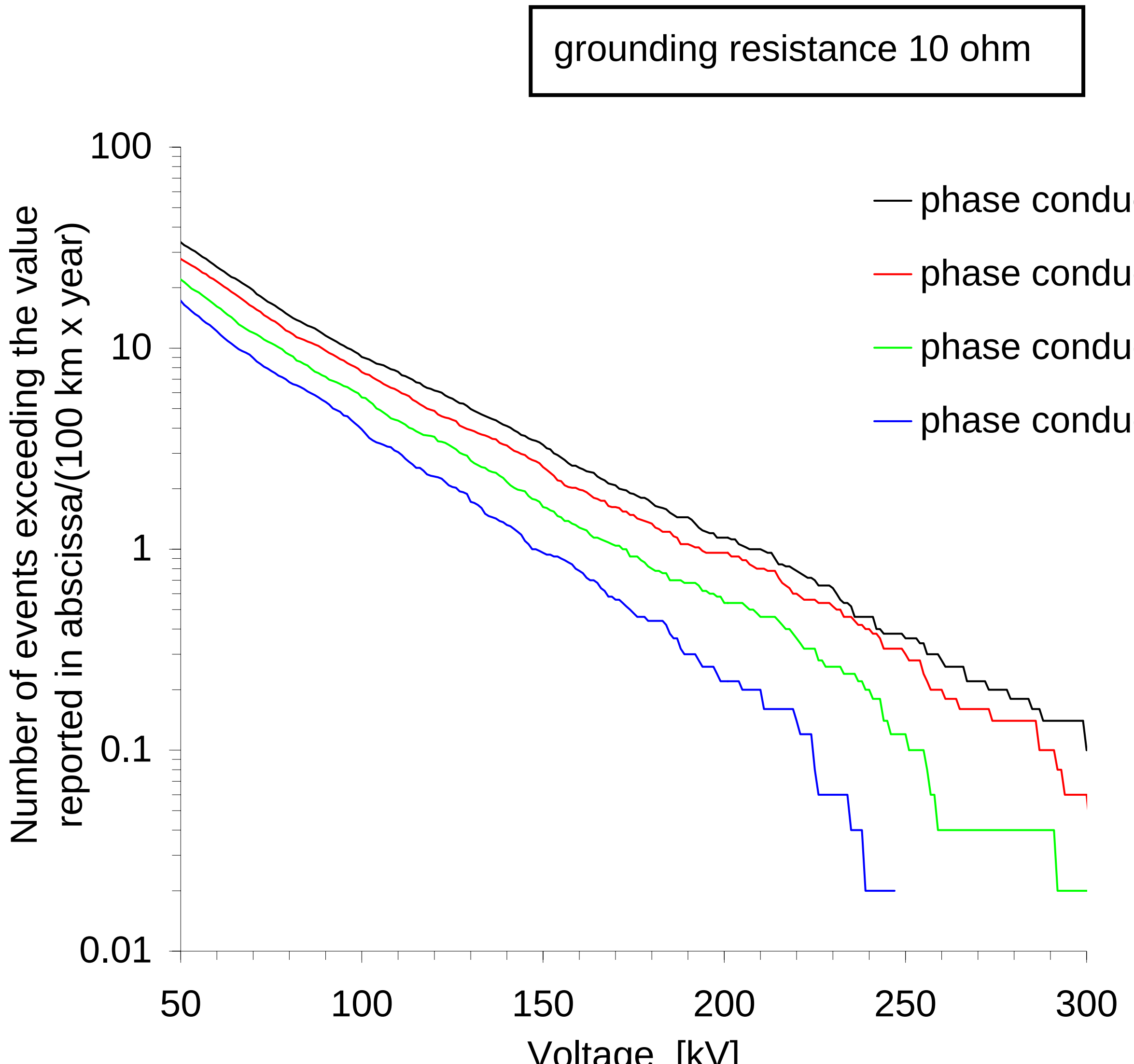
Cont'd



Influence of grounding resistance (Rt)

Statistical studies ACKN

Cont'd

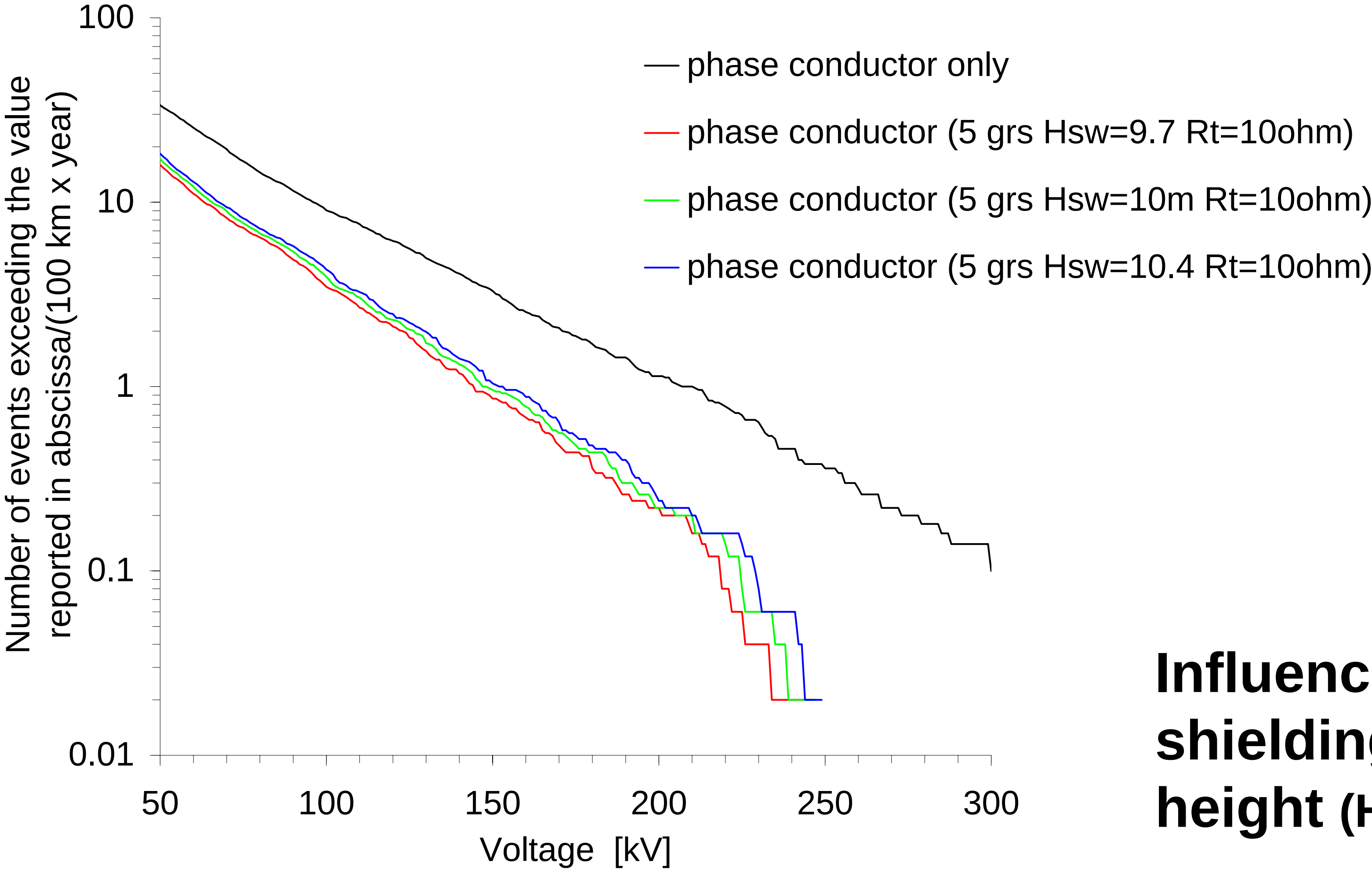


Influence of spacing between groundings

Statistical studies ACKN

Cont'd

phase conductor height 9m

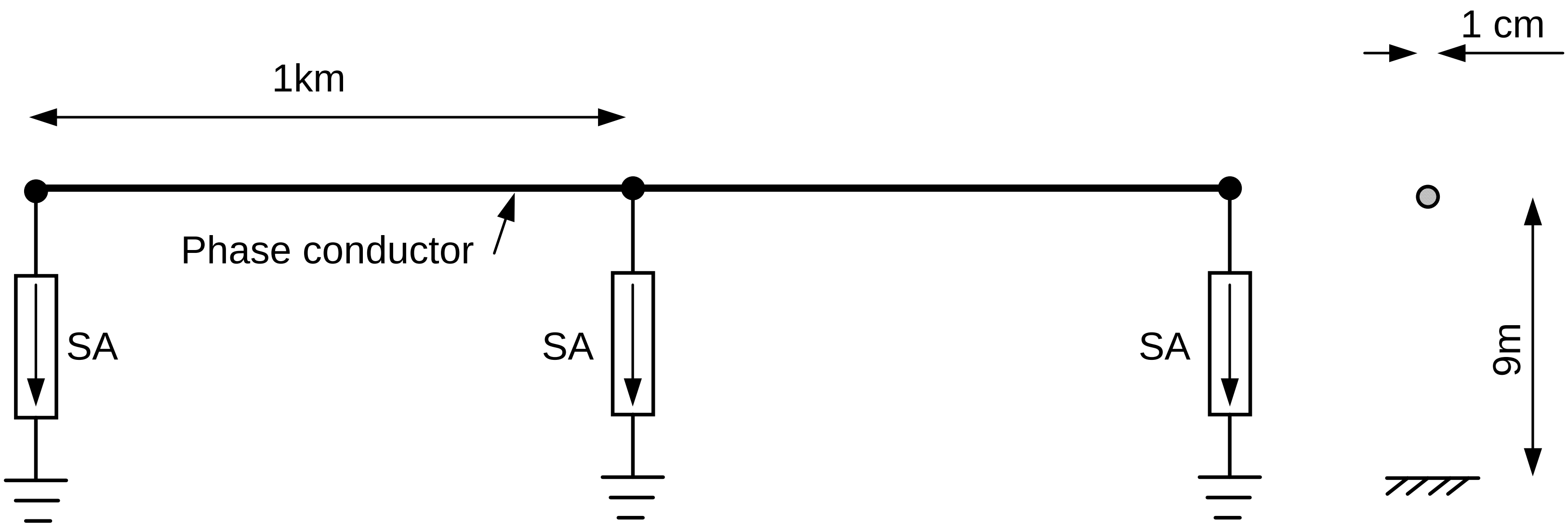


Influence of shielding wire height (Hsw)

Statistical studies ACKN

Cont'd

Influence of the presence of surge arresters



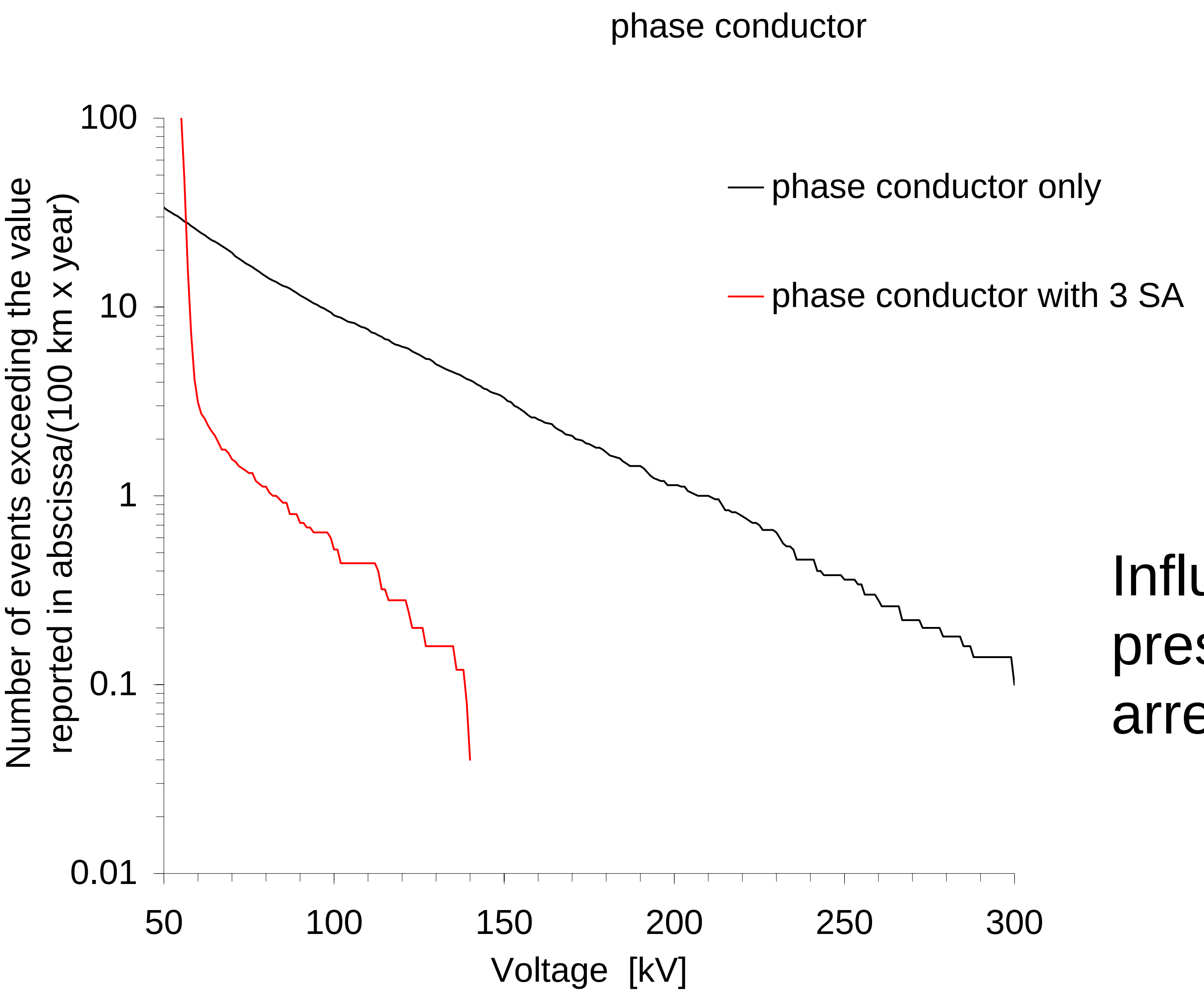
Statistical studies *Cont'd*

I [A]	V [kV]
0.0015	34.7
0.002	43.3
0.01	48.5
0.1	51.9
1	55.5
5000	79.1
10000	85.0
20000	94.4

Assumed non-linear characteristic of the surge arrester.

Statistical studies ACKN

Cont'd



Influence of the presence of surge arresters

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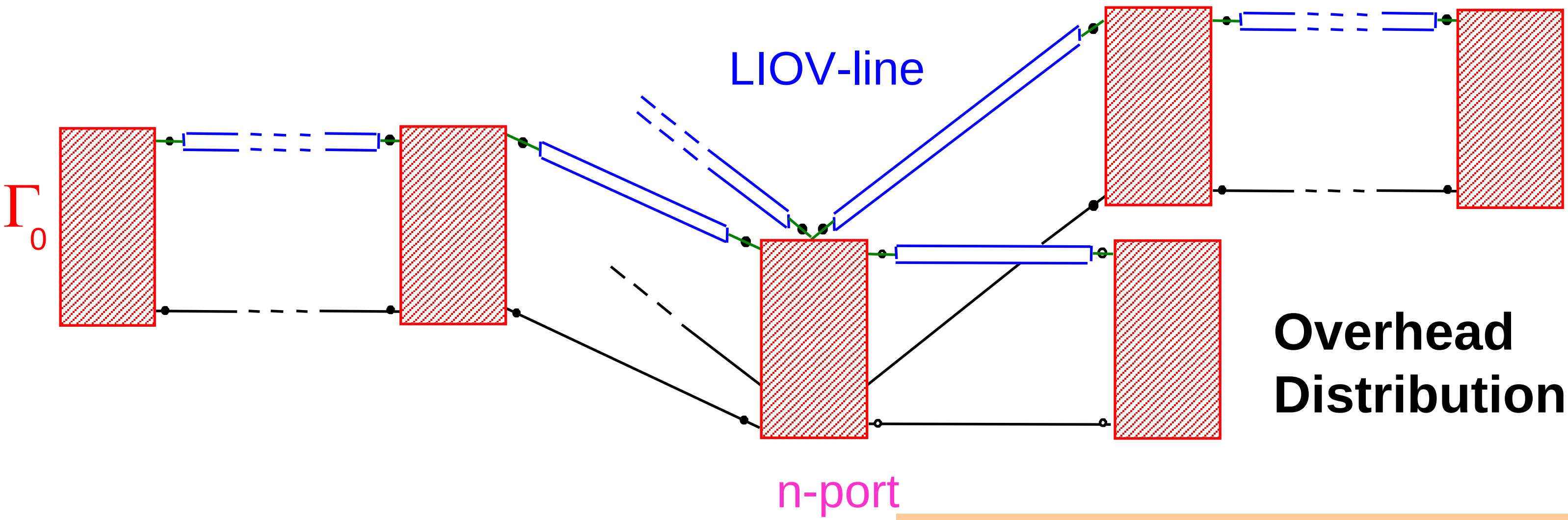
   - Return-Stroke Current Model
   - LEMP model
   - Coupling Model

3. Application of LIOV
   - Sensitivity analysis
   - Statistical studies

4. **Interface with EMTP**

5. Conclusions

Interface with the EMTP



Overhead Distribution Line

The LIOV code calculates:

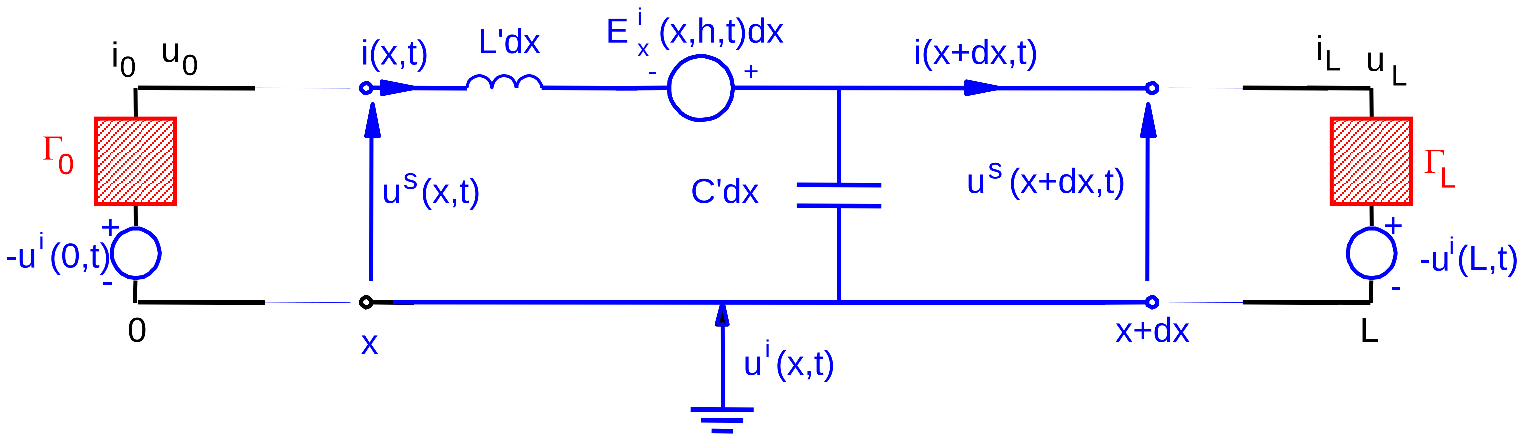
- **LEMP**
- **Coupling**

Its link with EMTP has been realized in collaboration with **ENEL-CESI (Univ. Bologna)**
Other methods for linking LIOV with EMTP have been proposed **EdF (EPFL)**

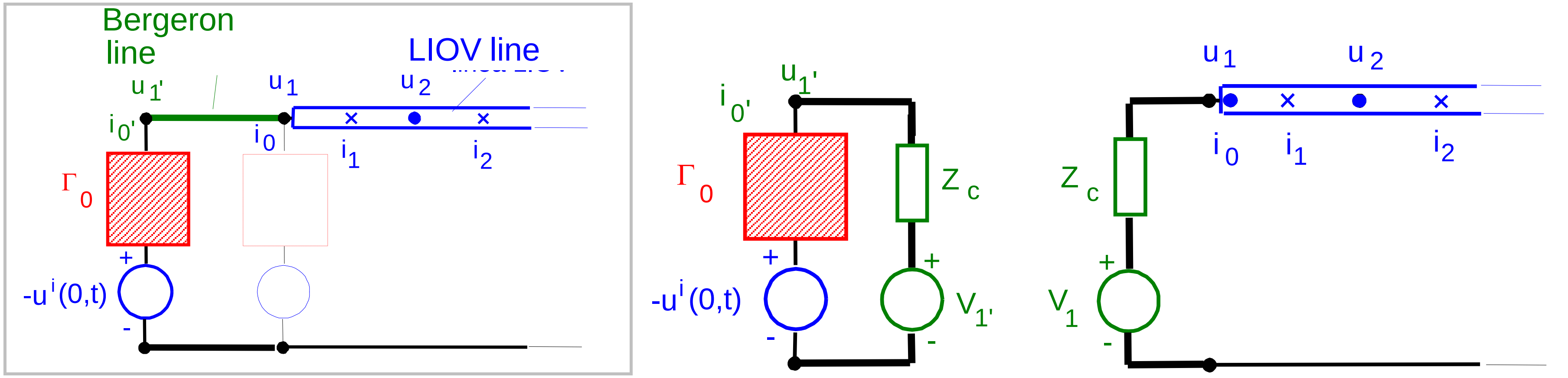
The EMTP :

- **calculates the boundary conditions**
- **makes available a large library of power components**

Interface with the EMTP *Cont'd*



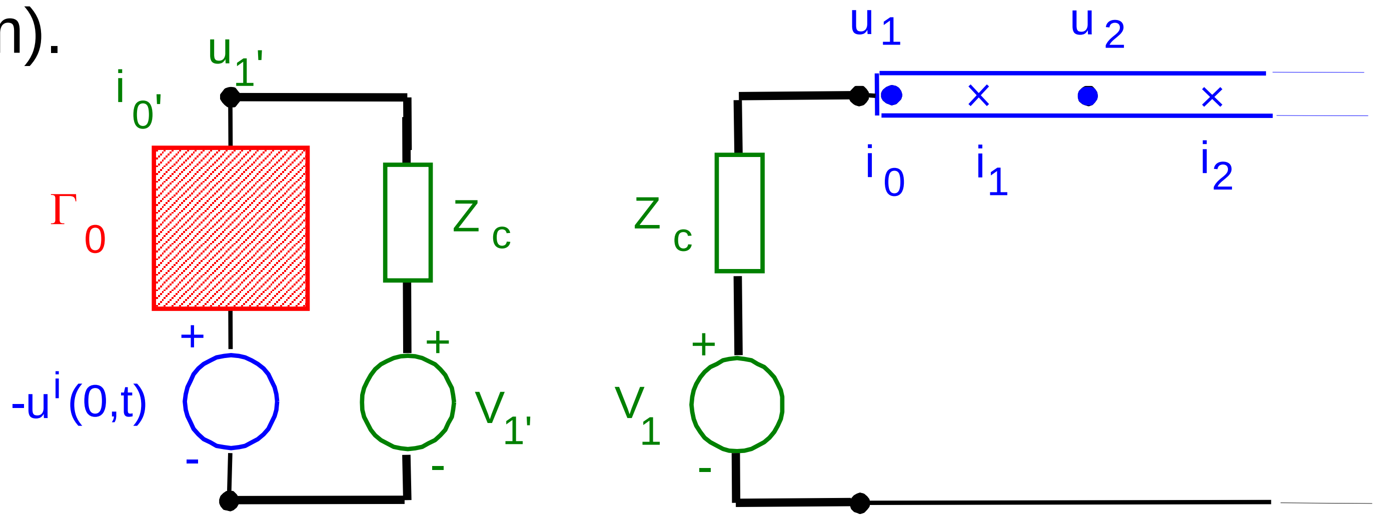
$$u^t = u^s + u^i = u^s - \int_0^h E_z^i(x,t)dz$$



Link between LIOV and EMTP

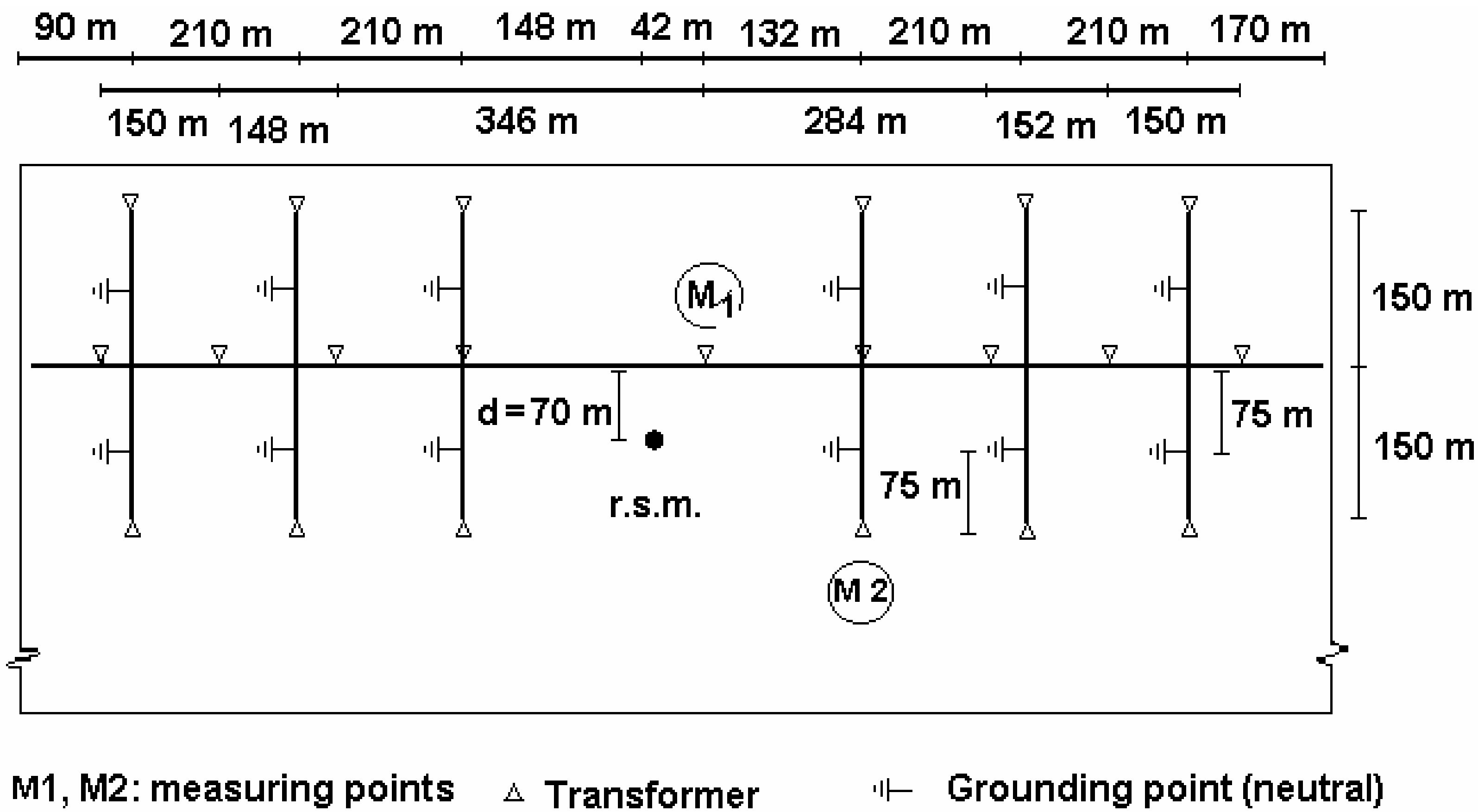
Interface with the EMTP ADD? *Cont'd*

- $u1$ and io are calculated by LIOV at time t and input to the EMTP voltage source $V1'$.
- Then, the EMTP solves the circuit on the left (boundary conditions), computes $u1'$, and input it to the LIOV voltage source $V1$ to determine the response of the LIOV-line at $t+\Delta t$.
- Δt is the integration time-step, set at the same value for both the LIOV and the EMTP, and fixed by the user (Δl is determined by the program).



See also Nucci et al., ICLP, 1994.

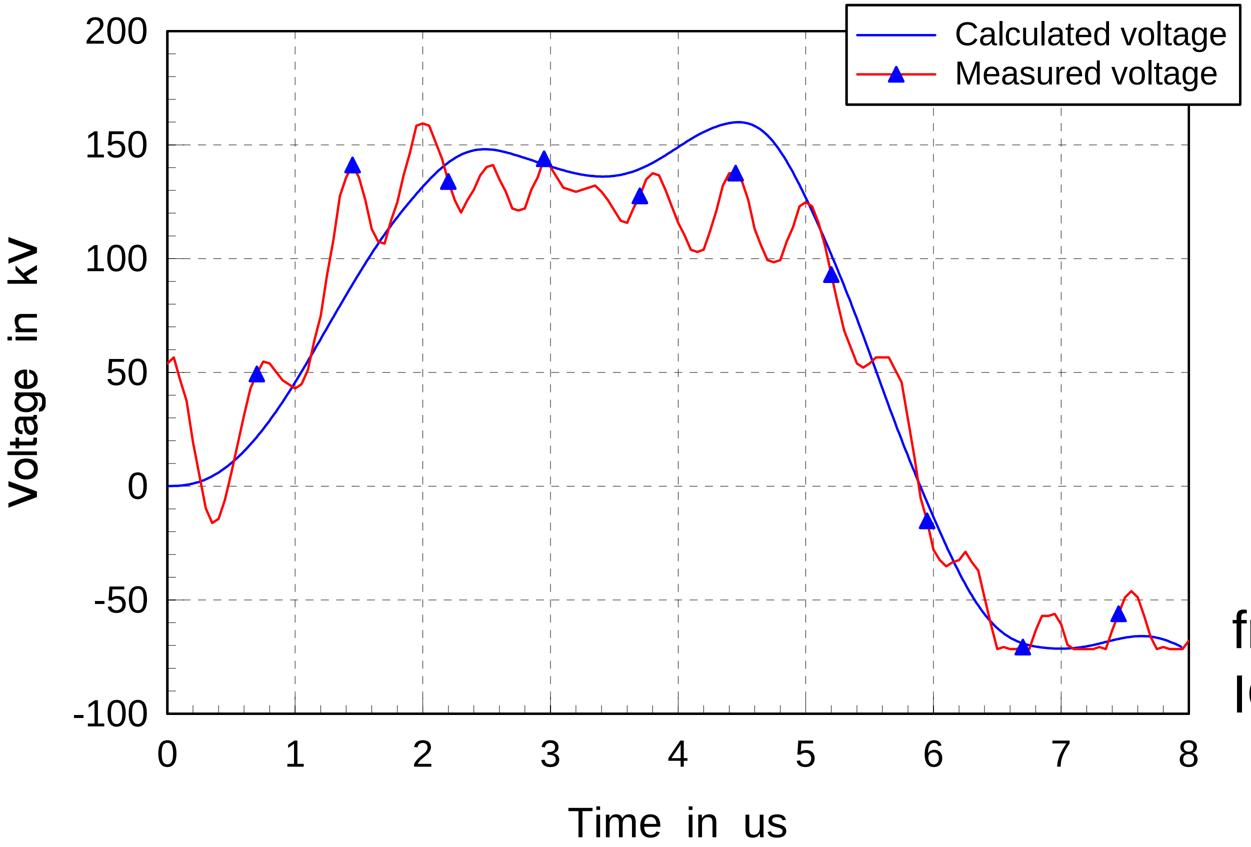
Interface with the EMTP *Cont'd*



Validation using data from a more complex system

Data: courtesy of Dr. A. Piantini, Univ. Saõ Paulo

Interface with the EMTP *Cont'd*

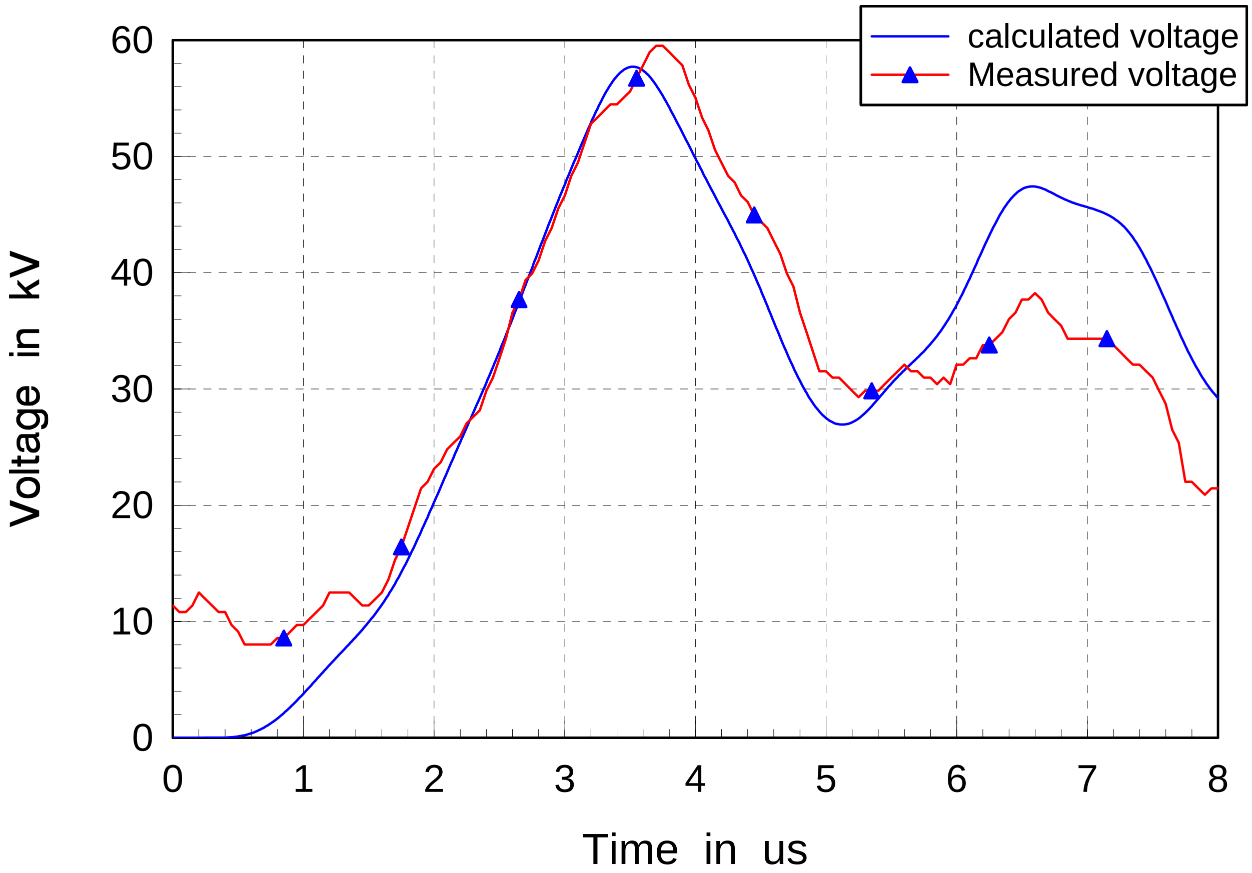


from Nucci et al., ICLP, 1998.

Validation using data from a more complex system

Data: courtesy of Dr. A. Piantini, Univ. Of São Paulo

Interface with the EMTP *Cont'd*



from Nucci et al., ICLP, 1998.

Validation using data from a more complex system

Data: courtesy of Dr. A. Piantini, Univ. Of São Paulo

Outline of the tutorial

1. Introduction
2. Theoretical basis of the LIOV code
   - Return-Stroke Current Model
   - LEMP model
   - Coupling Model
3. Application of LIOV
   - Sensitivity analysis
   - Statistical studies
4. Interface with EMTP
5. **Conclusions**

Conclusions

1. LIOV represents an improvement with respect to previous available tools (e.g. Rusck simplified formula).

2. the various models included in the code have been validated with existing experimental data

3. Influence of:
   - Ground resitivity
   - Line construction
   - Leader
   - Channel inclination and/or tortuosity
   - Corona
   - Presence of shielding wire (periodically grounded)
   - Surge arresters

   can be studied with reasonable accuracy.

4. The statistical study on the considerd overhead line shows that

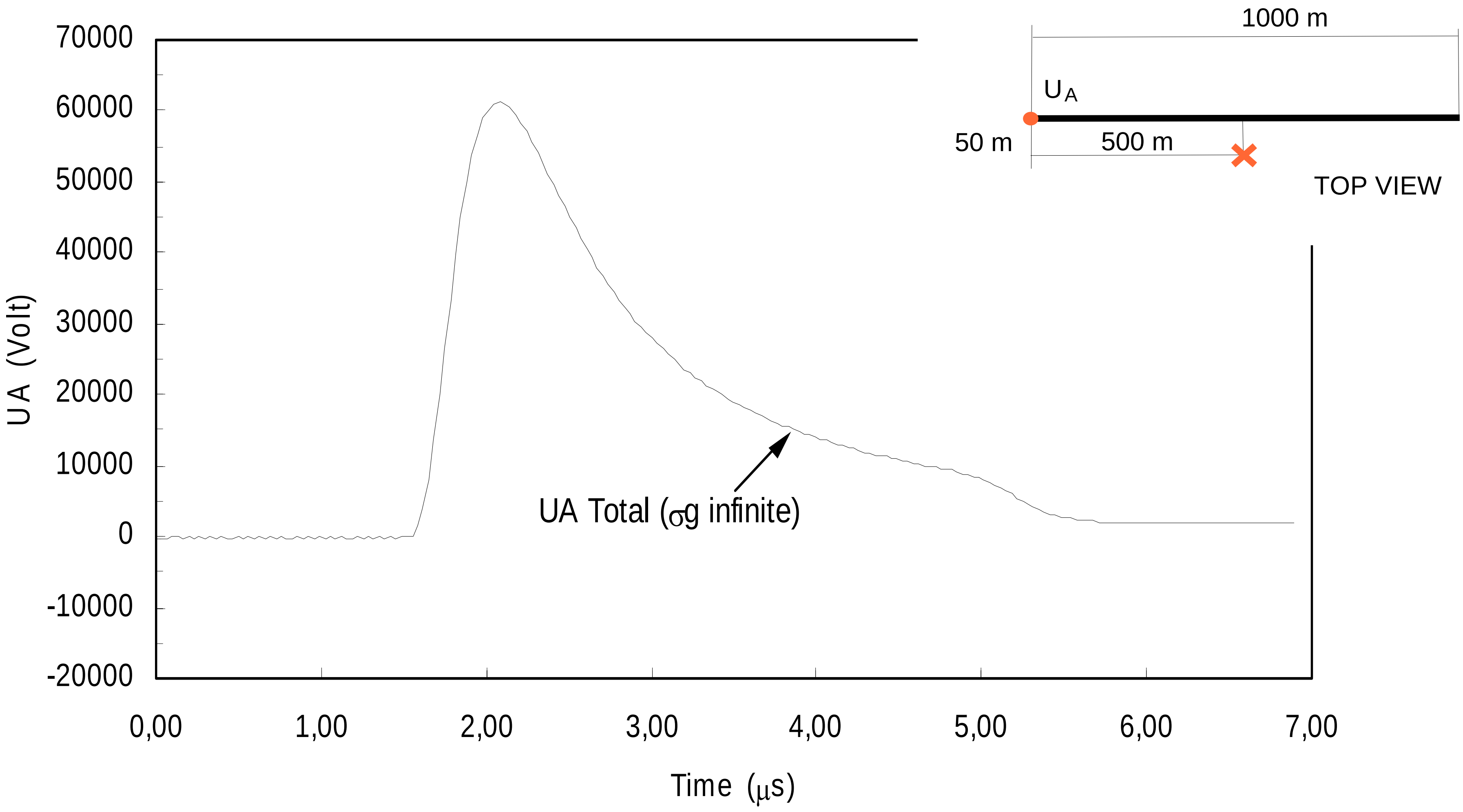
- Ground resistivity, line height and correlation factor (I_p-t_f) do affect the results
- The expression of the striking distance is important. However is progressively less important as the ground conductivity decreases
- Case of a perfectly conducting ground (no shielding wires):
  the maximum induced voltage appears at the point of the line nearest to the stroke location ==> the evaluation can be performed considering a single observation point
- Case of a lossy ground, or periodically grounded shielding wires:
  the maximum induced voltage does NOT necessarily appear at the point of the line nearest to the stroke location ==> the analysis has to be extended to all points along the line
- Grounding resistance of sw does affect the performance of the line
- Reasonable agreement with the available exp. data: more data are needed

Conclusions

5. More accurate models for grounding and surge arresters can be used in a straightforward manner using the LIOV-EMTP .
6. With LIOV-EMTP statistical analyis can be carried out on a specific distribution system with complex configuration

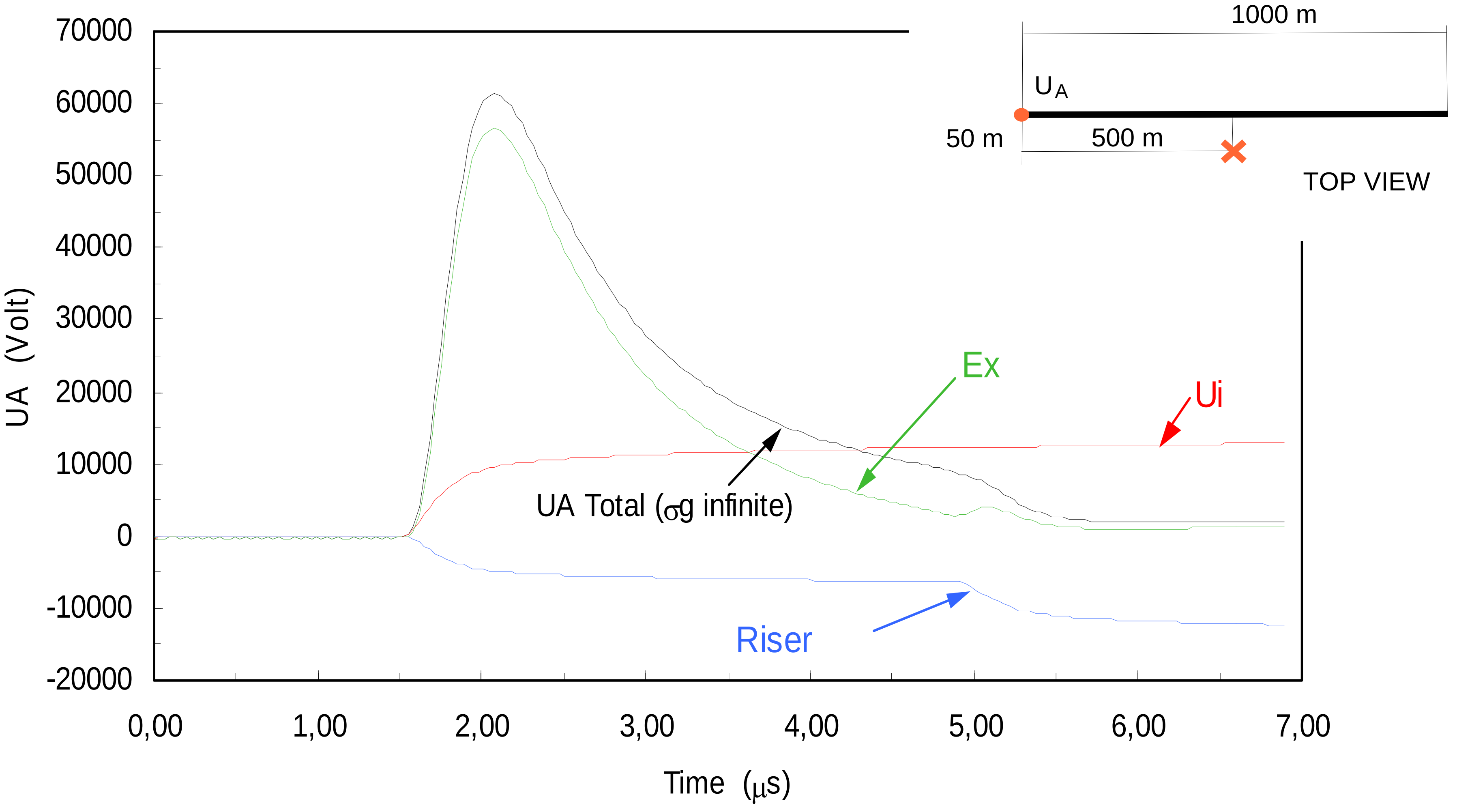
Sensitivity analysis *Cont.*

ground resistivity



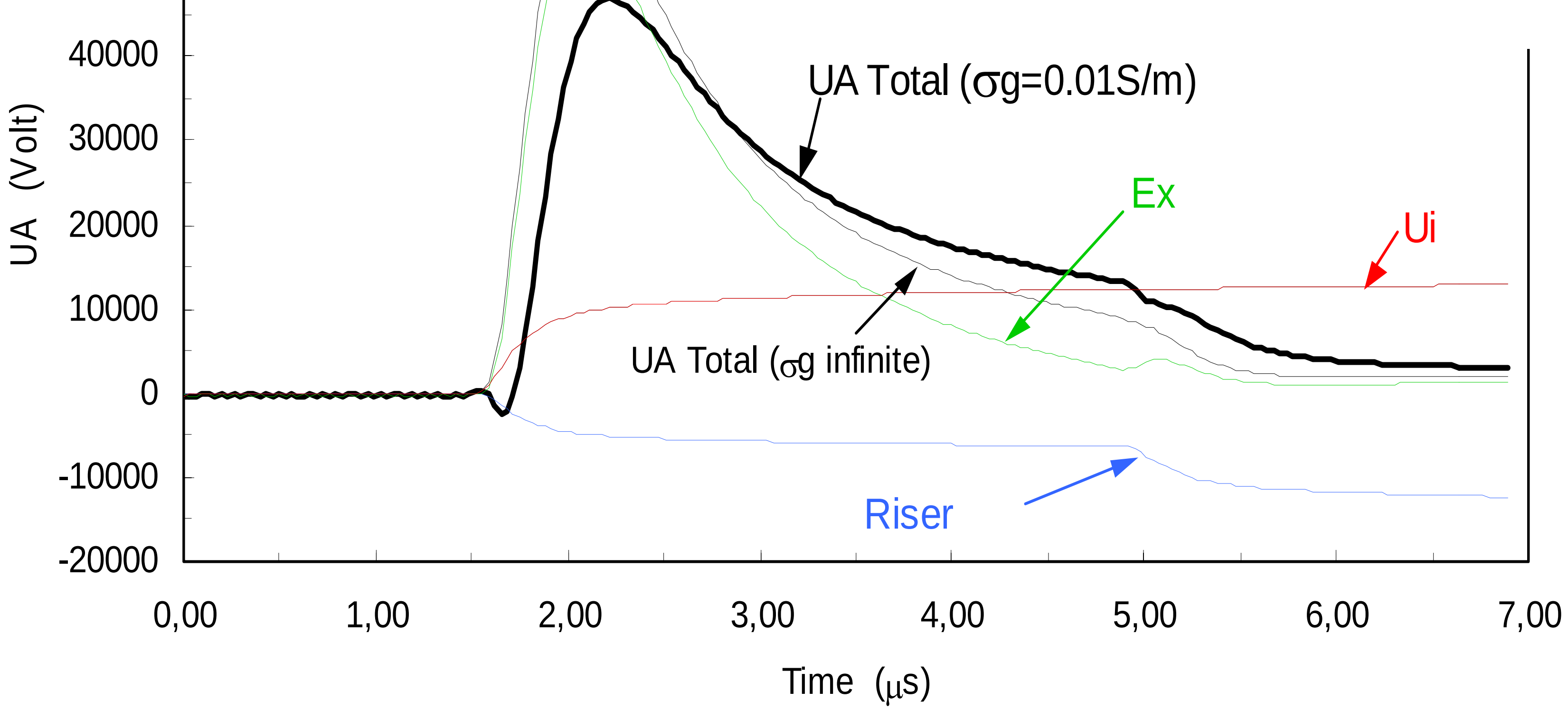
Sensitivity analysis *Cont.*

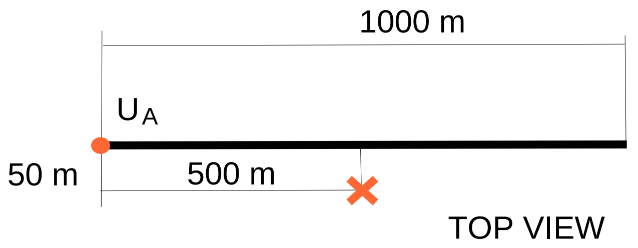
ground resistivity



Sensitivity analysis *Cont.*

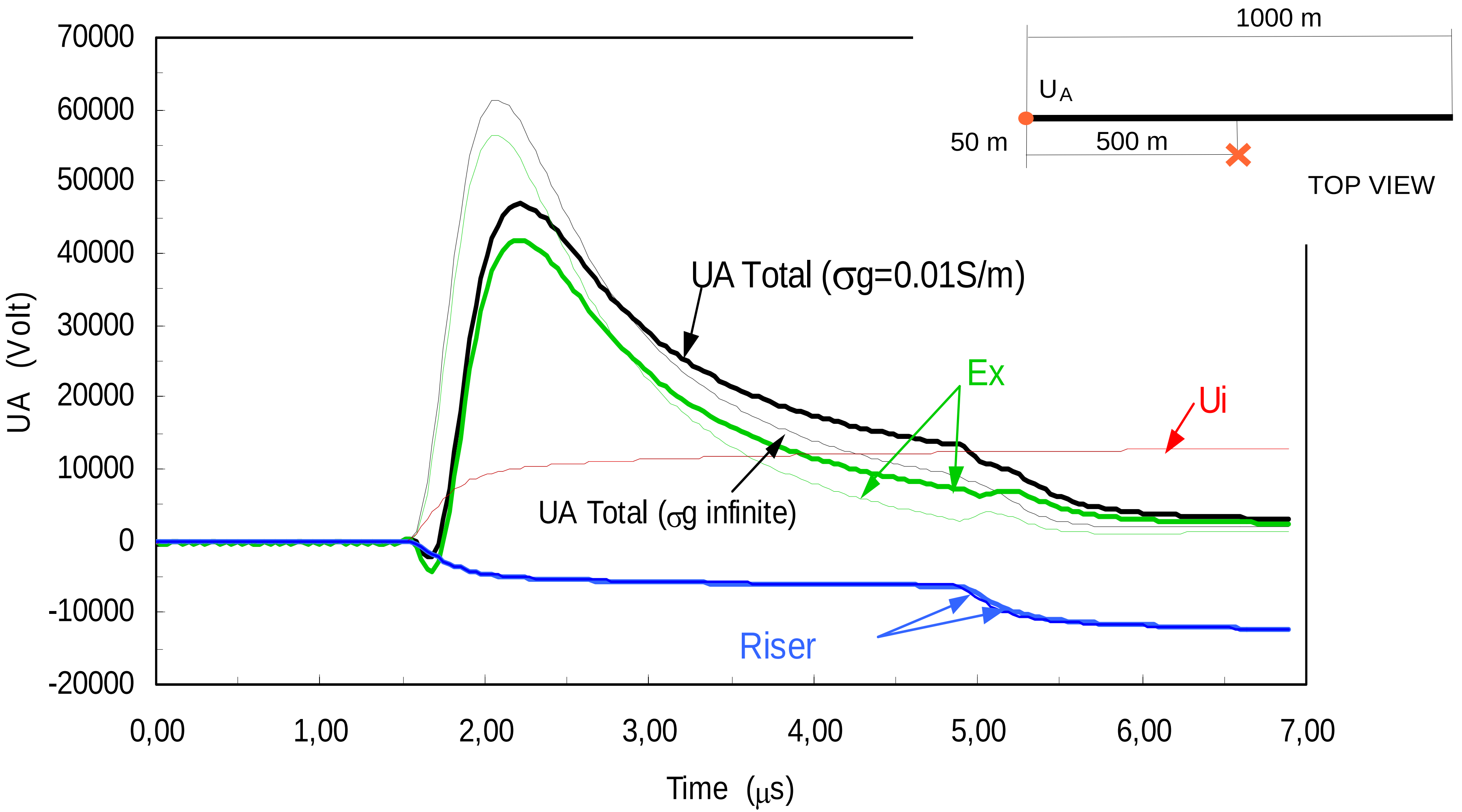
ground resistivity





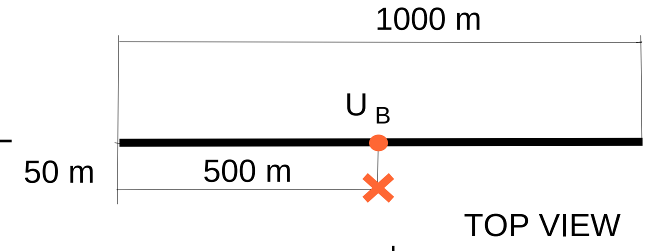
Sensitivity analysis *Cont.*

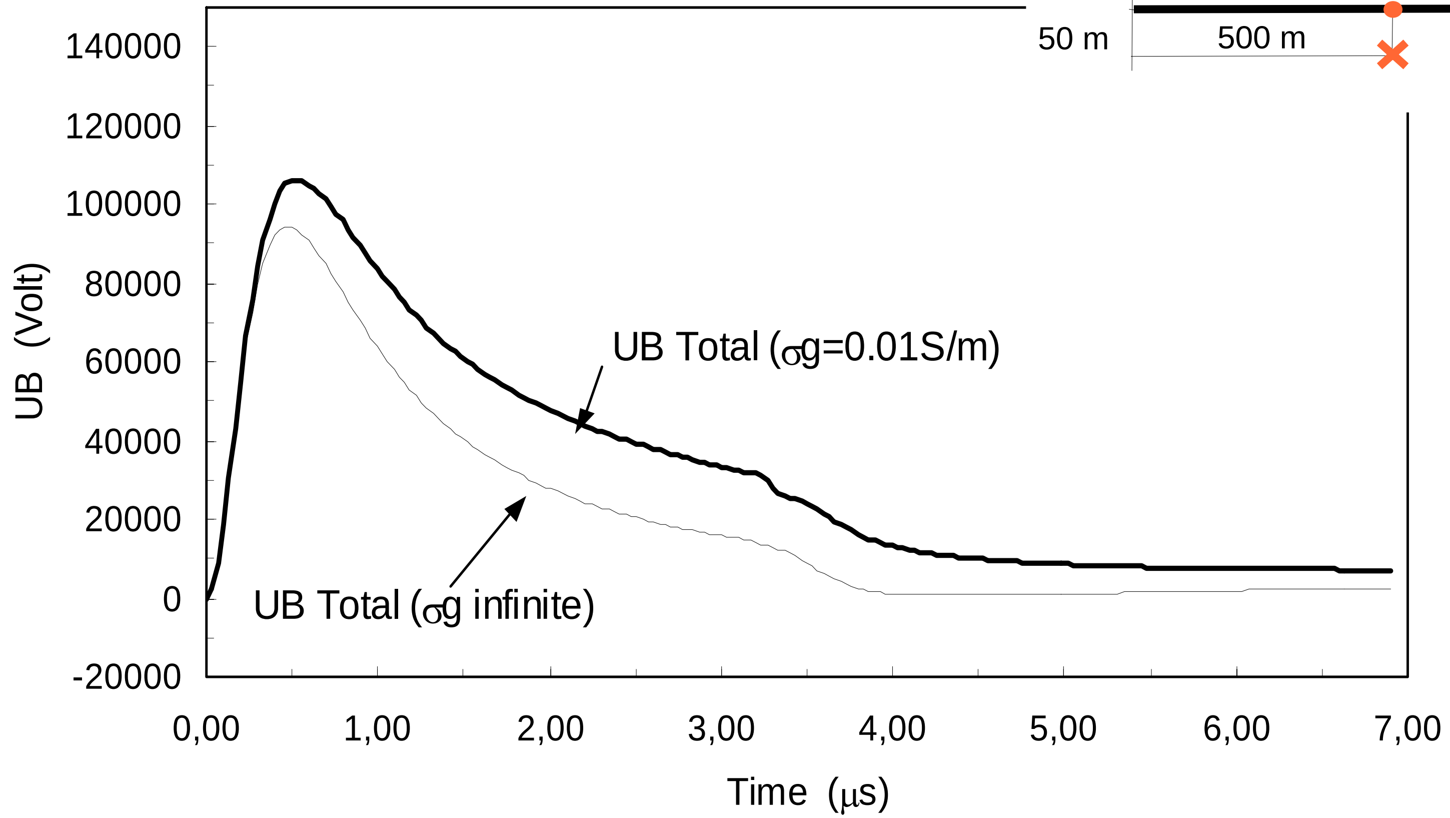
ground resistivity



Sensitivity analysis *Cont.*

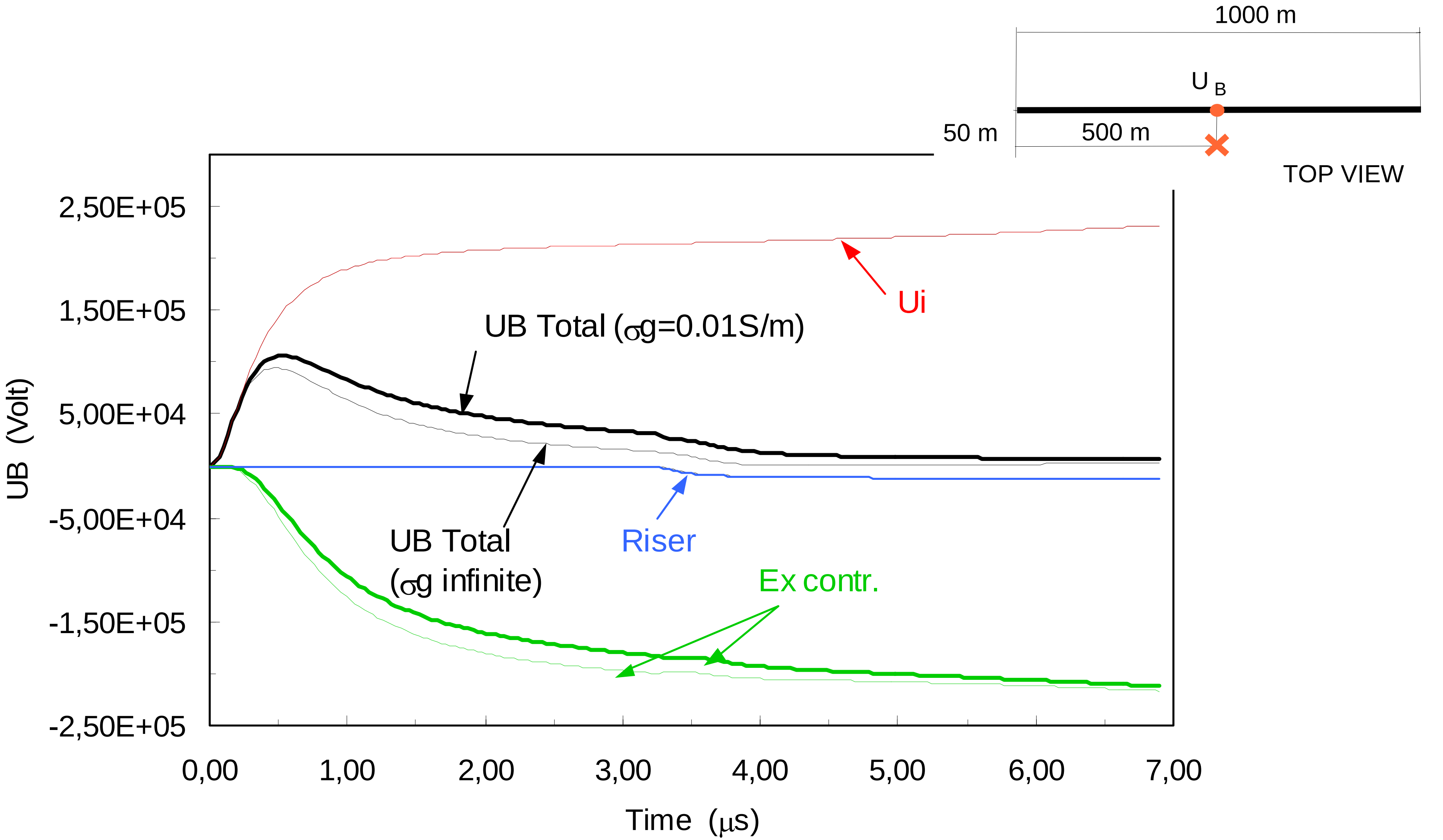
ground resistivity





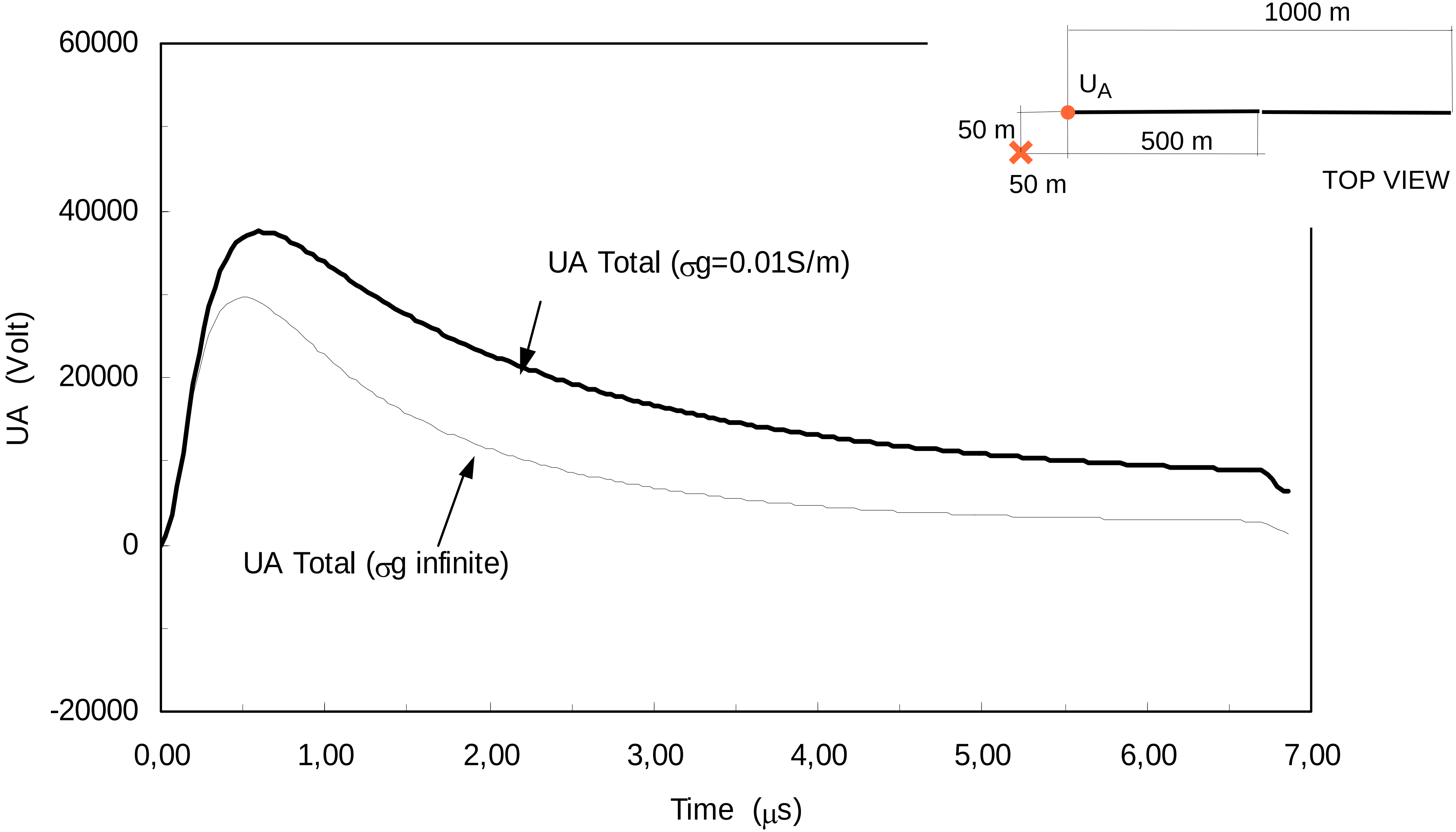
Sensitivity analysis *Cont.*

ground resistivity



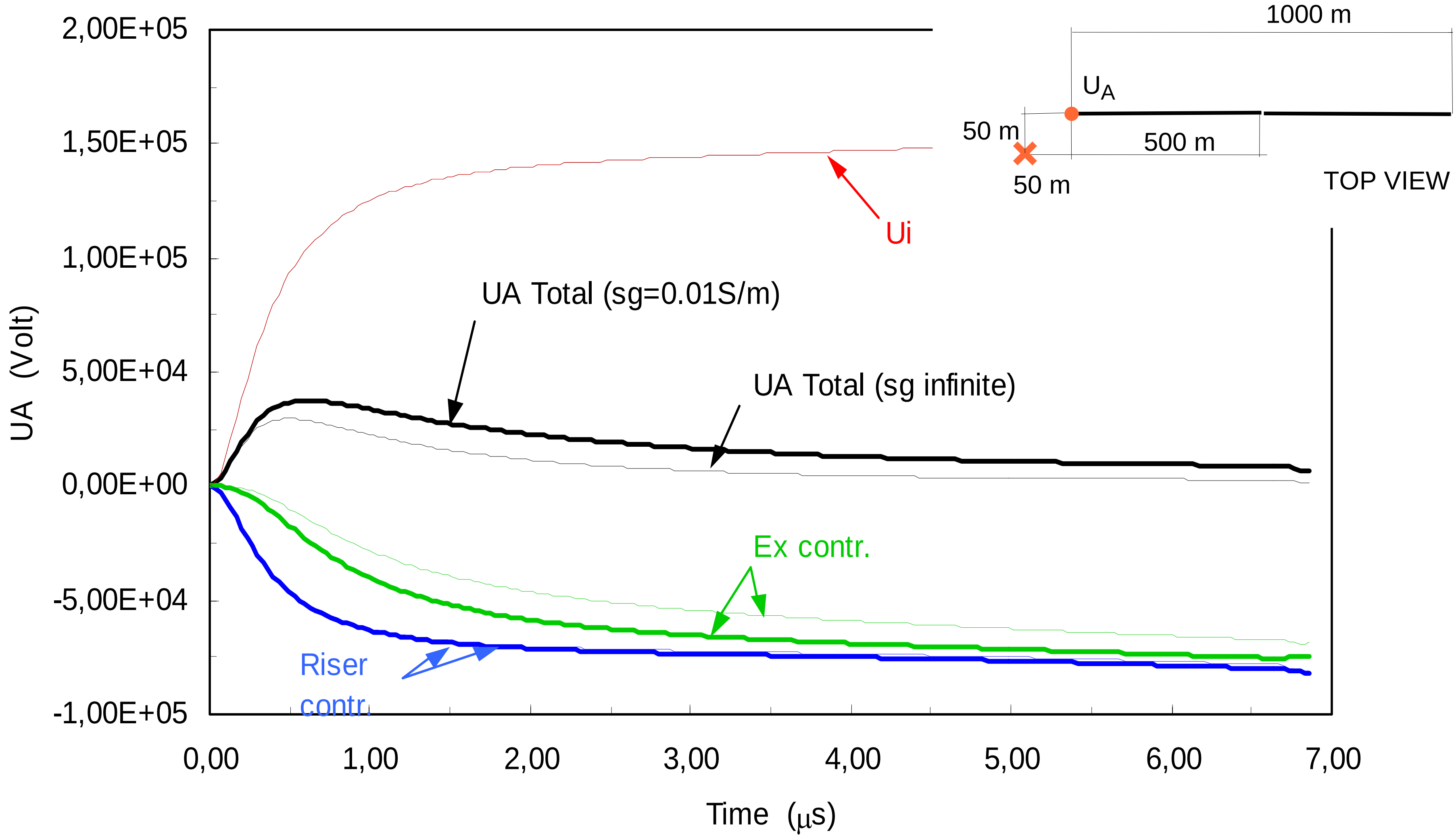
Sensitivity analysis *Cont.*

ground resistivity



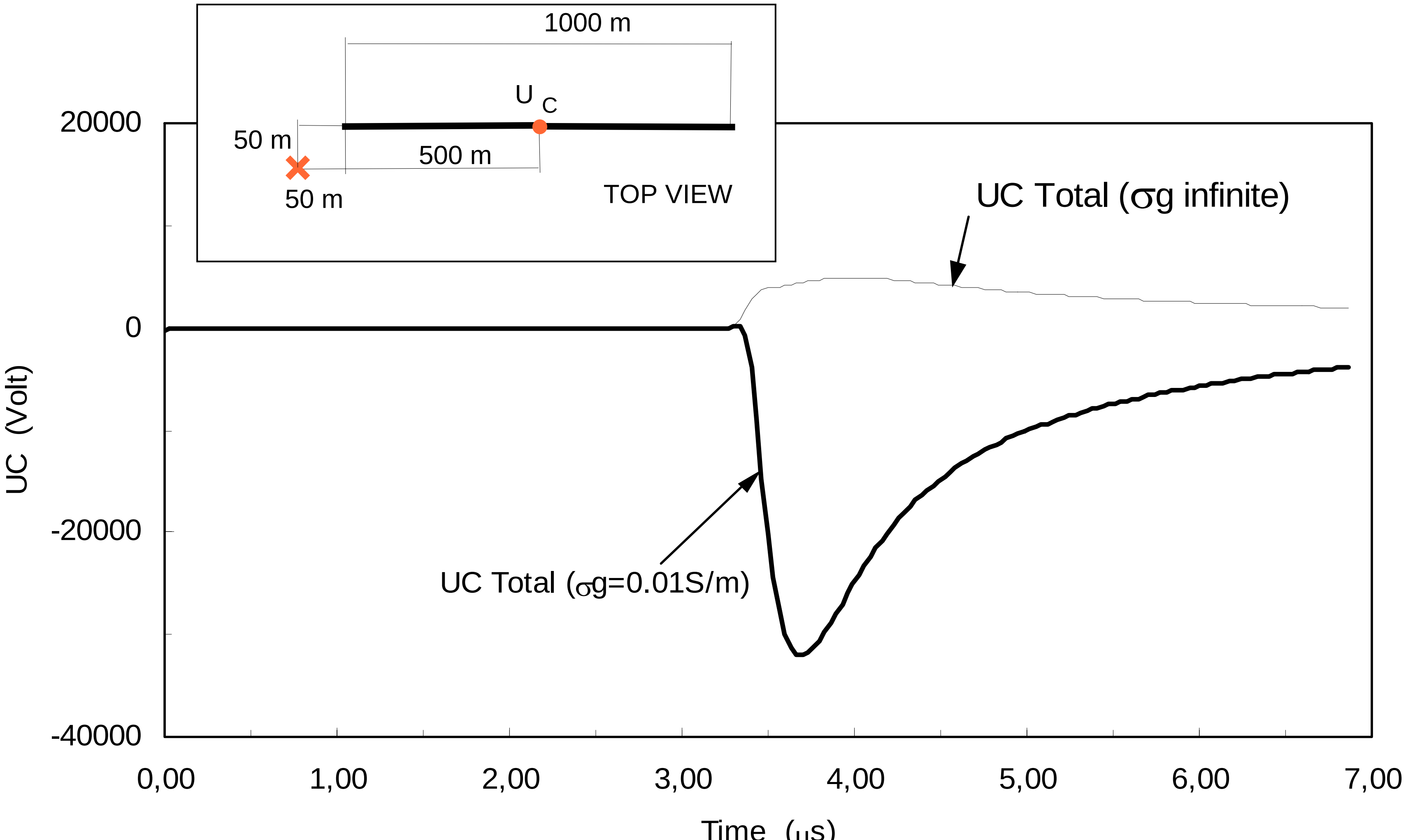
Sensitivity analysis *Cont.*

ground resistivity



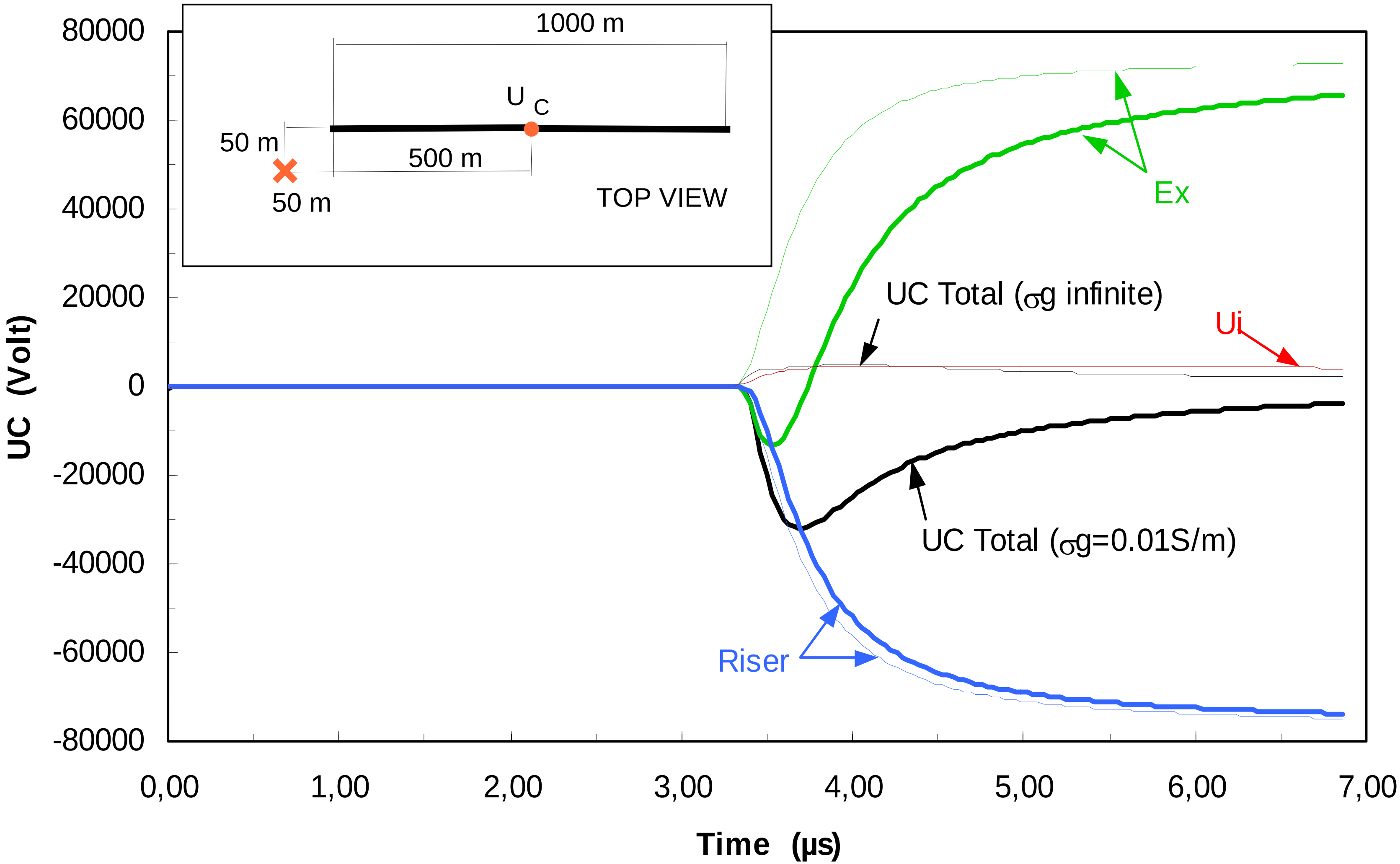
Sensitivity analysis *Cont.*

ground resistivity



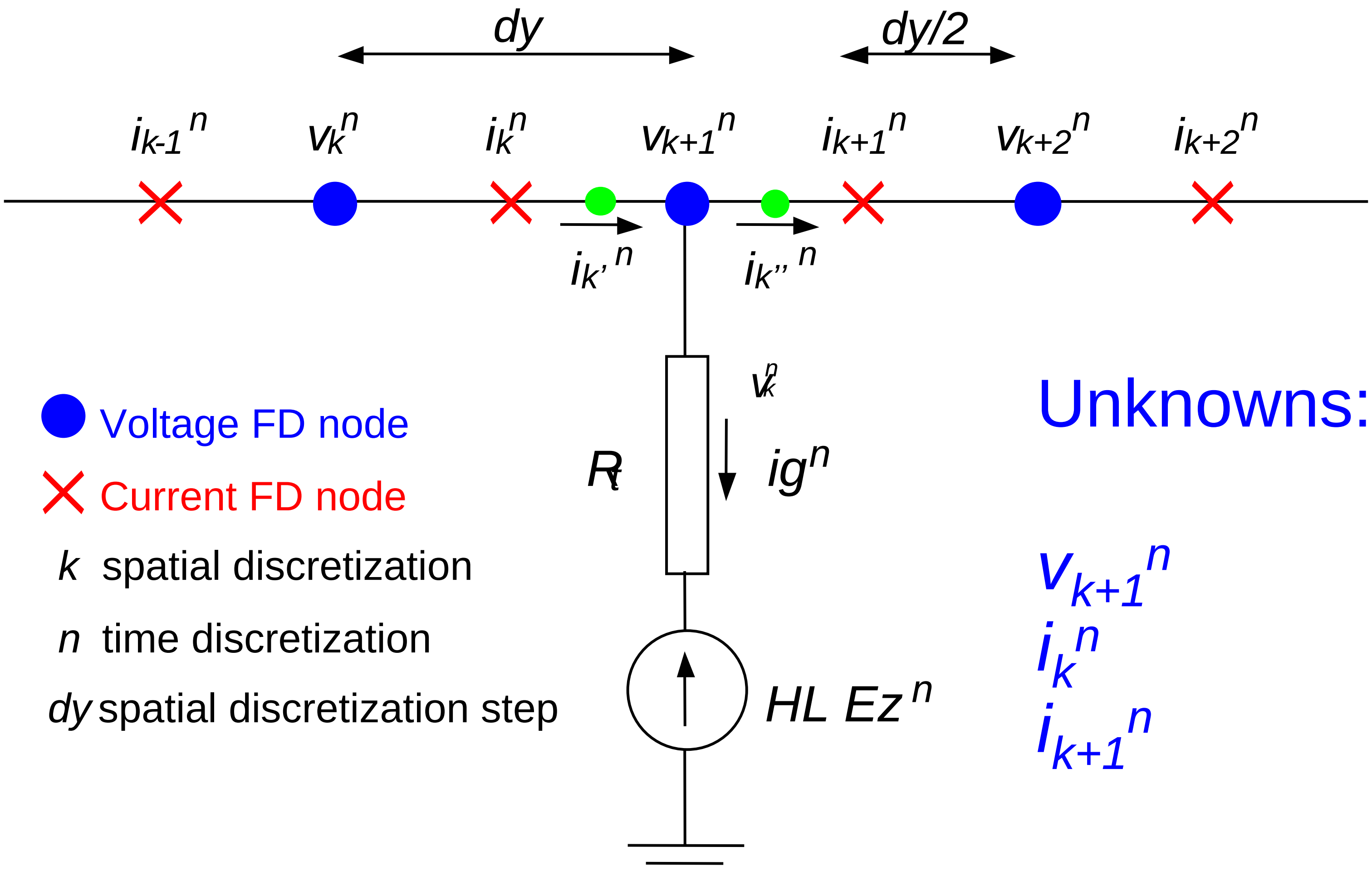
Sensitivity analysis *Cont.*

ground resistivity



Sensitivity analysis *Cont.*

Grounding at a generic point of a monoconductor line



Voltage FD node

Current FD node

k spatial discretization

n time discretization

dy spatial discretization step

Unknowns:

v_{k+1}^n

i_k^n

i_{k+1}^n

NOTE: line voltage and current are known at all discretization points along the line at time step *n* are known, except for the porblem unknowns

Sensitivity analysis *Cont.*

Grounding at a generic point of a monoconductor line

Ricordiamo la discretizzazione della prima equazione del modello di Agrawal:

$$\frac{\partial u^S(y,t)}{\partial y} + R' i(y,t) + L' \frac{\partial i(y,t)}{\partial t} = Ey(y,t) \qquad (1)$$

da cui:

$$\frac{v_{k+1}^n - v_k^n}{\Delta y} + R' \frac{i_k^n + i_k^{n-1}}{2} + L' \frac{i_k^n - i_k^{n-1}}{\Delta t} = \frac{Ey_k^n + Ey_k^{n-1}}{2} \qquad (2)$$

dalla precedente possiamo ricavare il valore di i_k^n:

$$i_k^n = A_3 \left[\frac{Ey_k^n + Ey_k^{n-1}}{2} - \frac{v_{k+1}^n - v_k^n}{\Delta y} + A_4 i_k^{n-1} \right] \qquad (3)$$

dove

$$A_3 = \left(\frac{L'}{\Delta t} + \frac{R'}{2} \right)^{-1} \qquad A_4 = \left(\frac{L'}{\Delta t} - \frac{R'}{2} \right)$$

Sensitivity analysis *Cont.*

Grounding at a generic point of a monoconductor line

Possiamo quindi scrivere per le correnti nei nodi *k* e *k+1* le seguenti equazioni:

$$i_k^n = A_3\left[\frac{Ey_k^n + Ey_k^{n-1}}{2} - \frac{v_{k+1}^n - v_k^n}{\Delta y} + A_4 i_k^{n-1}\right] \tag{4}$$

$$i_{k+1}^n = A_3\left[\frac{Ey_{k+1}^n + Ey_{k+1}^{n-1}}{2} - \frac{v_{k+2}^n - v_{k+1}^n}{\Delta y} + A_4 i_{k+1}^{n-1}\right] \tag{5}$$

Supponendo i versi delle correnti indicati nella figura precedente possiamo scrivere per le correnti $i_{k'}^n$ $i_{k''}^n$ ig^n l'equazione di Kirchoff delle correnti:

$$ig^n = i_{k'}^n - i_{k''}^n \tag{6}$$

Le correnti $i_{k'}^n$ $i_{k''}^n$ possono essere legate alle correnti dei nodi adiacenti mediante una interpolazione lineare:

$$i_{k'}^n = \frac{3i_k^n - i_{k-1}^n}{2} \tag{7}$$

$$i_{k''}^n = \frac{3i_{k+1}^n - i_{k+2}^n}{2} \tag{8}$$

Sensitivity analysis *Cont.*

Grounding at a generic point of a monoconductor line

Inoltre per la tensione $v_{k+1}{}^{n}$ possiamo scrivere la seguente equazione:

$$v_{k+1}^{n} = R_t ig^{n} + HL \cdot Ez^{n} \qquad (9)$$

Inserendo nella (4) le (6) (7) (8) otteniamo:

$$v_{k+1}^{n} = R\left[\frac{3i_k^n - i_{k-1}^n - 3i_{k+1}^n + i_{k+2}^n}{2}\right] + HL \cdot Ez^{n} \qquad (10)$$

Le (4) (5) e (10) costituiscono il sistema di equazioni che permette di determinare le incognite del problema.

Sensitivity analysis *Cont.*

Grounding at a generic point of a monoconductor line

L'estensione al caso di una linea multiconduttore risulta immediato dato che le equazioni (4) (5) e (10) risultano ancora valide sostituendo alle variabili le rispettive matrici:

$$[i]_k^n = [A3]\left(\frac{[Ey]_k^n + [Ey]_k^{n-1}}{2} - \frac{[v]_{k+1}^n - [v]_k^n}{\Delta y} + [A4][i]_k^{n-1} \right) \qquad (11)$$

$$[i]_{k+1}^n = [A3]\left(\frac{[Ey]_{k+1}^n + [Ey]_{k+1}^{n-1}}{2} - \frac{[v]_{k+2}^n - [v]_{k+1}^n}{\Delta y} + [A4][i]_{k+1}^{n-1} \right) \qquad (12)$$

$$[v]_{k+1}^n = [RK]\left(\frac{3[i]_k^n - [i]_{k-1}^n - 3[i]_{k+1}^n + [i]_{k+2}^n}{2} \right) + HL \cdot [Ez^n] \qquad (13)$$

dove

$$[i]_k^n = \begin{pmatrix} i1_k^n \\ i2_k^n \\ i3_k^n \\ \vdots \\ iNC_k^n \end{pmatrix} \quad [v]_k^n = \begin{pmatrix} v1_k^n \\ v2_k^n \\ v3_k^n \\ \vdots \\ vNC_k^n \end{pmatrix} \quad [Ey]_k^n = \begin{pmatrix} Ey1_k^n \\ Ey2_k^n \\ Ey3_k^n \\ \vdots \\ EyNC_k^n \end{pmatrix} \quad [Ez]_k^n = \begin{pmatrix} Ez1_k^n \\ Ez2_k^n \\ Ez3_k^n \\ \vdots \\ EzNC_k^n \end{pmatrix}$$

Sensitivity analysis *Cont.*

Grounding at a generic point of a monoconductor line

Le matrici presenti nelle (11) (12) (13) hanno le seguenti espressioni:

$$[RK] = \begin{pmatrix} RK_{11} & 0 & 0 & | & 0 \\ 0 & RK_{22} & 0 & | & 0 \\ 0 & 0 & RK_{33} & | & 0 \\ — & — & — & | & — \\ 0 & 0 & 0 & | & RK_{NCNC} \end{pmatrix}$$

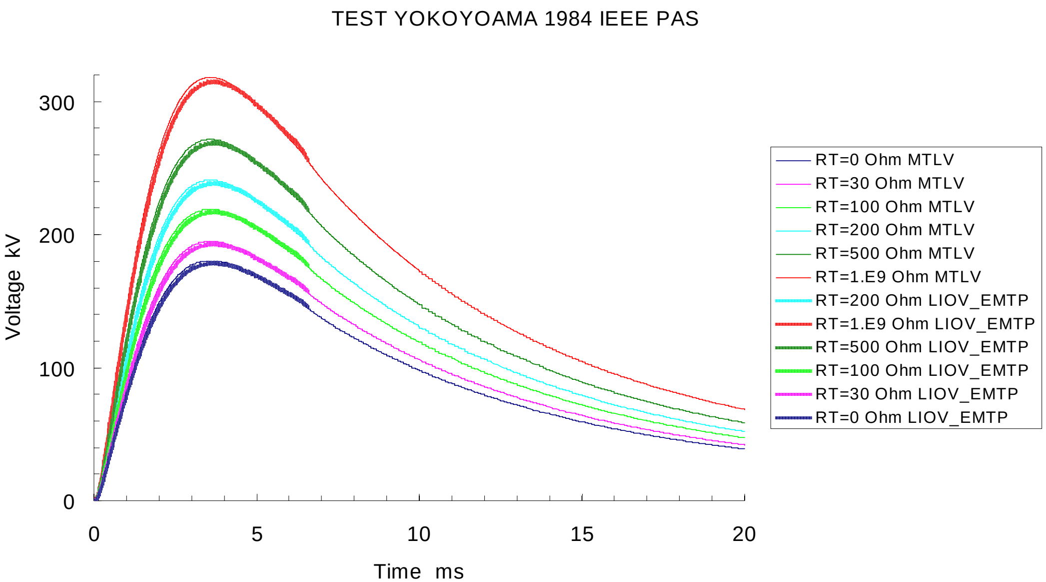
$$[A_3] = \frac{\lfloor L_{ij} \rfloor}{\Delta t} + \frac{\lfloor R_{ij} \rfloor}{2}$$

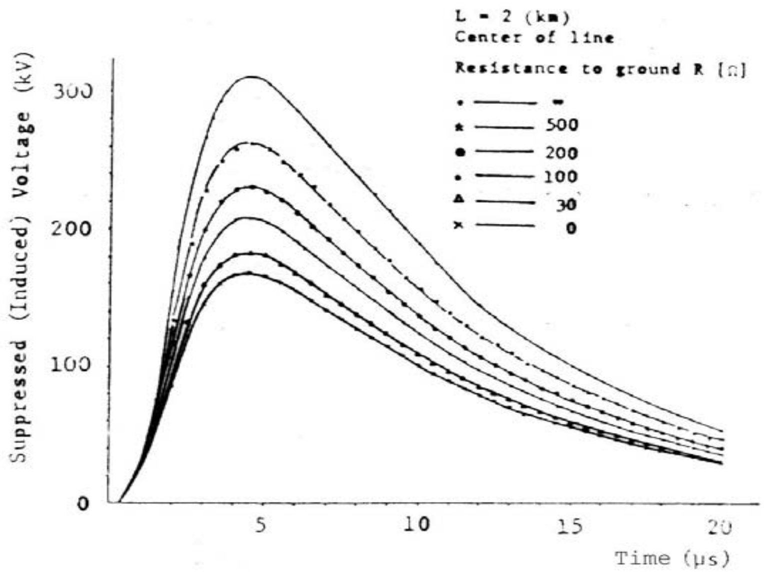
$$[A_4] = \frac{\lfloor L_{ij} \rfloor}{\Delta t} - \frac{\lfloor R_{ij} \rfloor}{2}$$

Dove RK_{ii} rappresenta la resistenza di messa a terra del conduttore i-esimo

Sensitivity analysis *Cont.*

Grounding at a generic point of a multiconductor line



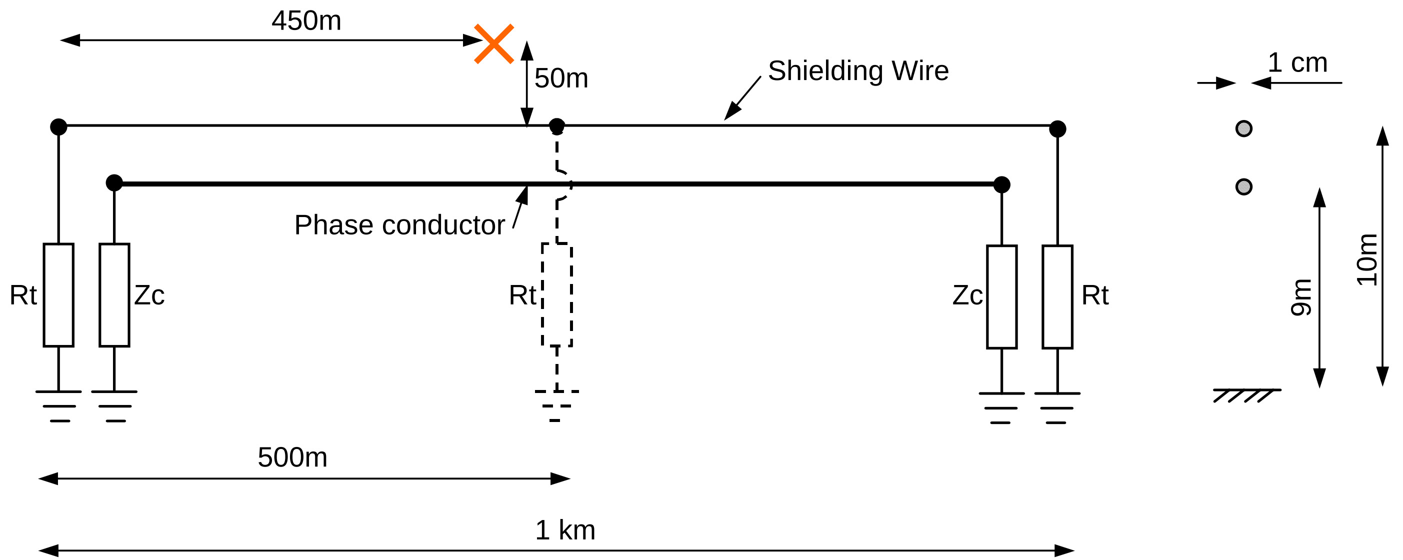


Effect of grounding resistance of a shielding wire (multi-conductors line)

Comparison with [S.Yokoyama - “Calculation of Lightning-Induced Voltages on Overhead Multiconductor Systems”, IEEE PAS Vol.103 No.1 Jan 1984 pp.100-108]

Sensitivity analysis *Cont.*

Effect of the shielding wire in a two-conductor line

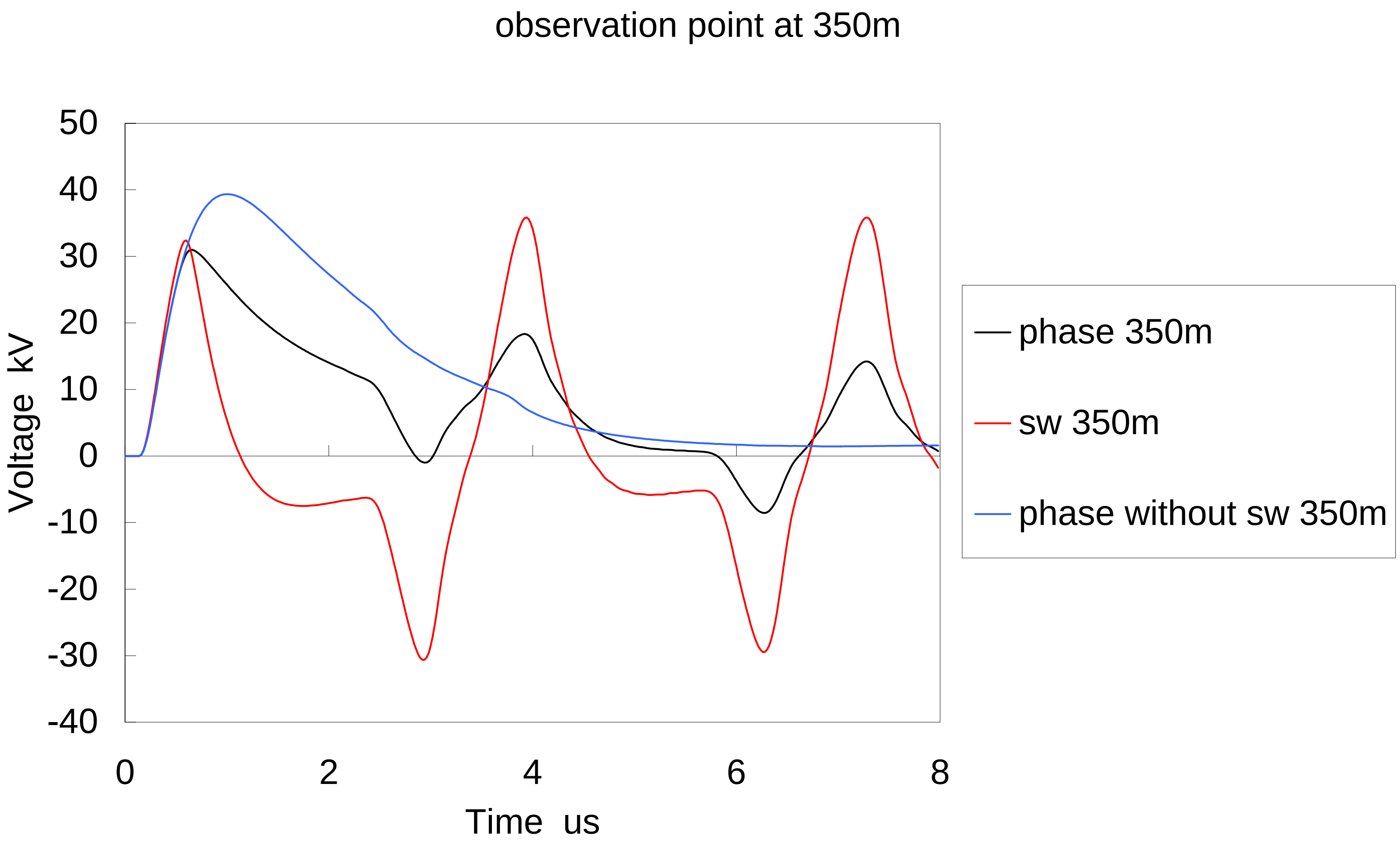


Rt=0 Ohm
Zc=491.3 Ohm

I=12 kA
di/dt=40 kA/us

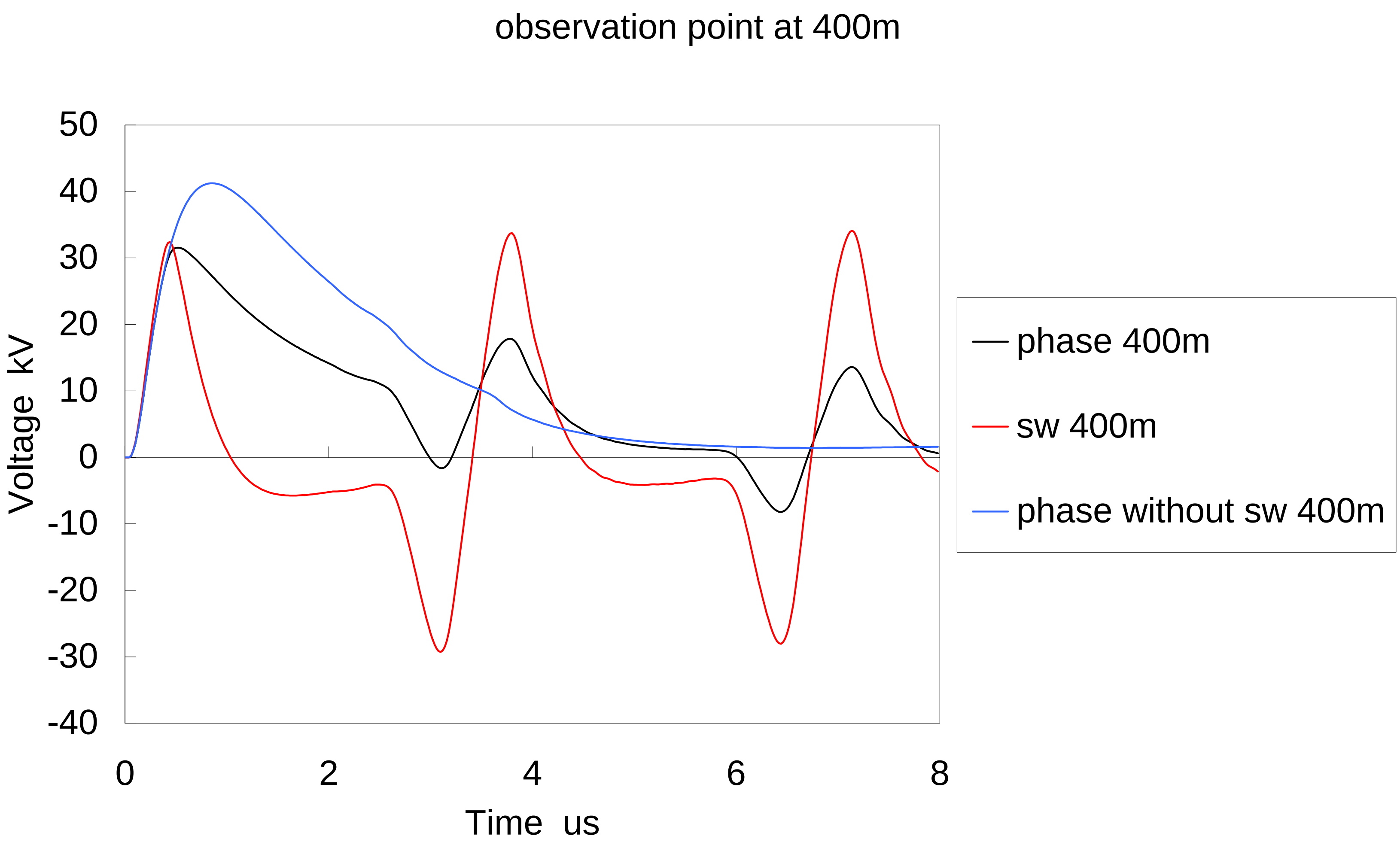
Sensitivity analysis *Cont.*

Effect of the shielding wire in a two-conductor line



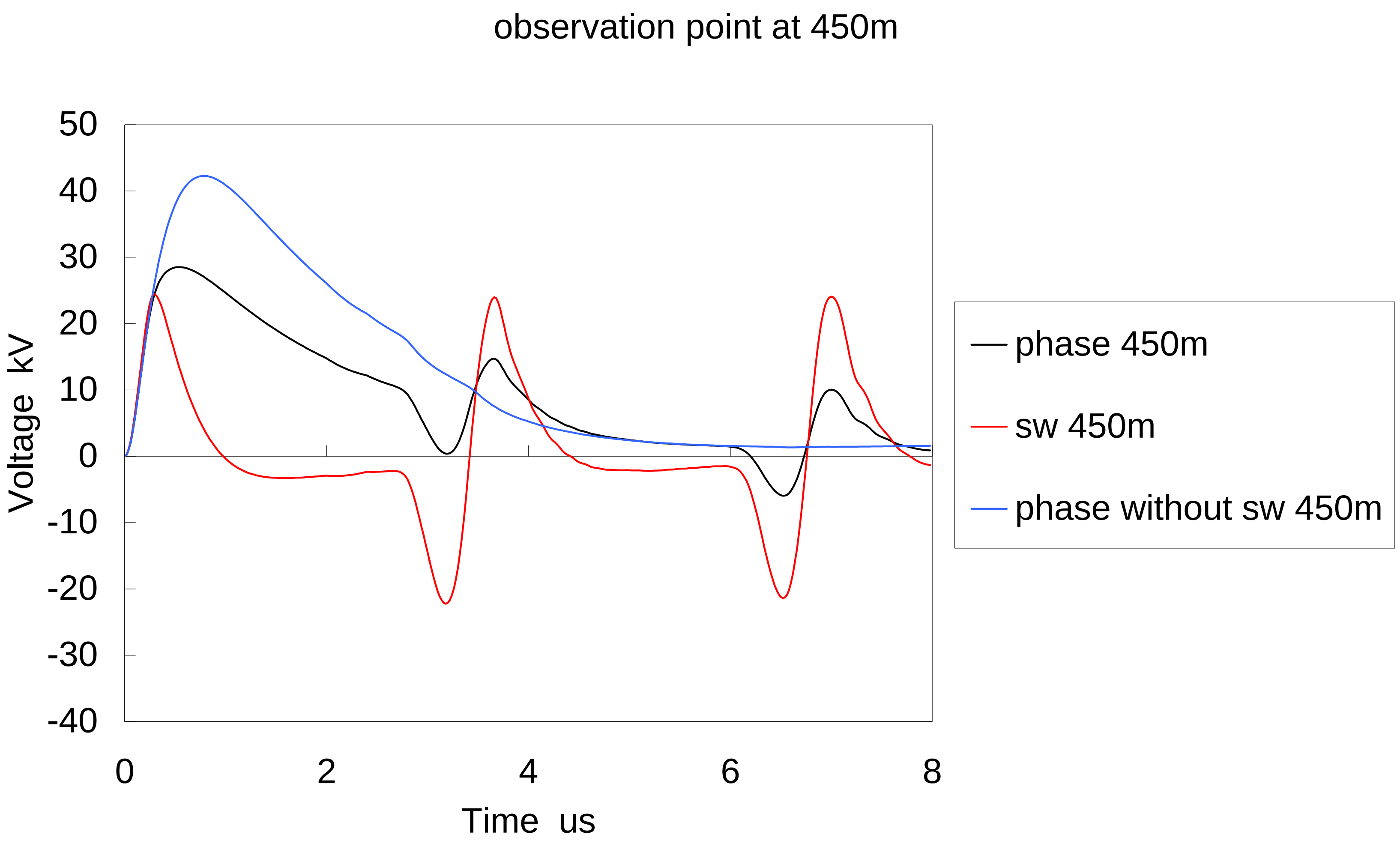
Sensitivity analysis *Cont.*

Effect of the shielding wire in a two-conductor line



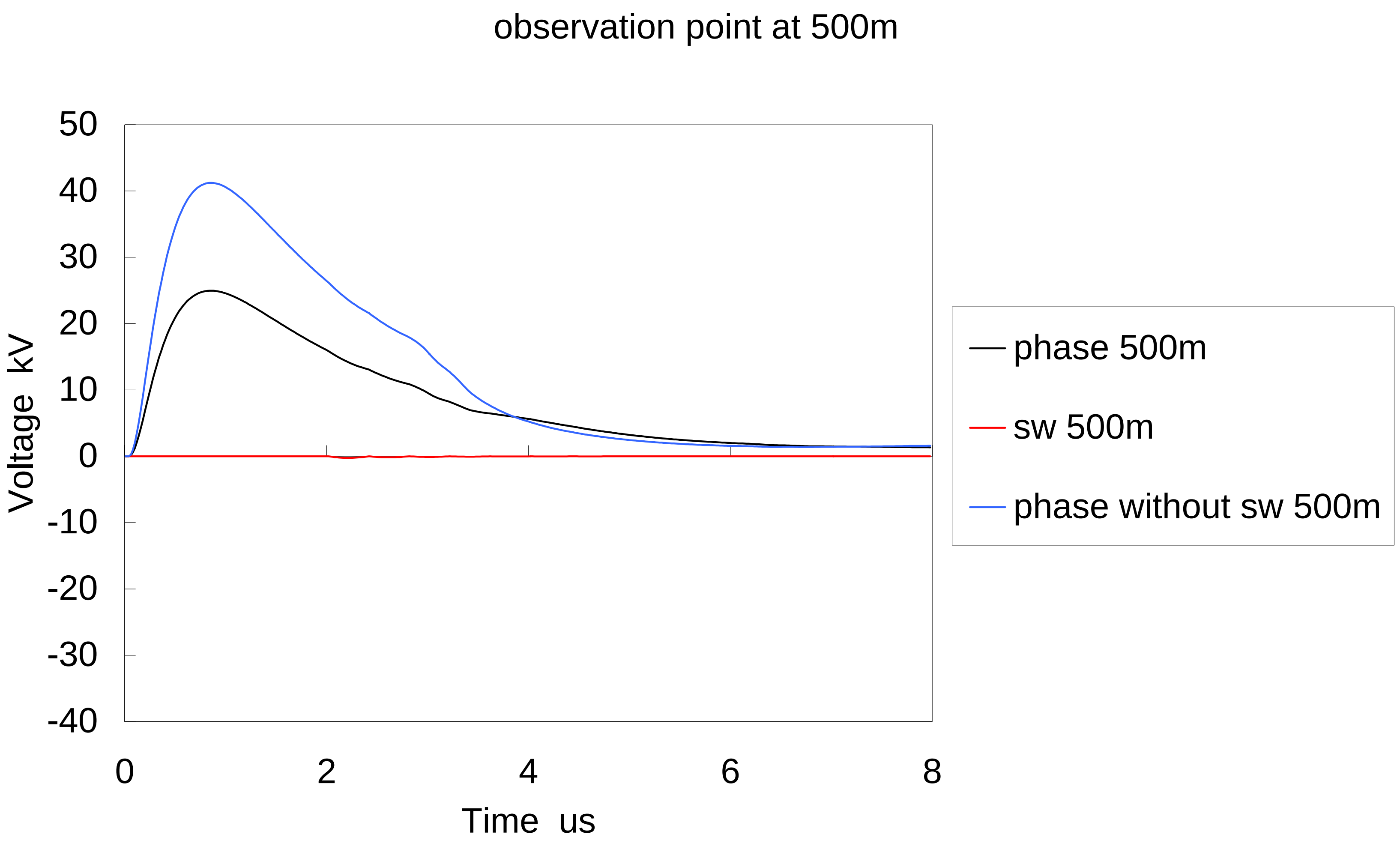
Sensitivity analysis *Cont.*

Effect of the shielding wire in a two-conductor line



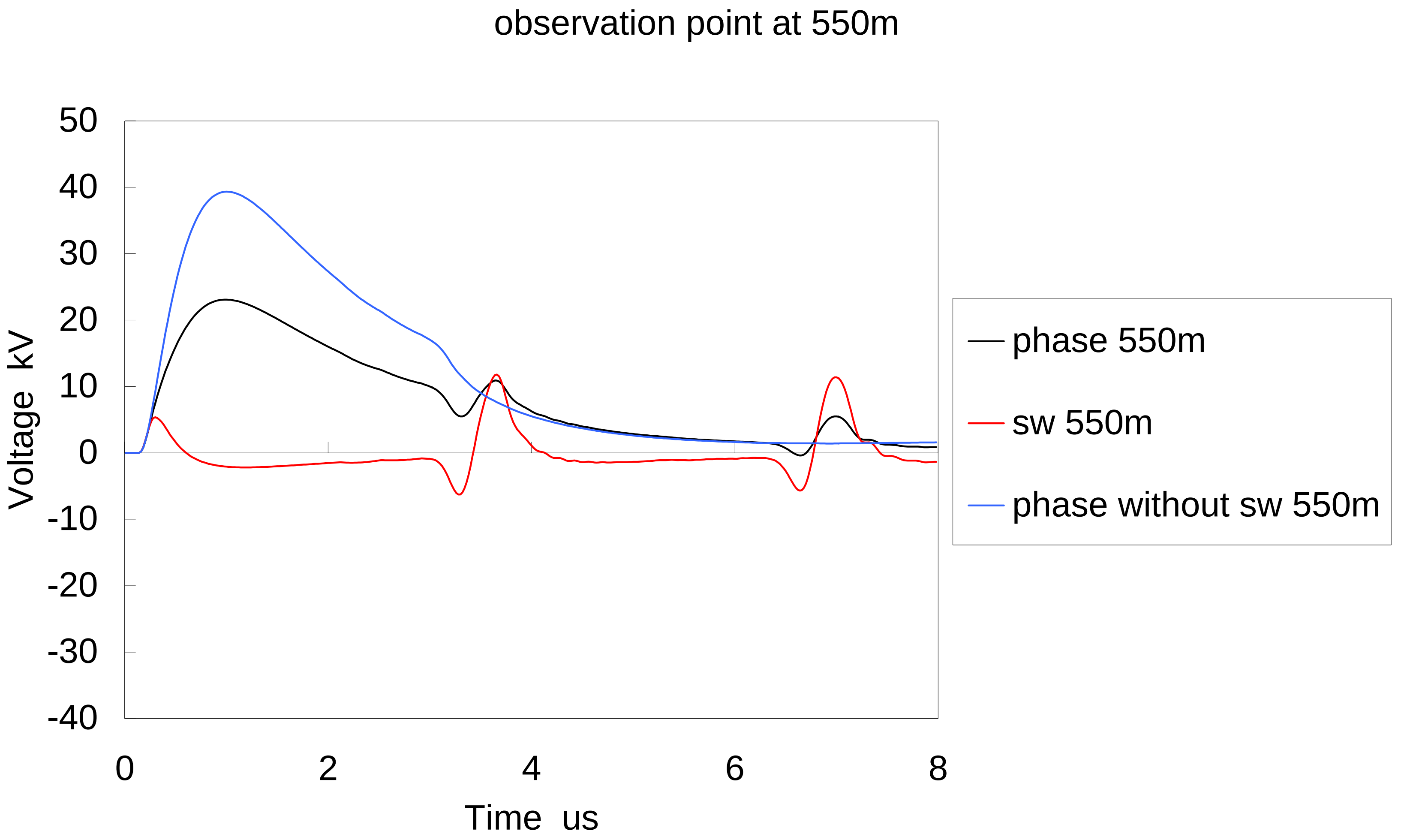
Sensitivity analysis *Cont.*

Effect of the shielding wire in a two-conductor line

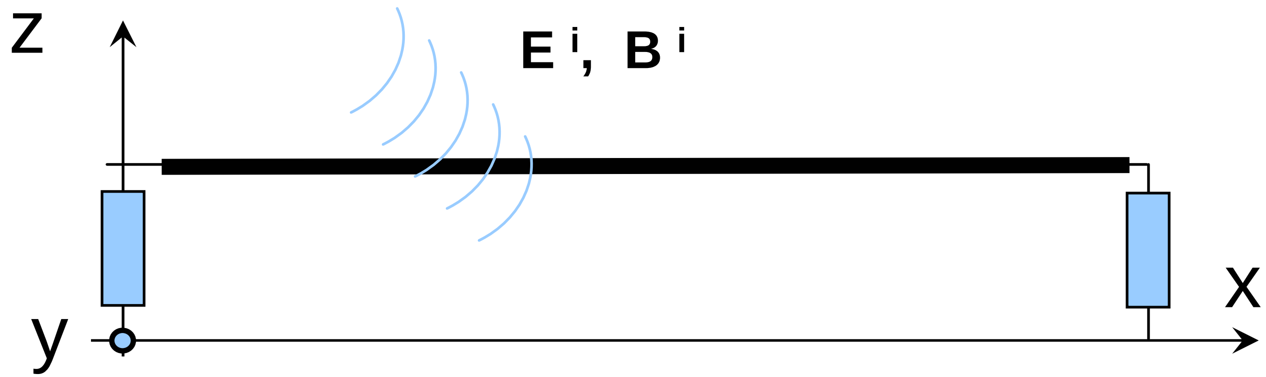


Sensitivity analysis *Cont.*

Effect of the shielding wire in a two-conductor line



On the influence of the em field component



$$\frac{\partial}{\partial t}\int_0^h B_y^i(x,z,t)\,dz = -E_x^i(x,h,t) + \frac{\partial}{\partial x}\int_0^h E_z^i(x,z,t)\,dz$$

Nucci and Rachidi, IEEE Trans. on EMC, Vol. 37, No. 4, November 1995.