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Lightning-Induced Voltages

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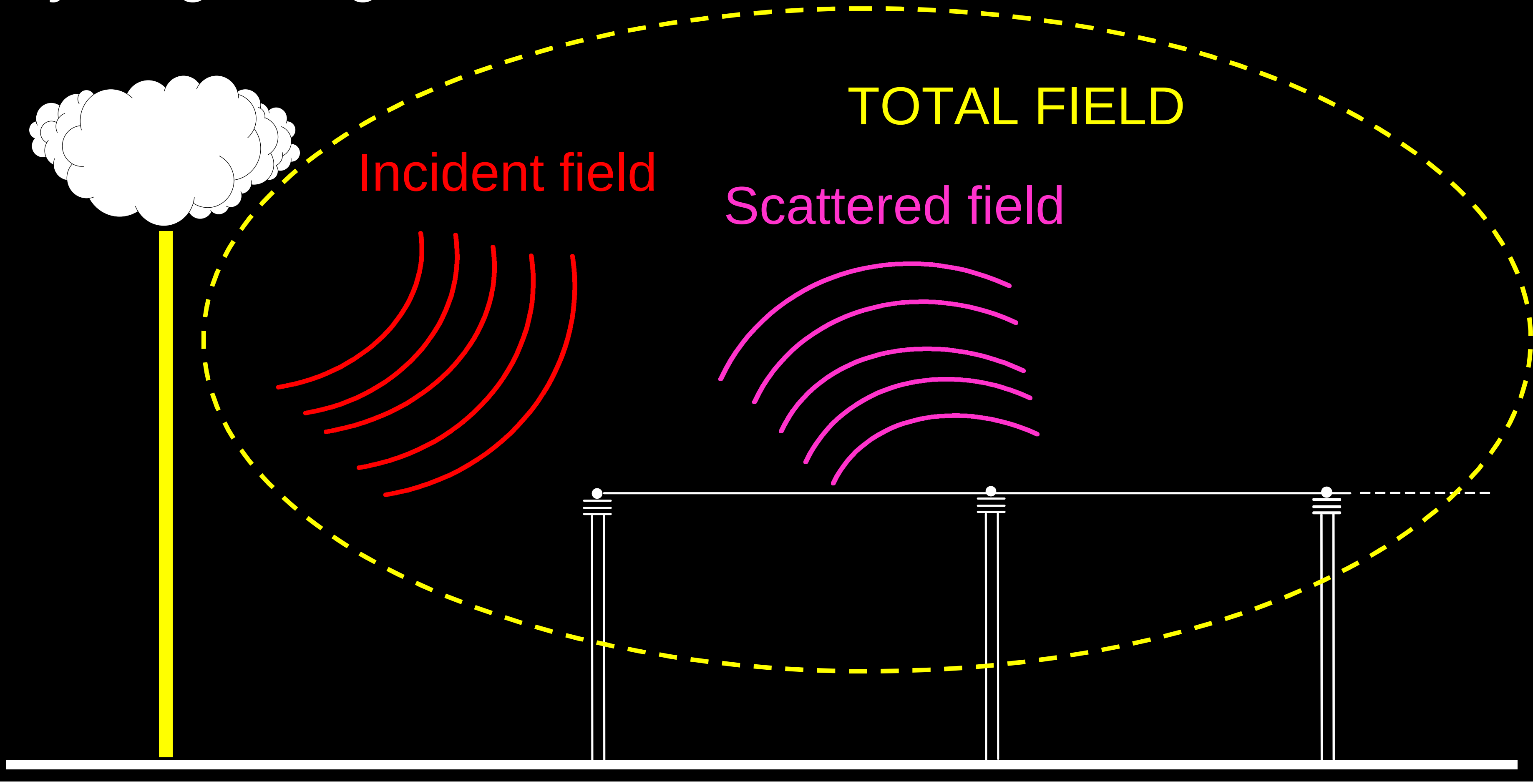
1. Aim of Presentation

To give some answers to the questions that are most commonly raised by engineers and scientific researchers dealing with the problem of protection against lightning-induced voltages.

2. What causes induced voltages ?

Electromagnetic coupling between the field radiated by a lightning stroke and the line conductors



2. What causes induced voltages ? *Cont.*

Essentially the return-stroke phase is responsible of the induced voltage

However, when lightning strikes the ground nearby the line at close distance from the line, also the preceding leader phase can results in a significant induced voltage

3. How to evaluate them?

Return-Stroke Current

i (0,t) → **RSC** → i (z,t)

Lightning ElectroMagnetic Pulse (appr. expr. for E horiz.)

i (z,t) → **LEMP** → E, B

ElectroMagnetic Coupling

E, B → **EMC** → V, I

3. How to evaluate them? *Cont.*

Return-stroke current models

A review of the various return-stroke models has been recently made by Rakov and Uman on IEEE EMC Transactions, Special Issue on Lightning, 1998 where they have discussed, among others, the following ‘engineering’ models

- Bruce-Golde (BG)
- Transmission Line (TL) *Uman, McLain, Krider*
- Traveling Current Source (TCS) *Heidler*
- Modified Transm. Line - Linear (MTLL) *Rakov and Dulzon*
- Modified Transm. Line - Exponential (MTLE) *Nucci et al.*
- Diendorfer-Uman (DU)

3. How to evaluate them? *Cont.*

Return-stroke current models

Experimental validation

Given a channel-base current ==>
the RSC model must reproduce the
corresponding Electromagnetic field

For **Natural lightning**:

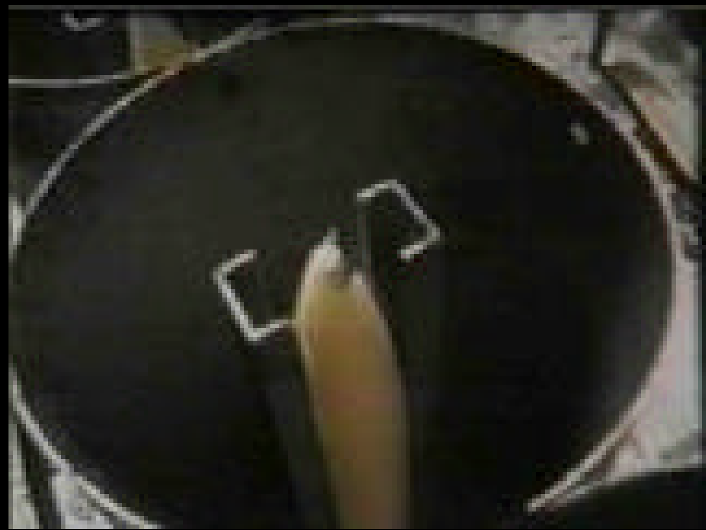
PROBLEM: practically no existing data sets of simultaneously measured current and fields

Data of this kind have been collected using the **Triggered lightning** technique

3. How to evaluate them? *Cont.*

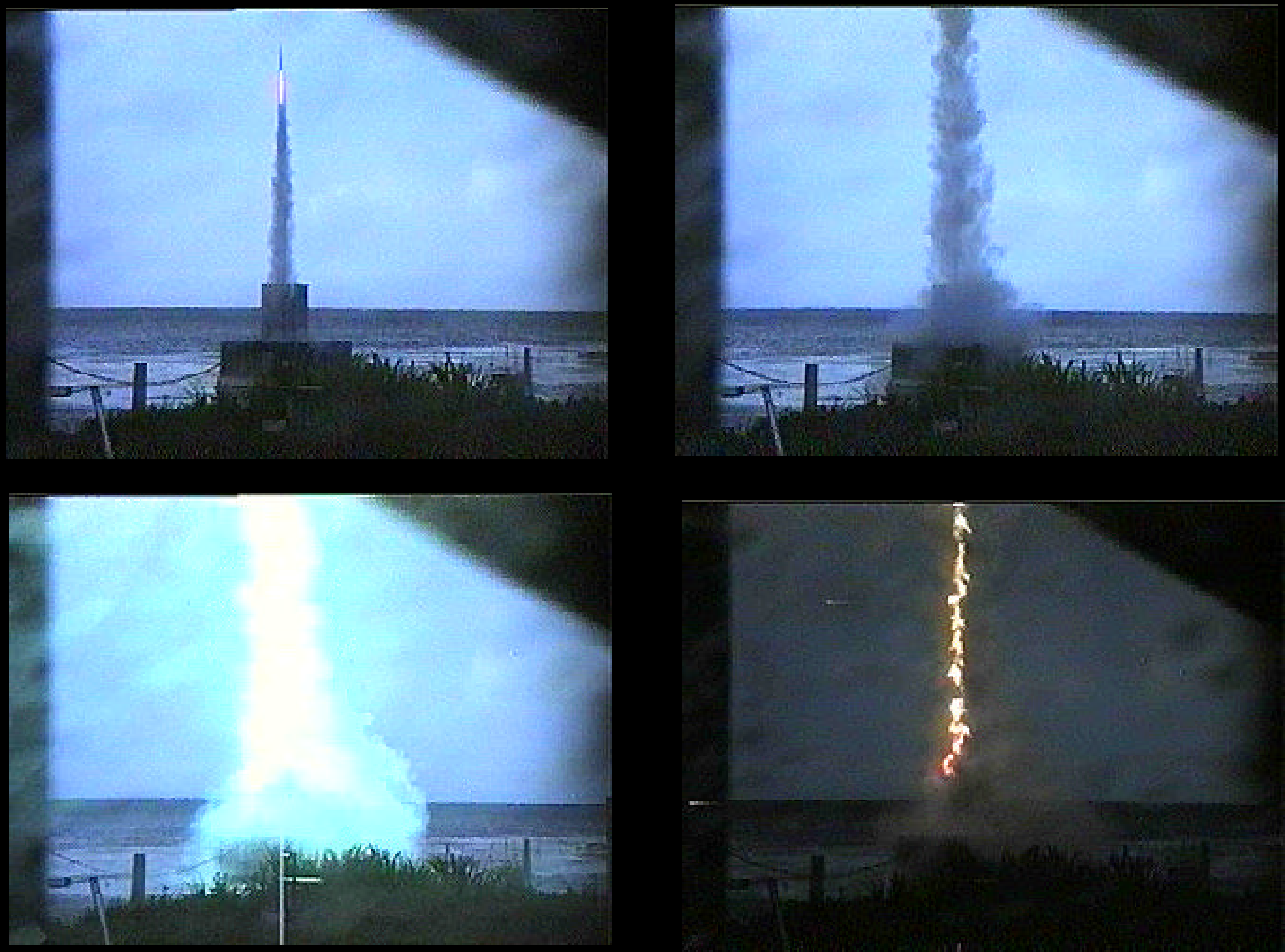
Return-stroke current models

- TRIGGERED LIGHTNING: Lightning is artificially initiated firing small rockets trailing grounded wires upward a few hundred meters under thunderstorms.



3. How to evaluate them? *Cont.*

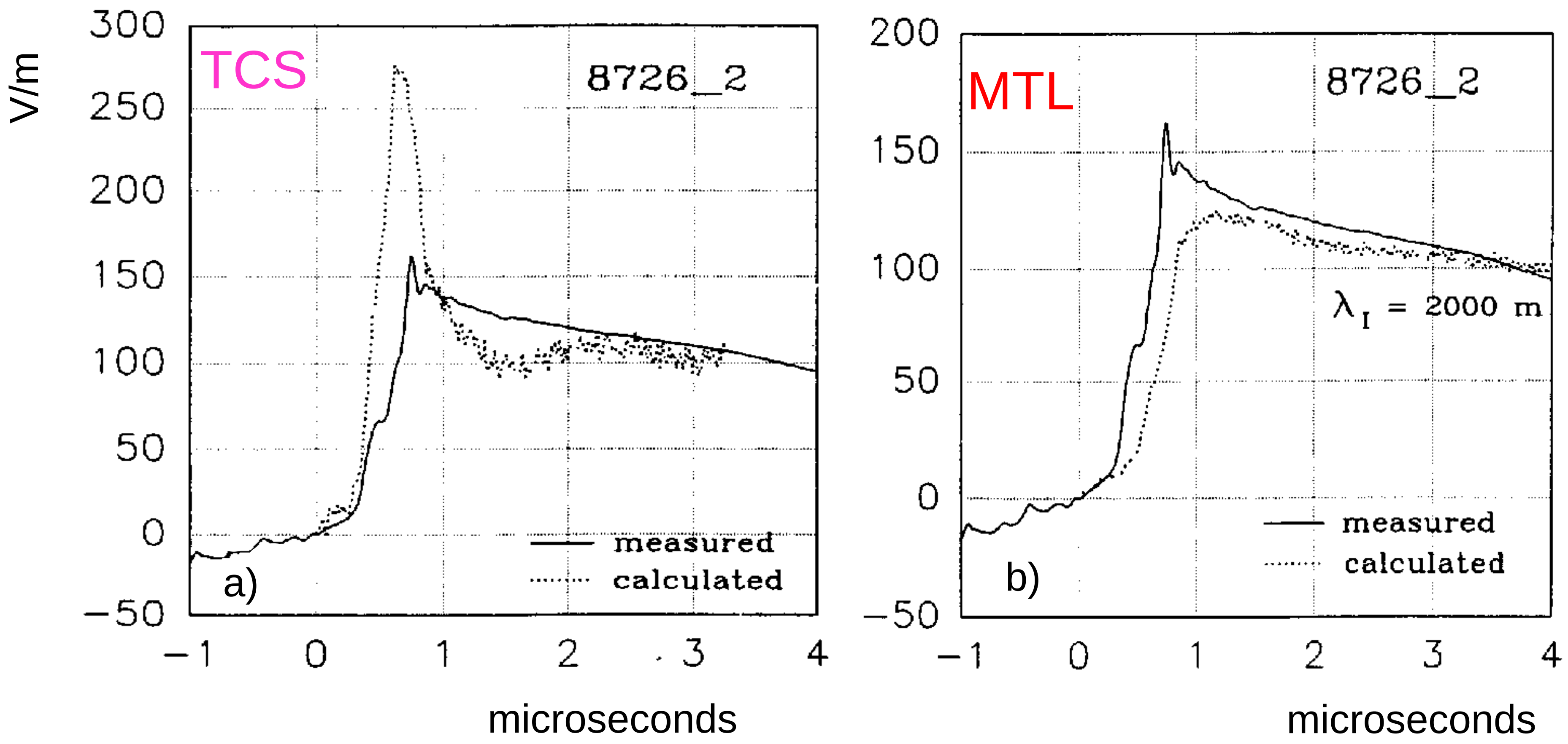
Return-stroke current models



Triggered lightning: A sequence of frames

3. How to evaluate them? *Cont.*

Return-stroke current models



Validation by means of triggered lightning

3. How to evaluate them? *Cont.*

Electromagnetic coupling

Basically, three coupling models have been used:

- *Rusck* [1958]
- *Chowdhuri* [1969]
- *Agrawal et al.* [1980]

Of the three models only the Agrawal one is ‘rigorous’ for a general external field excitation

However, for a lightning channel perpendicular to the ground plane ===> Rusck = Agrawal

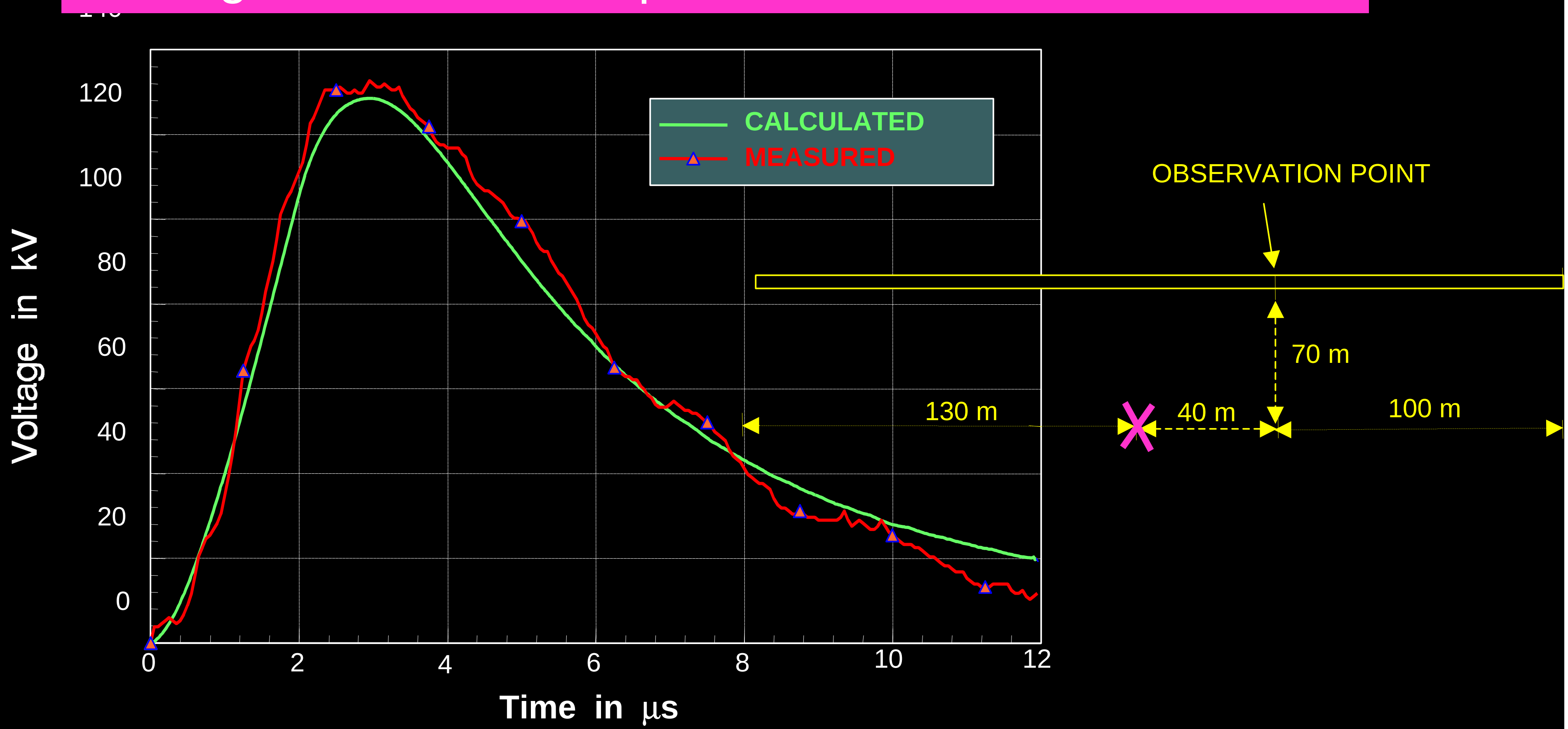
3. How to evaluate them? *Cont.*

The Agrawal model: Experimental validation

Reduced scale model at the University Of São Paulo - Brazil

3. How to evaluate them? *Cont.*

The Agrawal model: Experimental validation

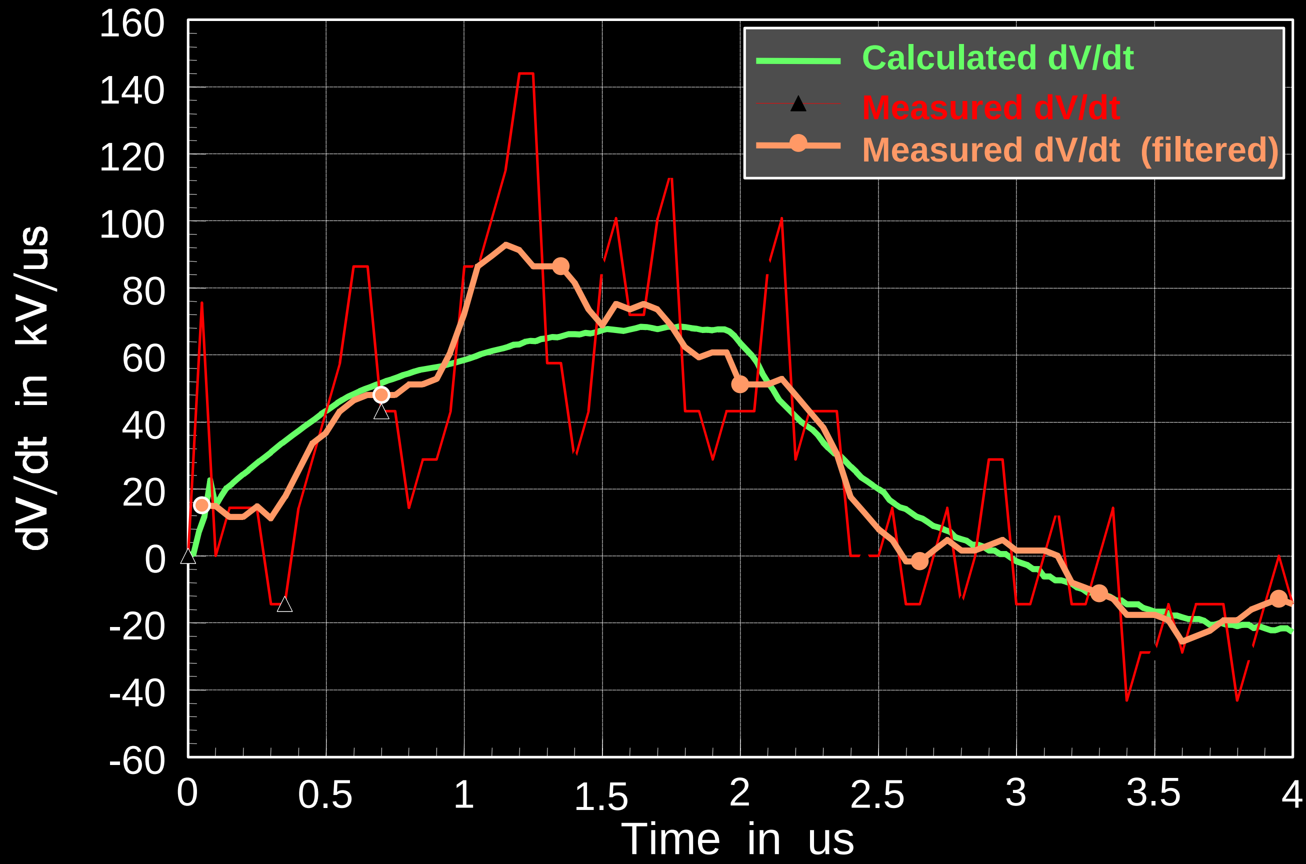


Using reduced-scale line model

Experimental data: by A. Piantini, Univ. Of São Paulo

3. How to evaluate them? *Cont.*

The Agrawal model: Experimental validation

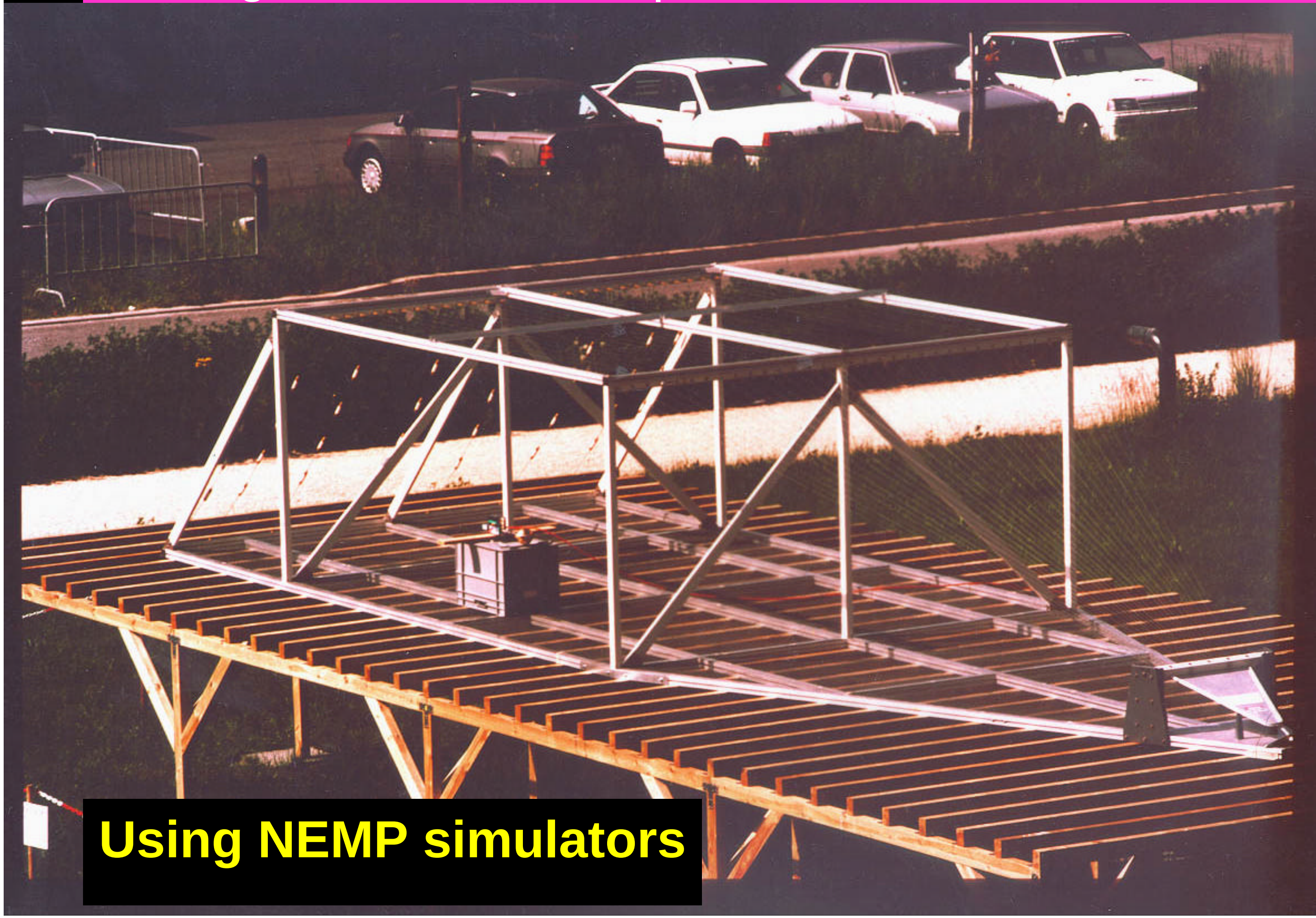


Using reduced-scale line model

Experimental data: by A. Piantini, Univ. Of São Paulo

3. How to evaluate them? *Cont.*

The Agrawal model: Experimental validation



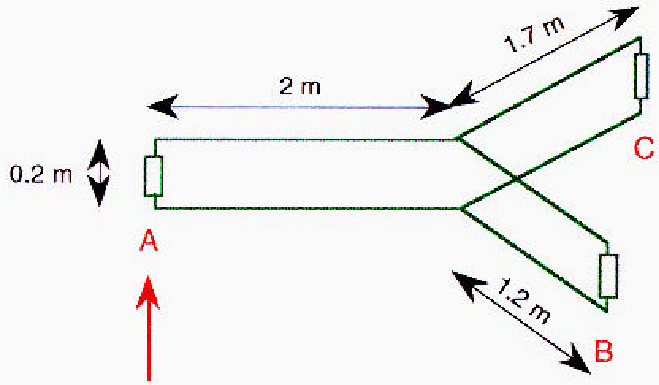
Using NEMP simulators

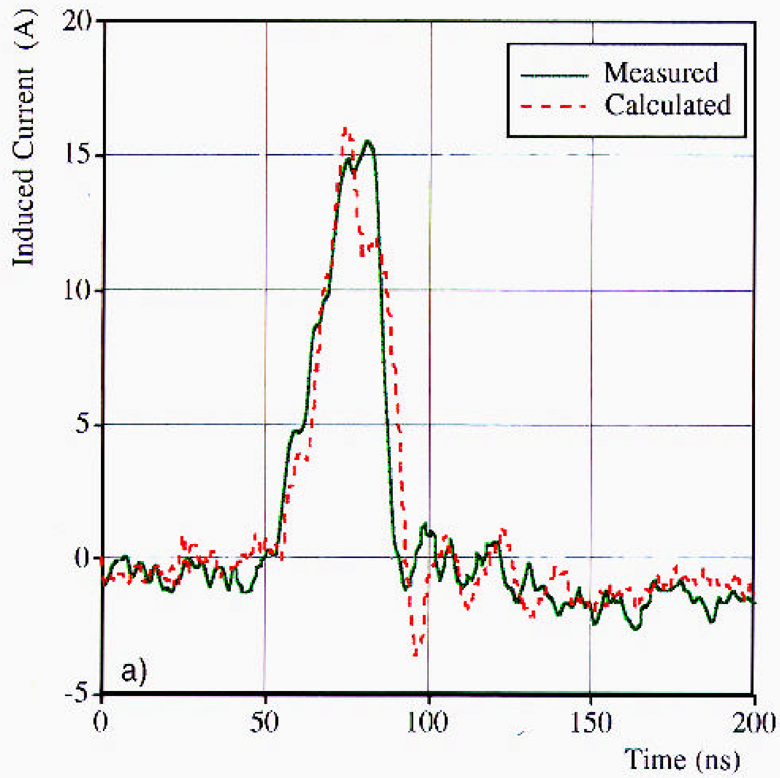
3. How to evaluate them? *Cont.*

The Agrawal model: Experimental validation

Comparison with Experimental Results
(Line matched at A, B, C)

Using NEMP simulators





3. How to evaluate them? *Cont.*

Which component of the LEMP does affect most the induced voltages?

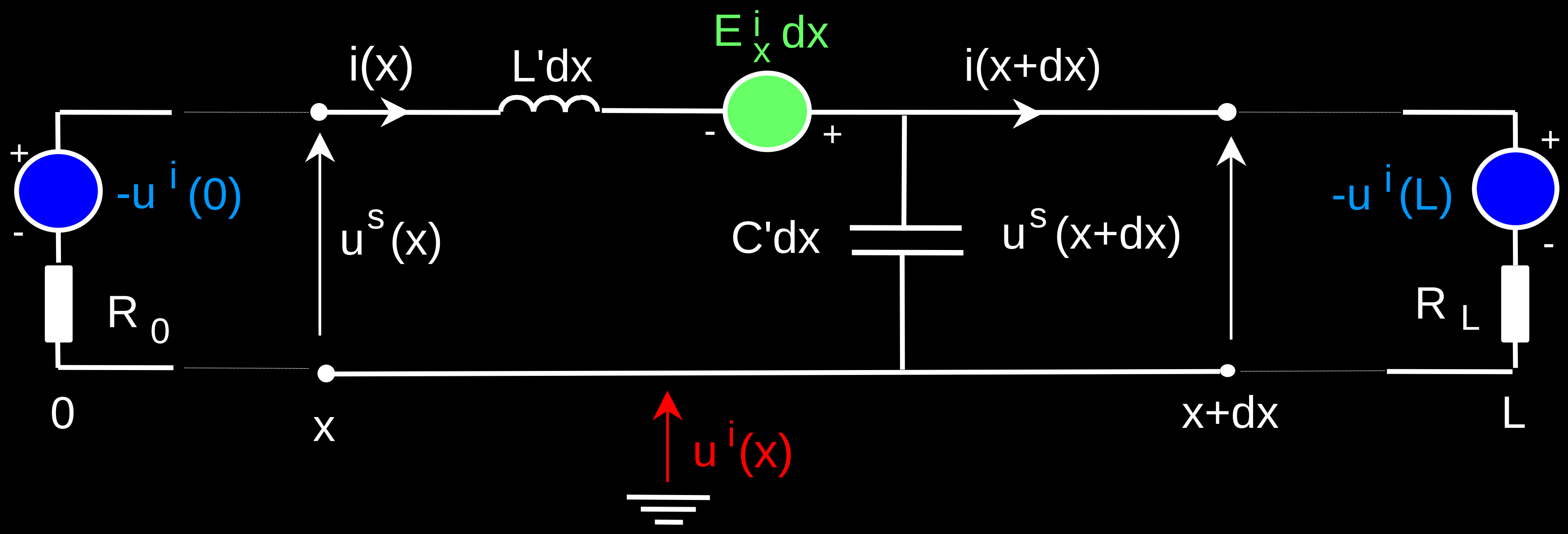
Vertical E component?

Horizontal E component?

Other components?

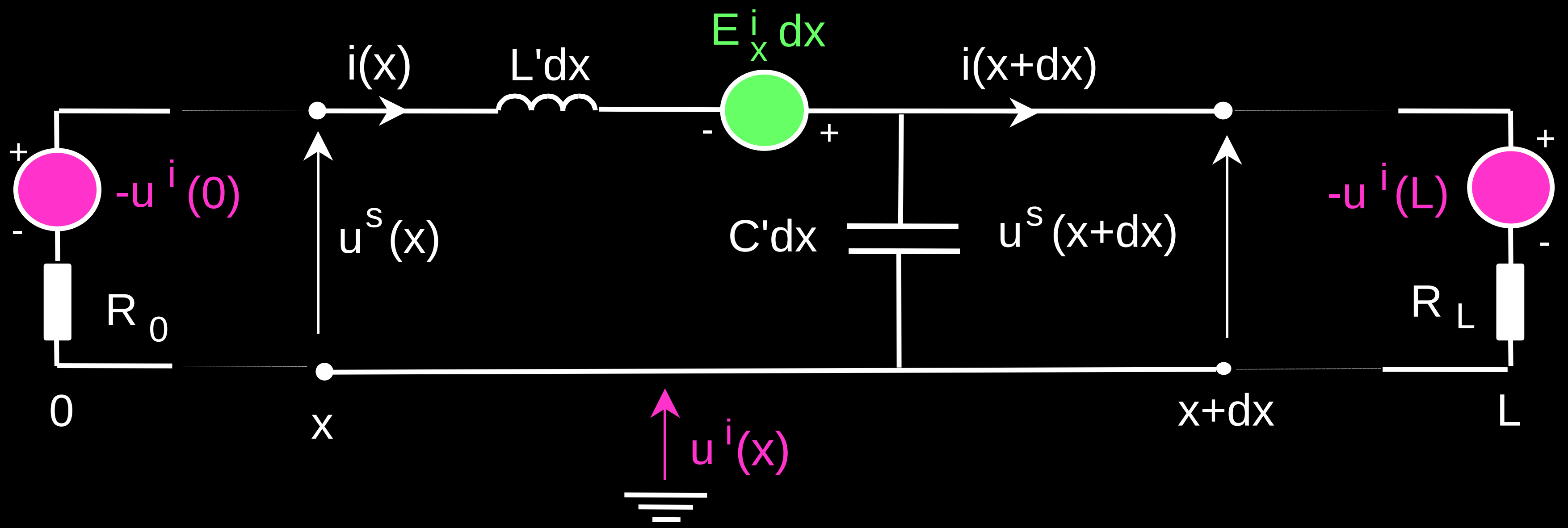
Let us assume, for simplicity, a lossless line

3. How to evaluate them? *Cont.*



Agrawal et al.

3. How to evaluate them? *Cont.*



Agrawal et al.

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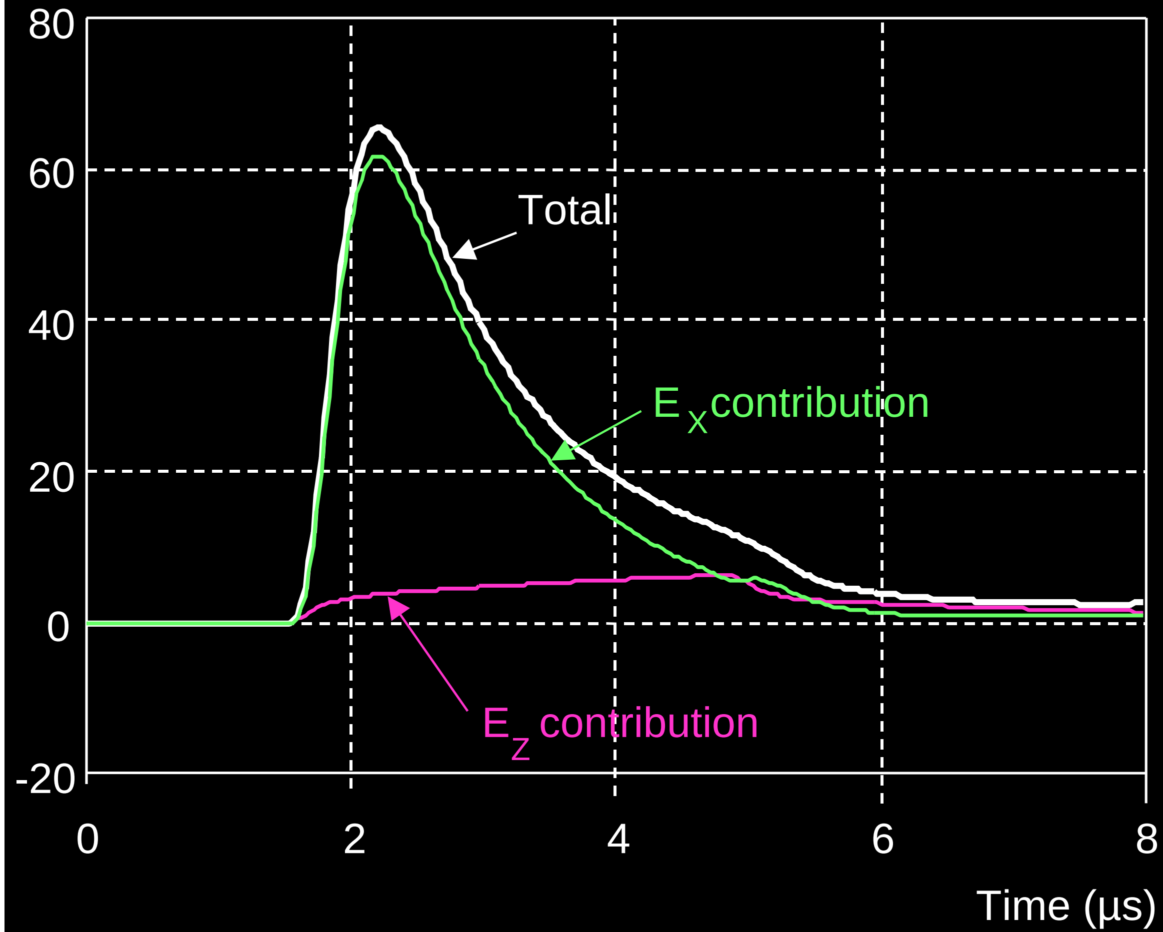
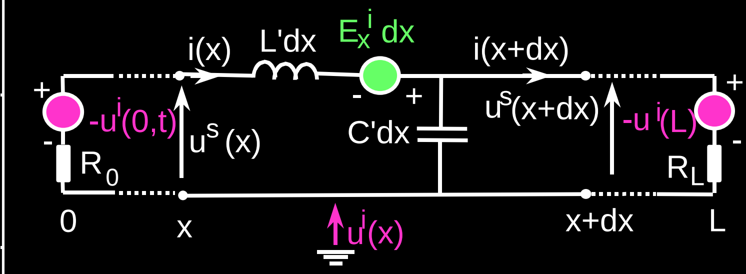
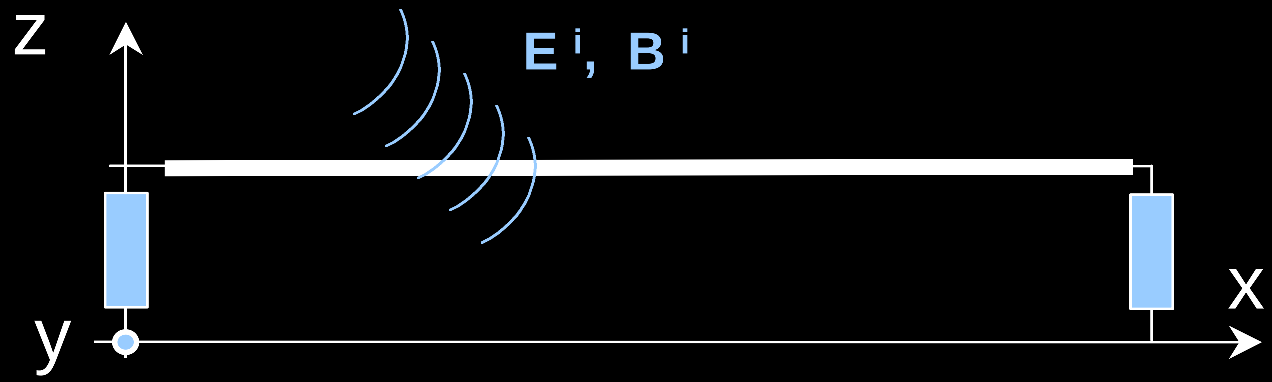




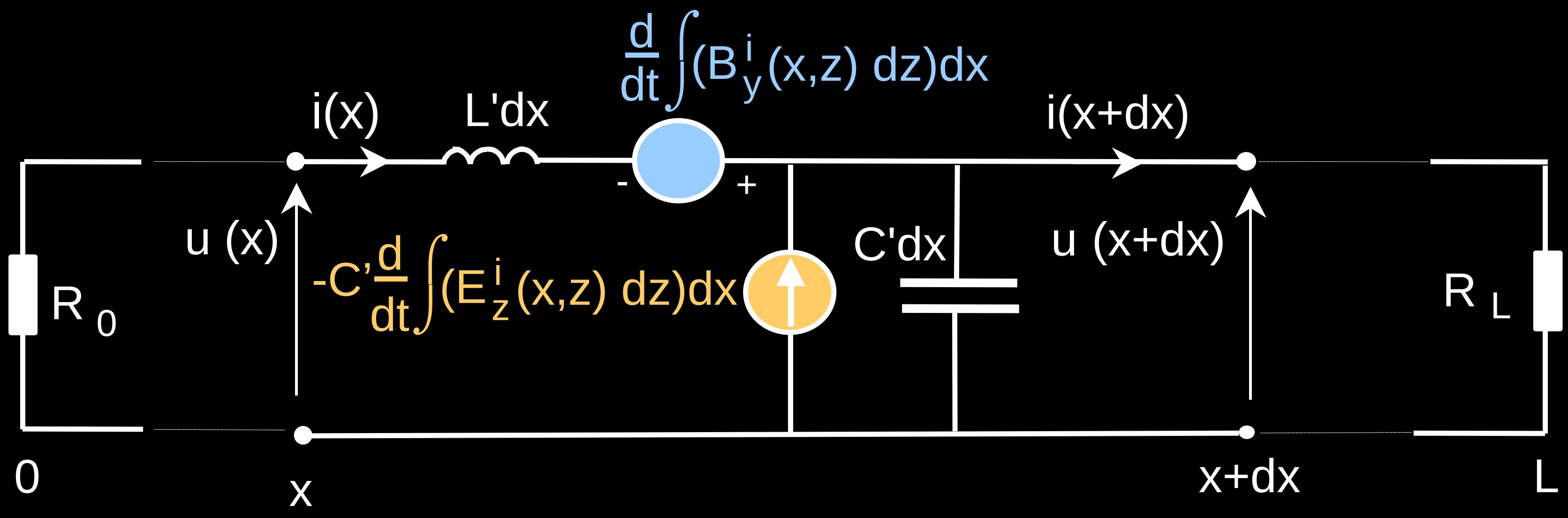
3. How to evaluate them? *Cont.*



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

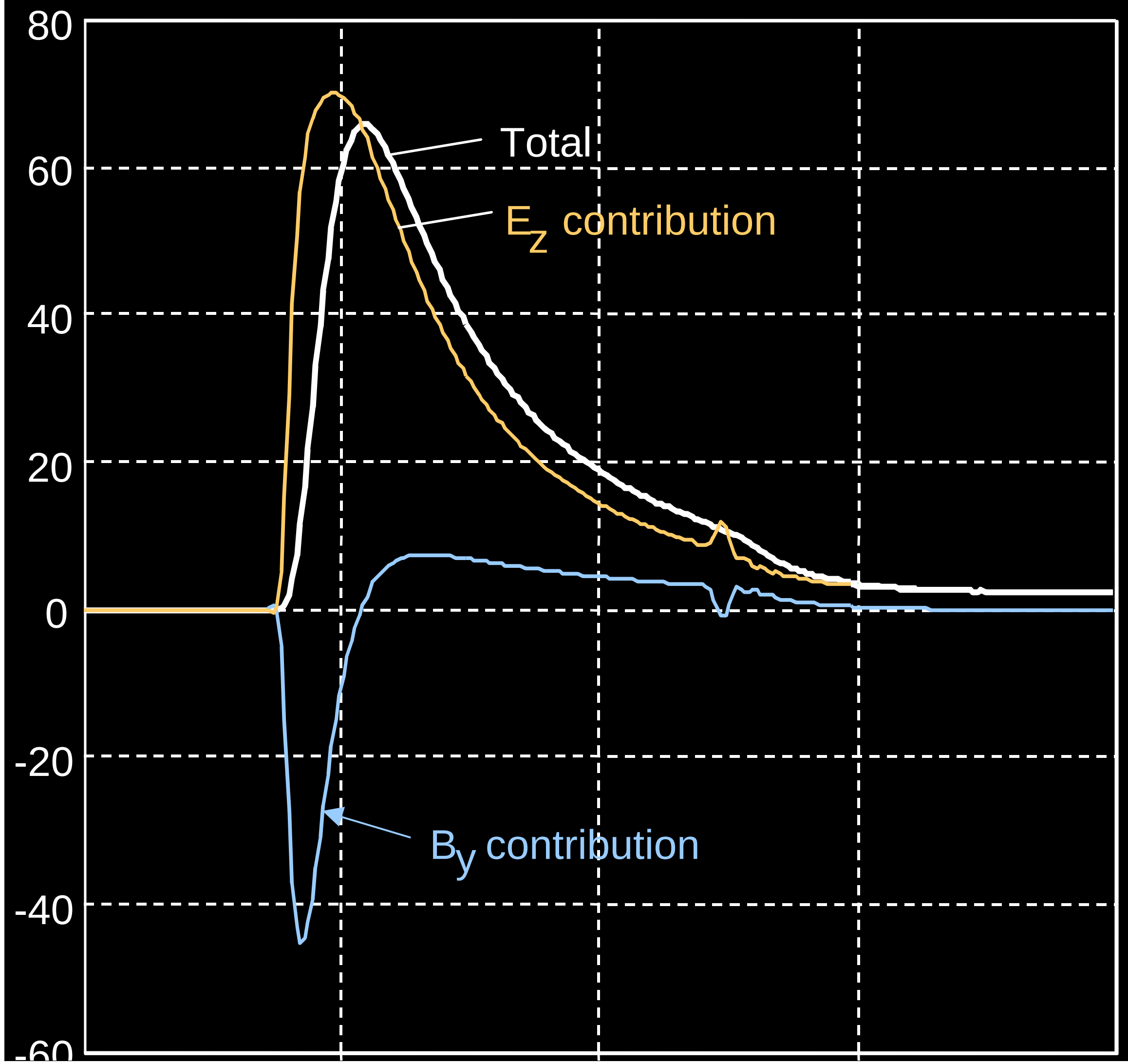
Nucci and Rachidi, IEEE Trans. on EMC,
Vol. 37, No. 4, November 1995.

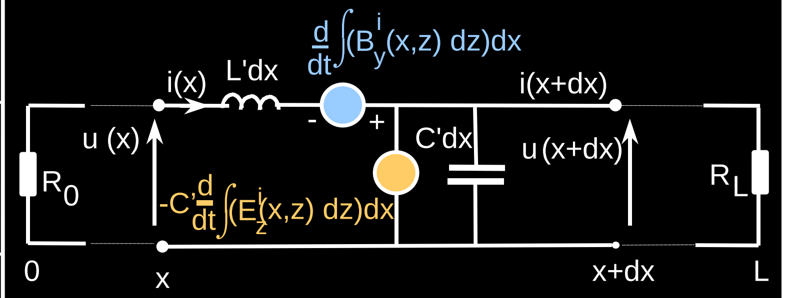
3. How to evaluate them? *Cont.*



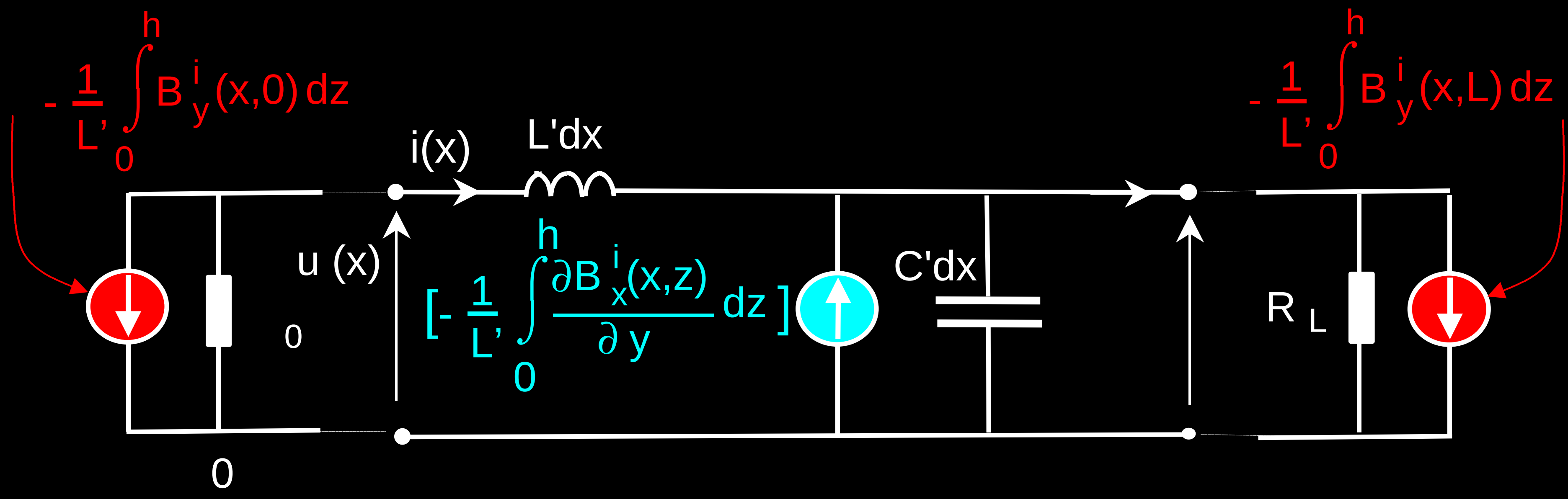
Taylor et al.

3. How to evaluate them? *Cont.*



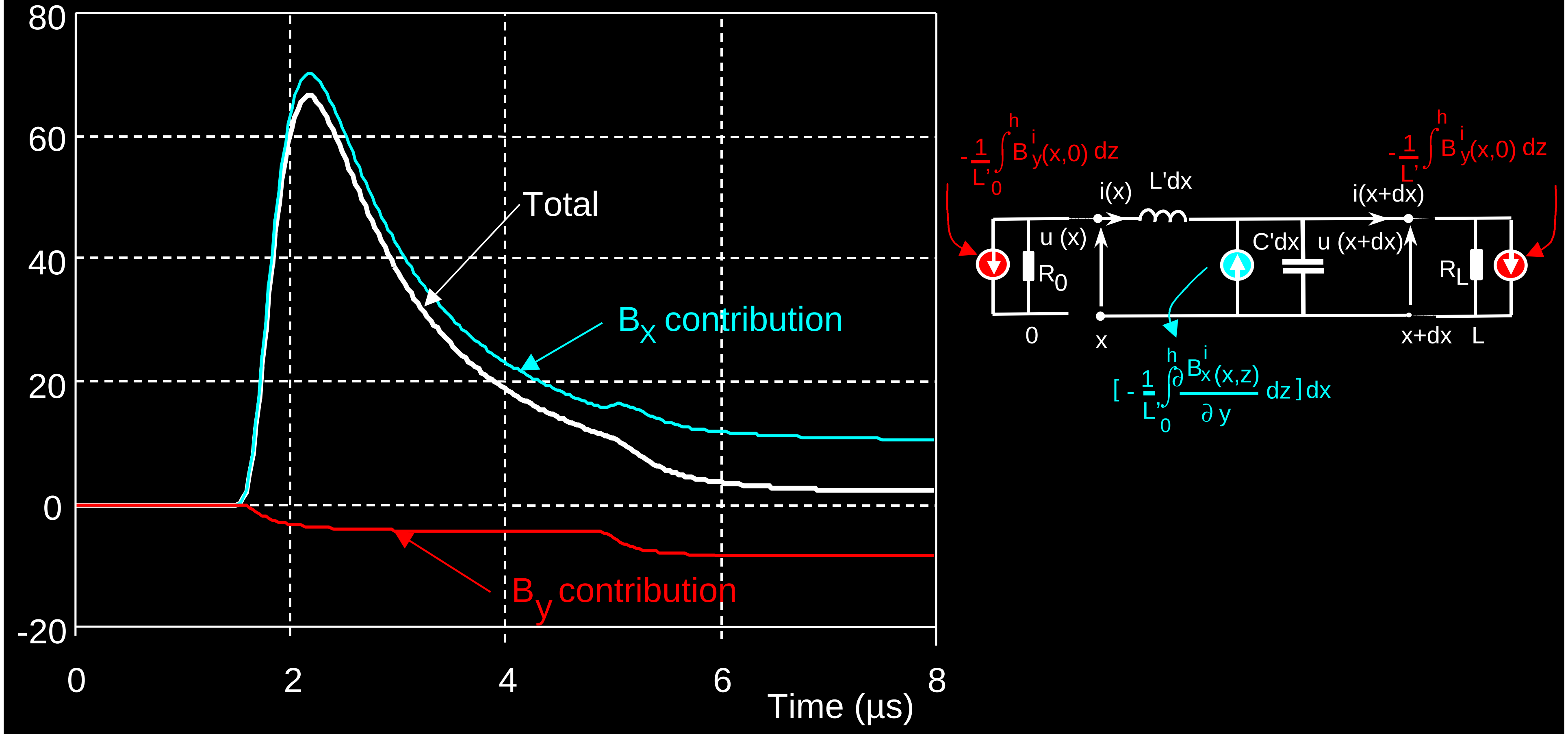


3. How to evaluate them? *Cont.*



Rachidi

3. How to evaluate them? *Cont*



3. ? *Cont.*

The contribution of a given electromagnetic field component in the coupling mechanism depends strongly on the used model.

Thus, when speaking about the contribution of a given electromagnetic field component to the induced voltages, one has to specify the coupling

.

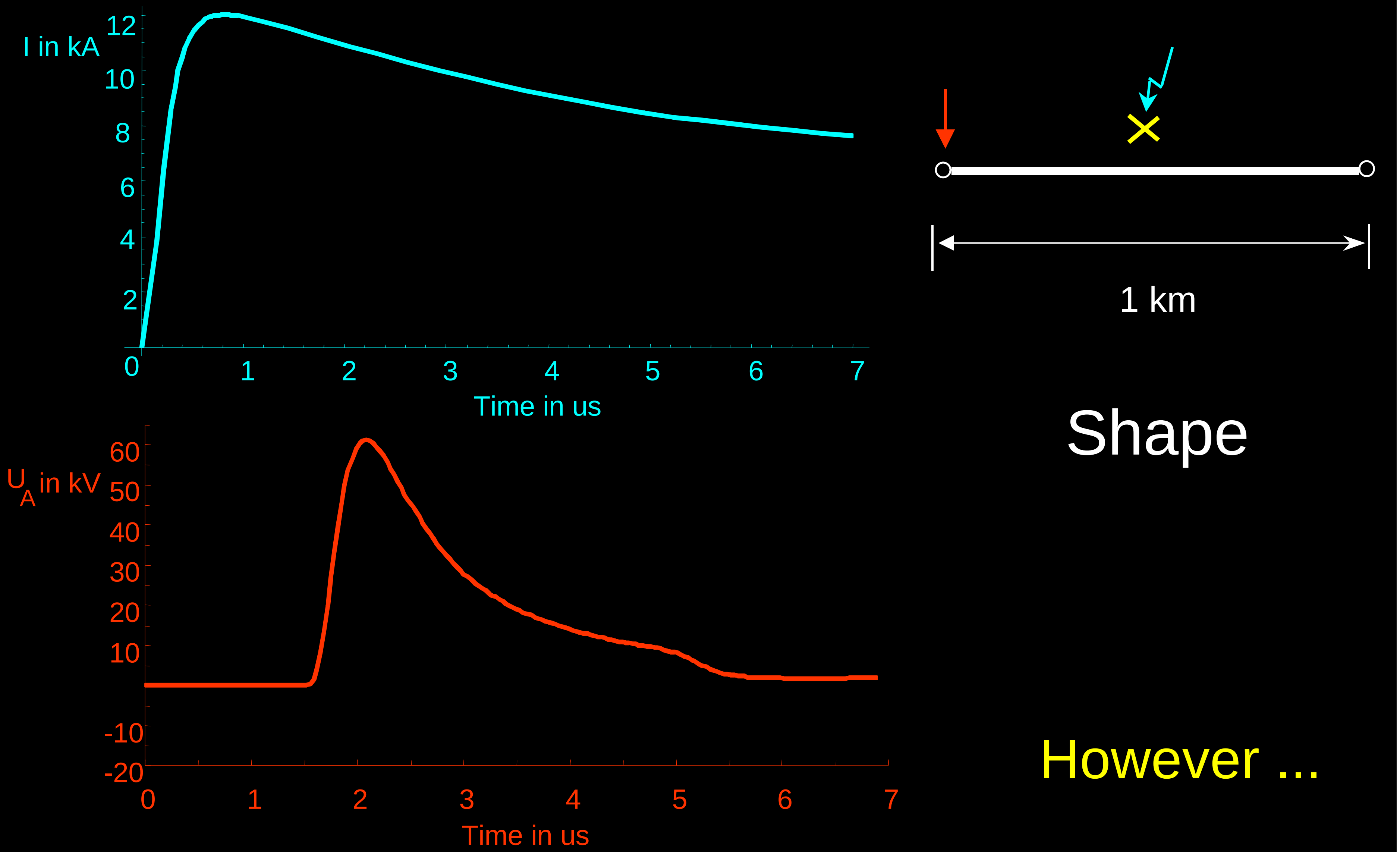
4. are for lightning induced

Induced voltage magnitude and shape significantly depend on

- lightning return stroke parameters (channel-base current parameters, return stroke velocity),
- distance and relative position with respect to the transmission line,
- line configuration and terminations.

Induced overvoltages can reach magnitudes up to few hundreds of kV and can therefore cause line flashover.

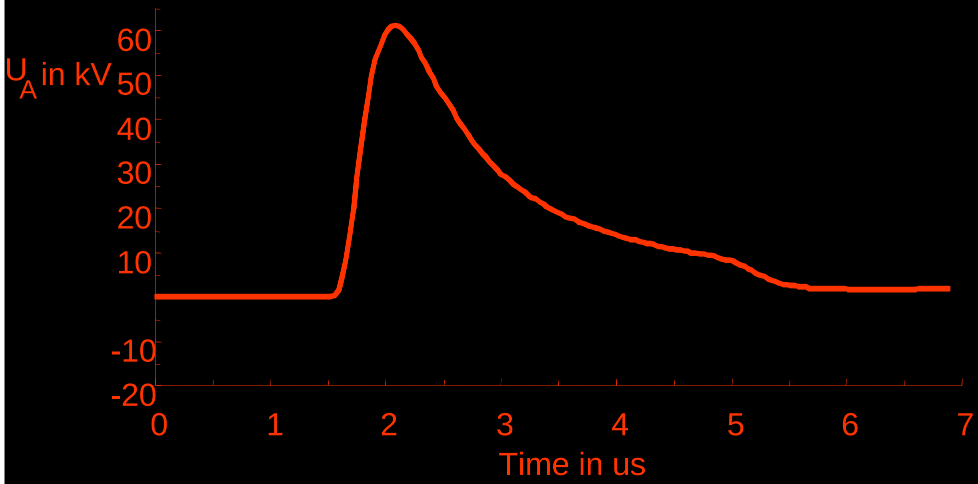
4. What magnitudes and shape are typical for lightning-induced overvoltages ? *Cont.*

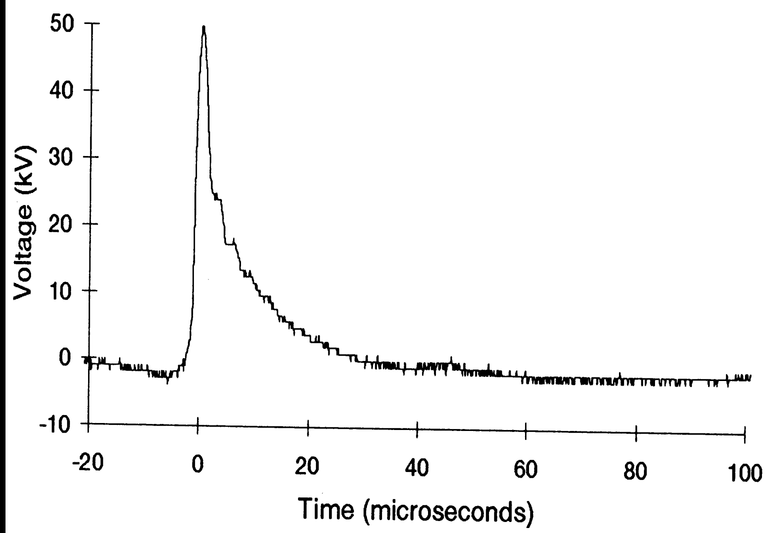


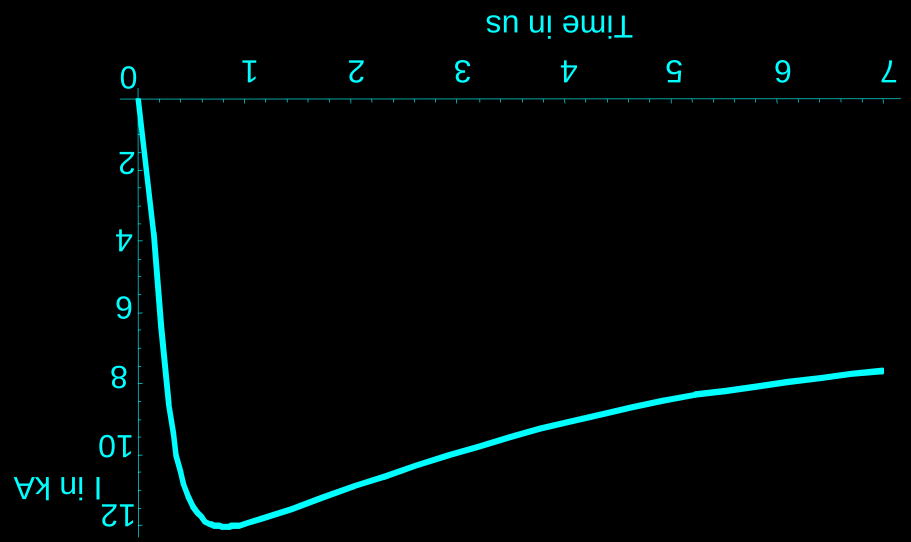
Shape

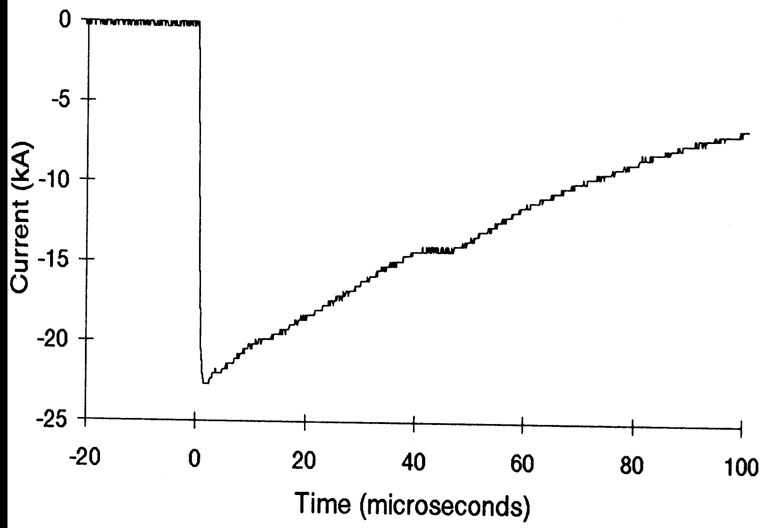
However ...

4. What magnitudes and shape are typical for lightning-induced overvoltages ? *Cont.*









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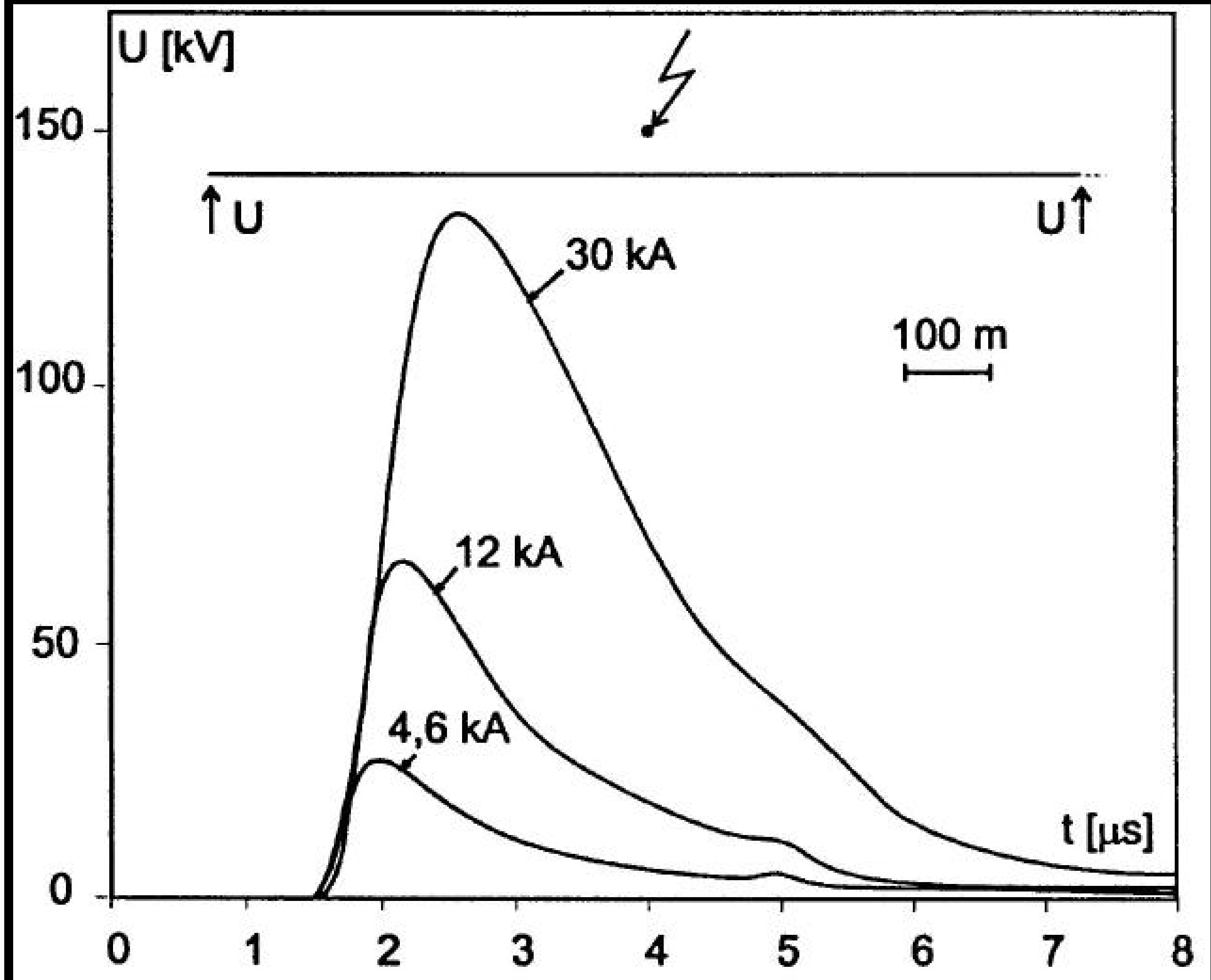
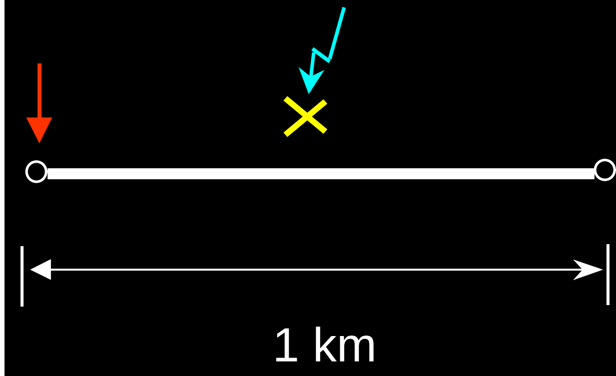




Magnitude

However ...

4. What magnitudes and shape are typical for lightning-induced overvoltages ? *Cont.*

For perfectly conducting grounds and for an infinitely long wire

$$U_{max} = Z_0 \frac{I_{max} h}{d}$$

where $Z_0 = 1/4\pi \sqrt{\mu_0 / \varepsilon_o} = 30\Omega$

the simplified Rusck formula allows for a satisfactory estimation

HOWEVER …

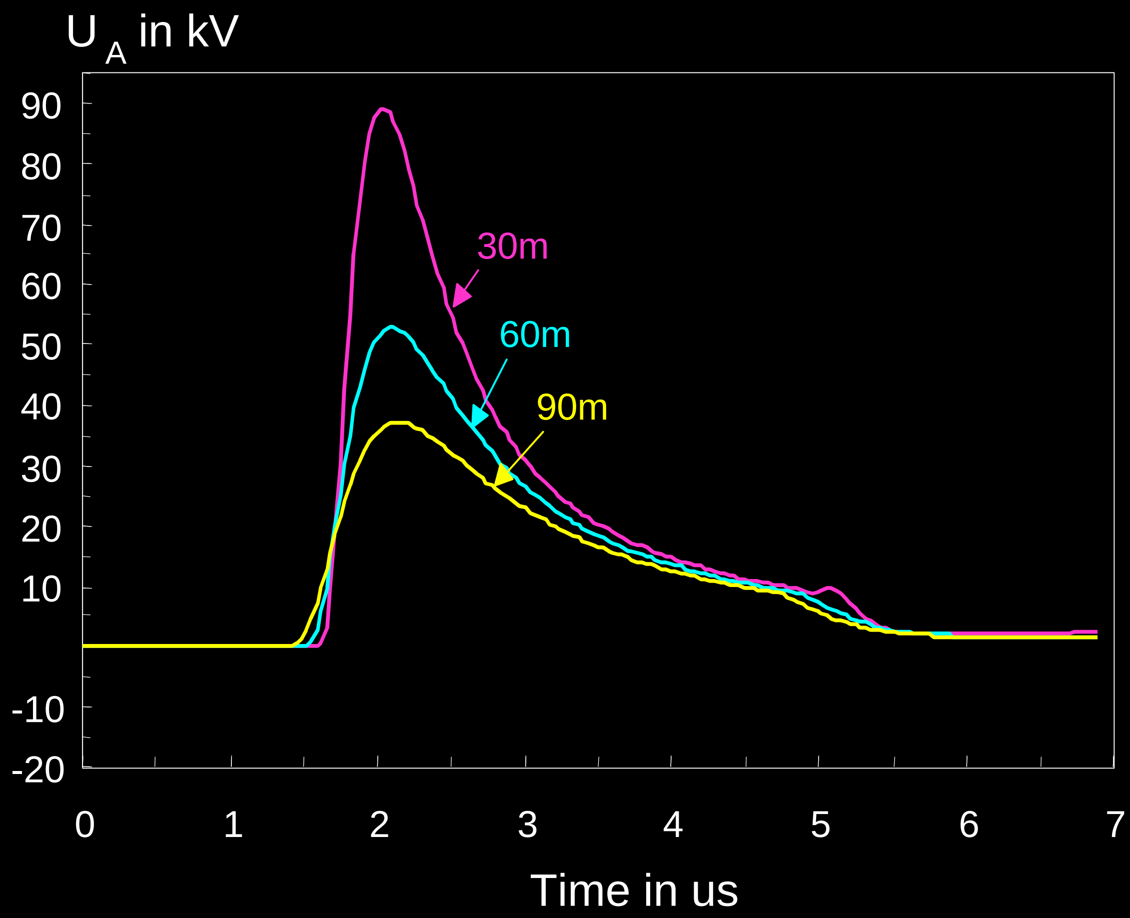
5. How far away can lightning strokes be that cause an induced voltage flashover ?

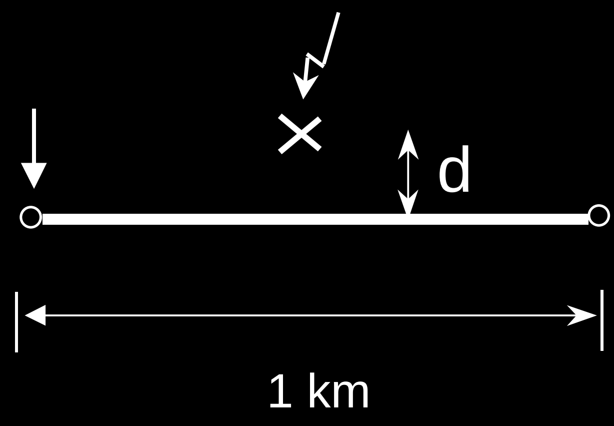
Generally within 200 m

However it depends on many parameters
(=> computer code)

Lightning strokes occurring beyond a few hundred meters from the line can cause a line flashover for poor conducting soils (De La Rosa et al., IEEE Trans. on PWDR, 1988)

6. How does the induced voltage drop as a function of distance from the line ?

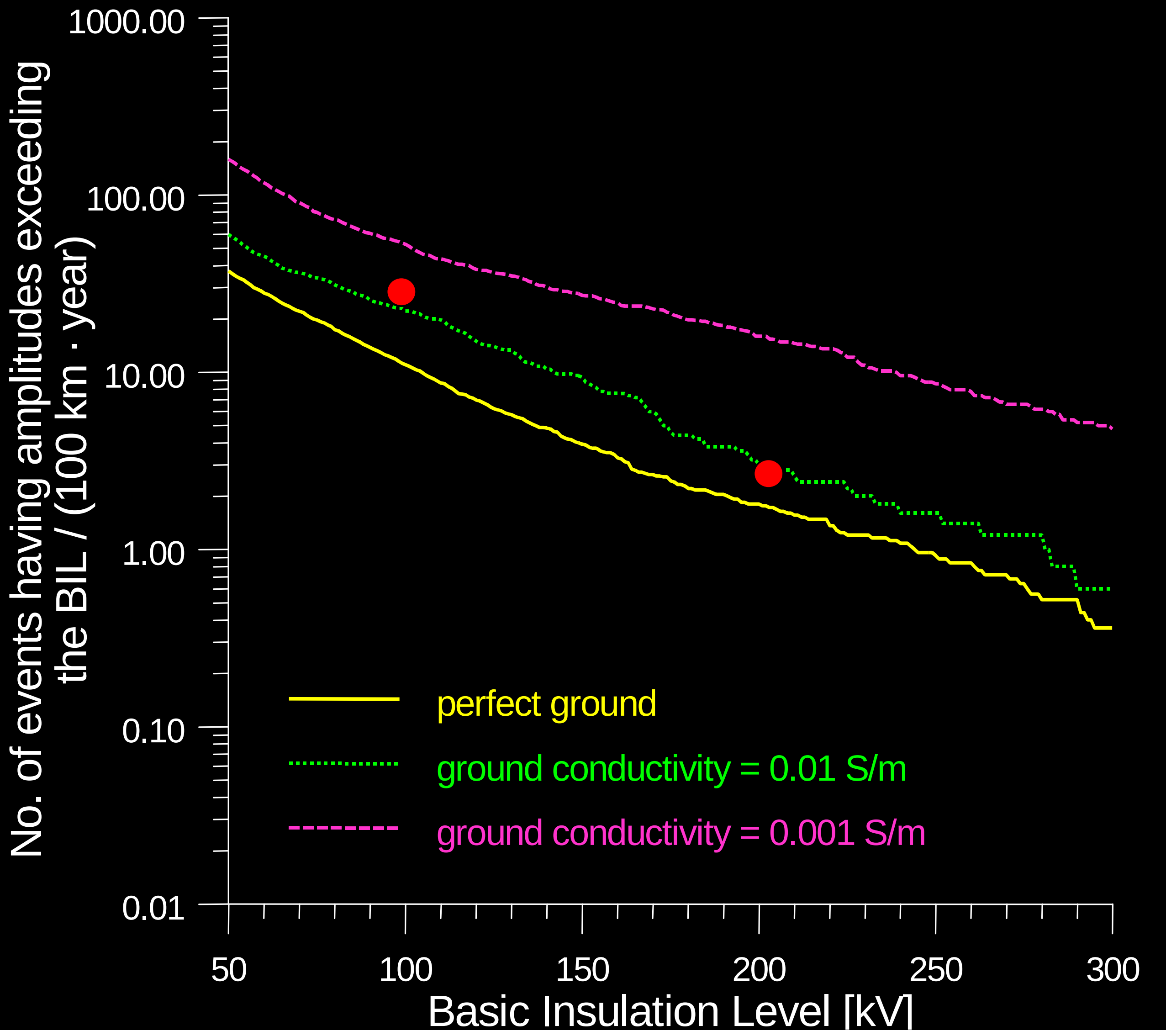




Perfectly conducting ground and stroke location equidistant to the line termination => nearly proportionally to 1/d

HOWEVER ...

7. What BIL is needed to prevent induced flashovers ?



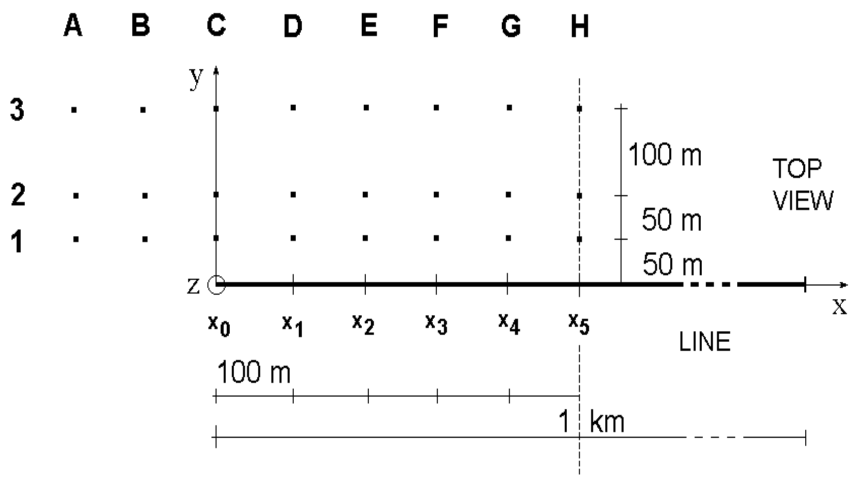
8. What arrester spacing is needed to prevent flashover?

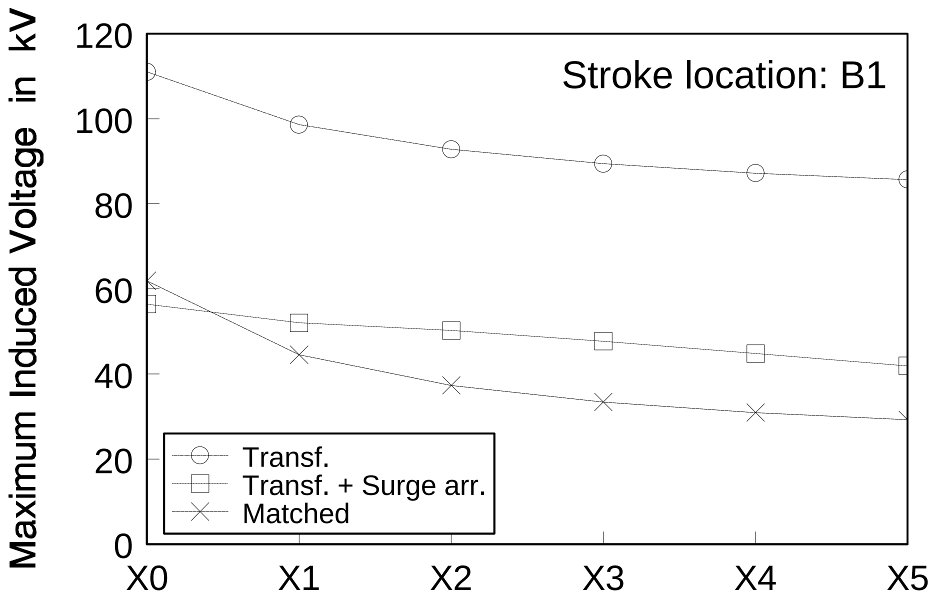
In order to prevent direct-stroke flashover, arrester spacings of 300-400 m is generally recommended.

For the case of induced flashovers, a given configuration of line arresters can result in different performances depending on the location of lightning strike [29].

Further studies are needed in this respect.

8. What arrester spacing is needed to prevent flashover?





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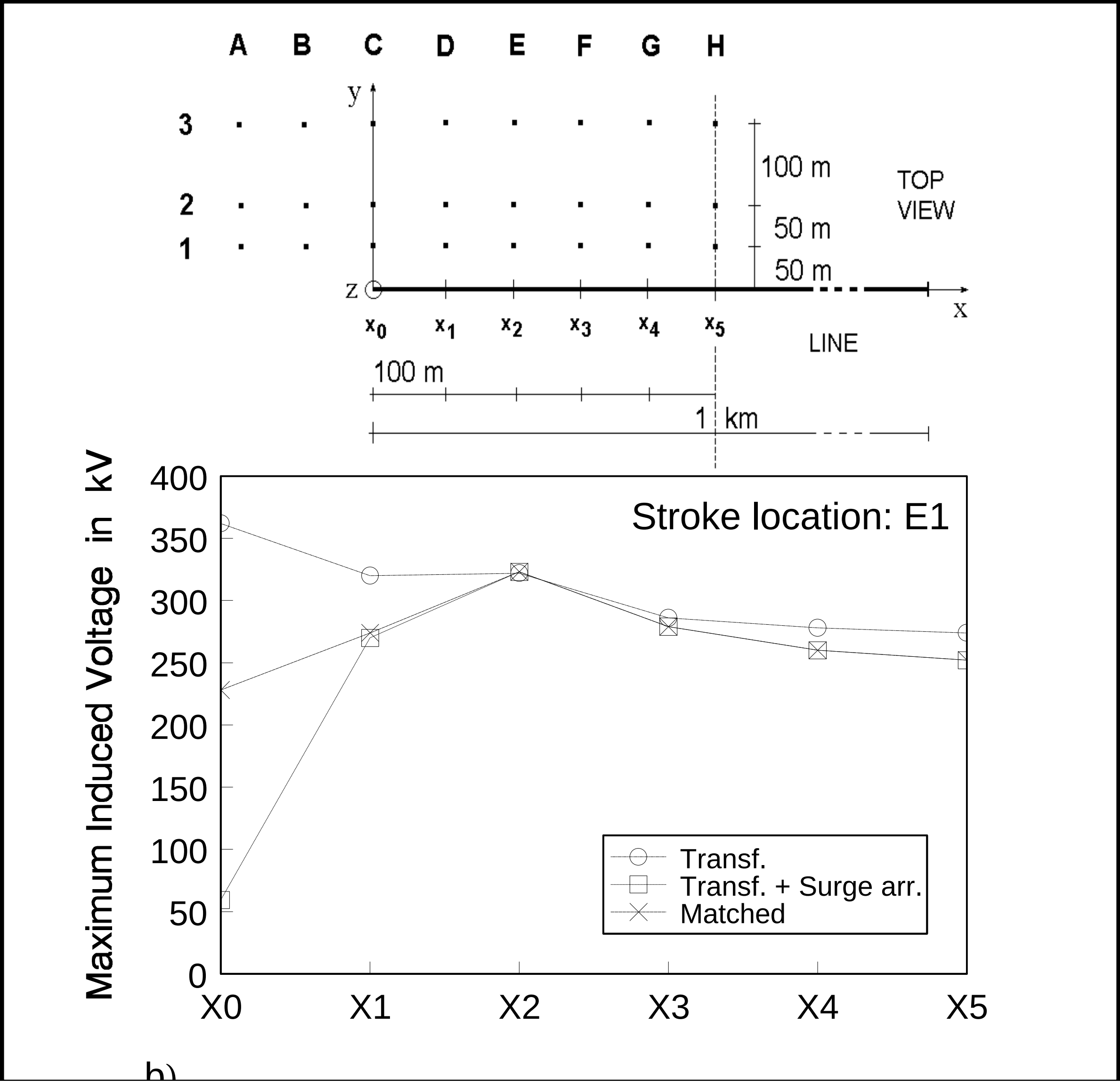

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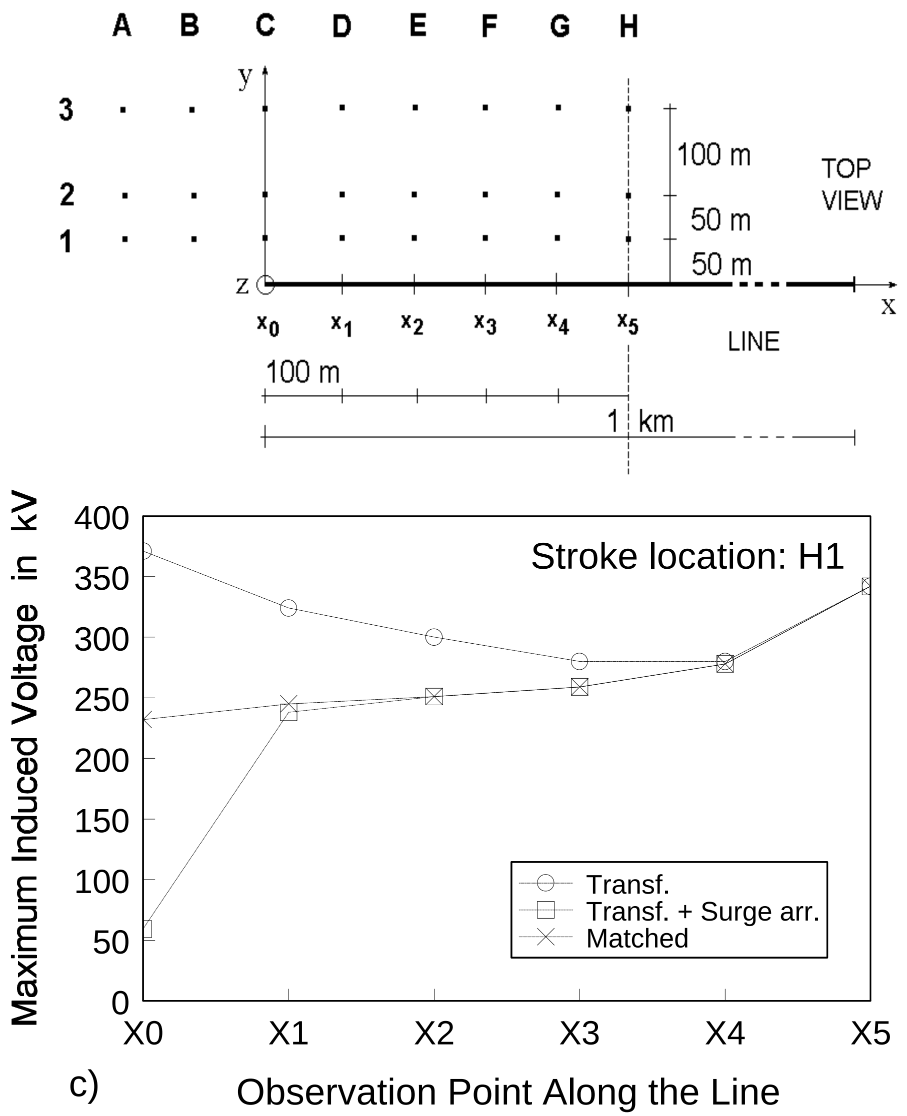
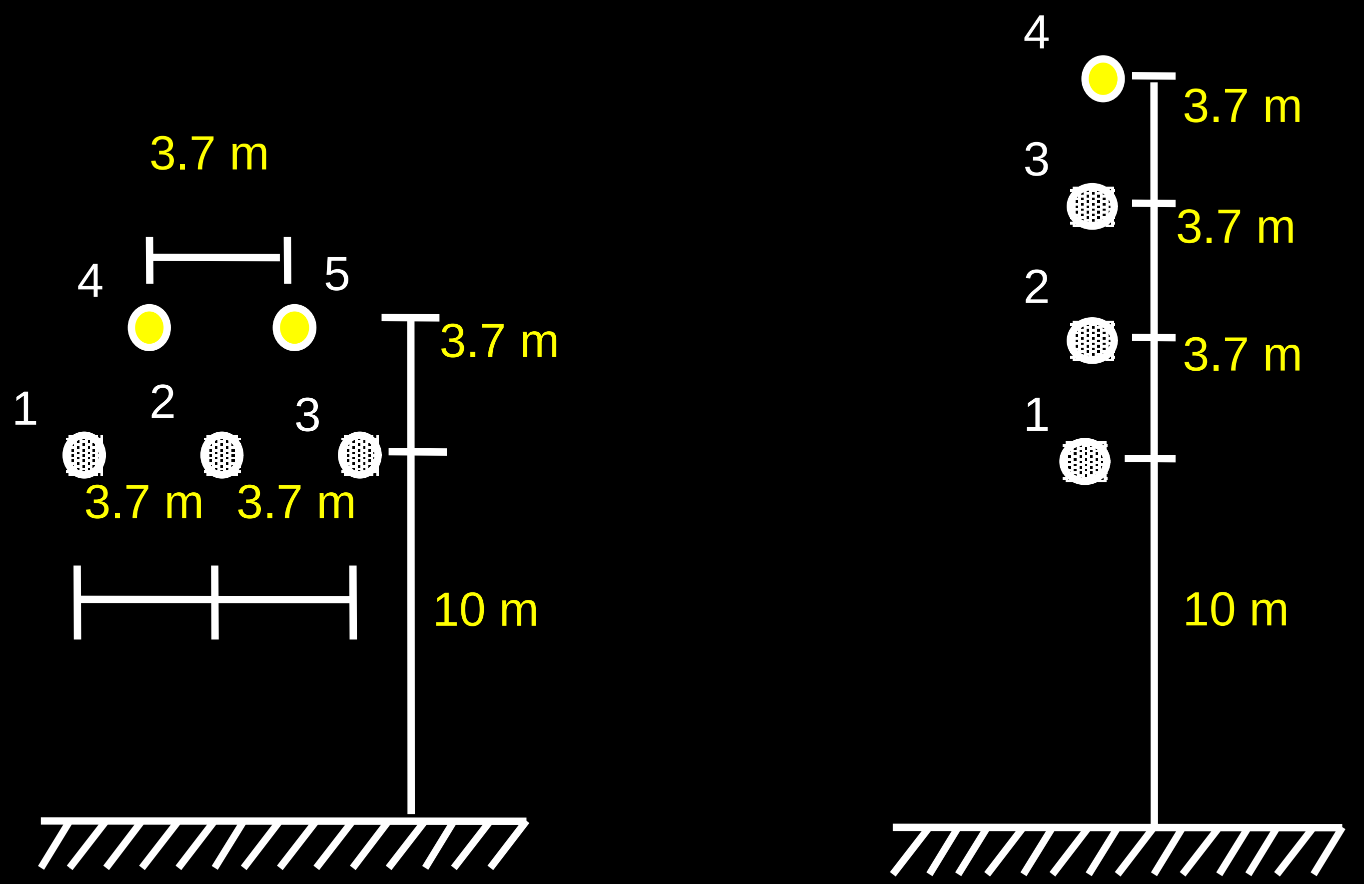


9. Will a shield wire help ?



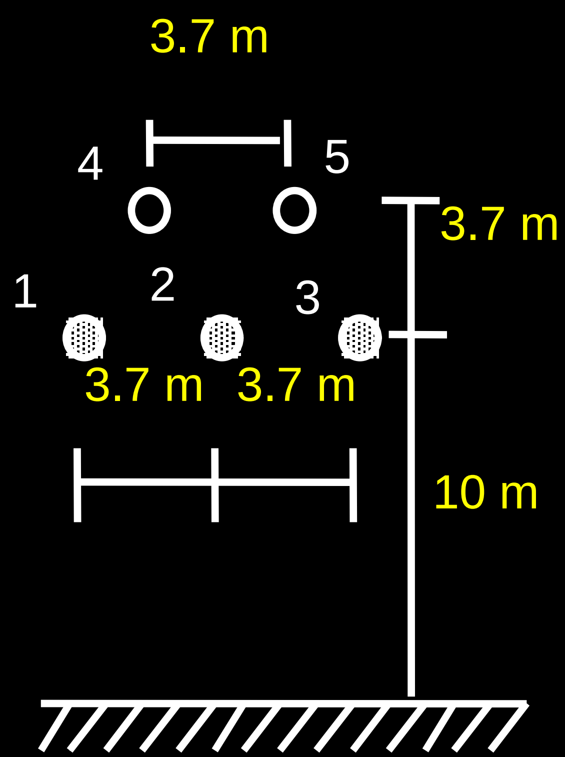
9. Will a shield wire help ? *Cont.*

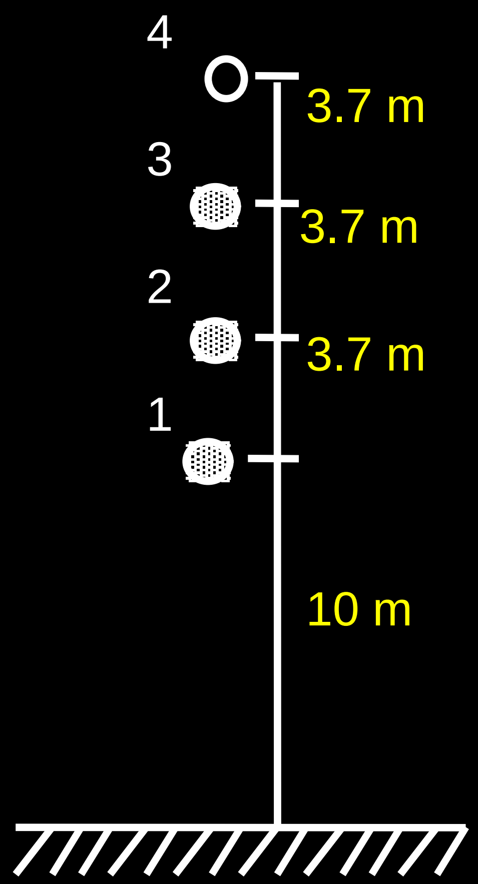
Shield wires help in reducing the magnitude of induced voltages by a factor of about 20 to 40 %.

wire	Protective Ratio	Vertical Config.	Horizontal Config.
1	PR_1	0.81	0.67
2	PR_2	0.78	0.60
3	PR_3	0.72	0.67

This implies about the same reduction of the fault frequency.

10. Is horizontal or vertical construction best ?





10. Is horizontal or vertical construction best ? *Cont.*

Ratio between peak values of the induced voltages on a line conductor V_i and those corresponding to a single-conductor line of the same height $V(h_i)$.

Voltage Ratio	Vertical Configuration	Horizontal Configuration
$V_1/V(h_1)$	0.75	0.85
$V_2/V(h_2)$	0.79	0.81
$V_3/V(h_3)$	0.89	0.85

10. Is horizontal or vertical construction best ? *Cont.*

The induced voltage magnitude for typical distribution lines is virtually proportional to the line height.

As a consequence, an important factor determining the magnitude of lightning-induced voltage is the line height above ground, rather than the type of construction.

In general, a construction allowing a shorter height for the conductors is epected to experience lower induced overvoltages.

11. What effect does pole grounding and ground resistivity have ?

Influence of pole grounding

Pole grounding affects the performance of the ground wire in reducing the induced overvoltages.

In general, lower the pole ground impedance, better the performance of the ground wire.

11. **What effect does pole grounding and ground resistivity have ?** *Cont.*

Influence of ground resistivity

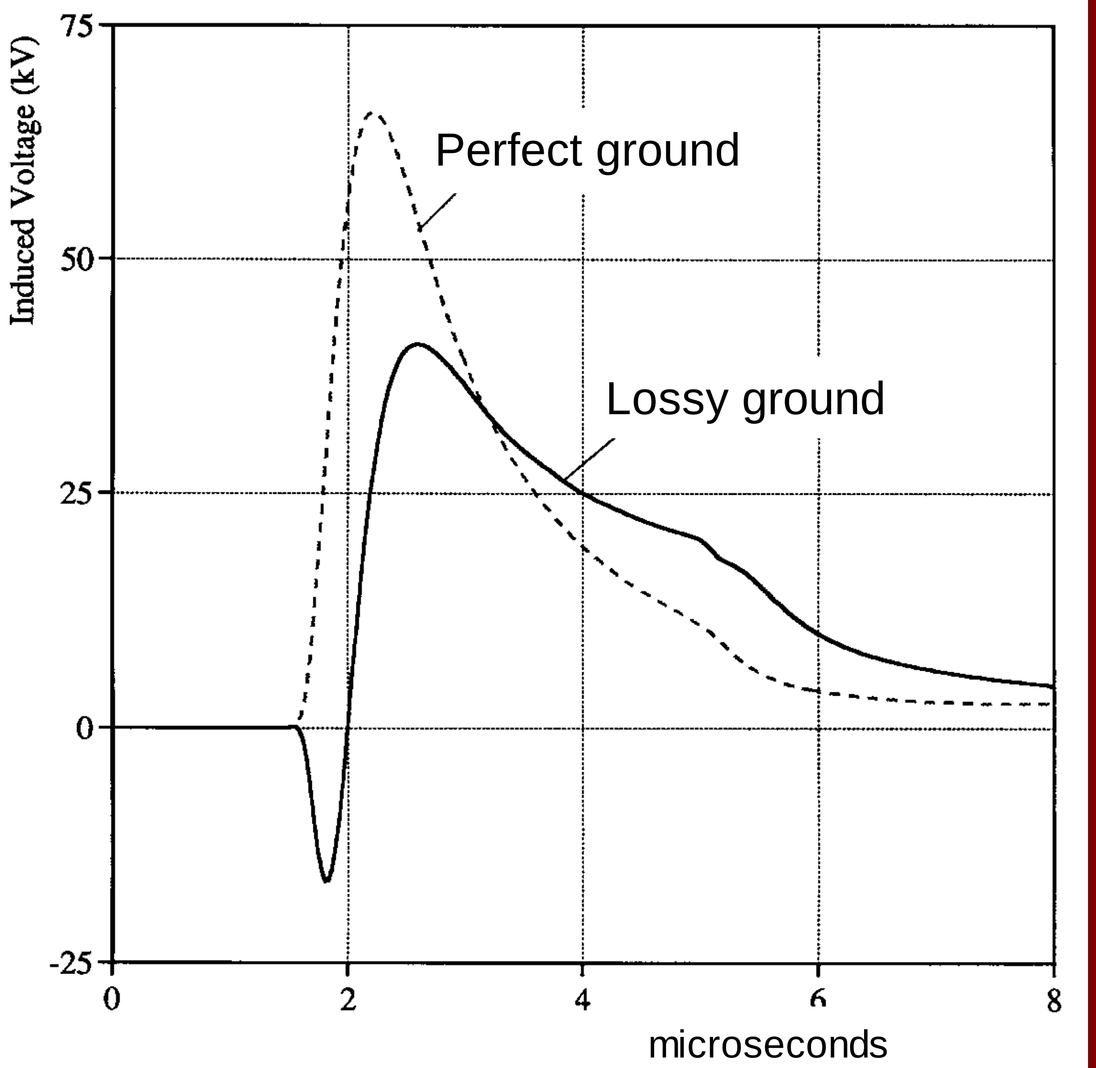
The ground resistivity affects:

1. electromagnetic field

2. propagation of the surges

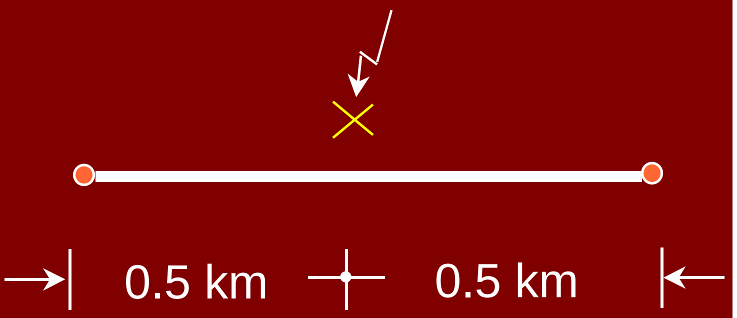
11. What effect does pole grounding and ground resistivity have ? *Cont.*

Influence of ground resistivity *Cont.*



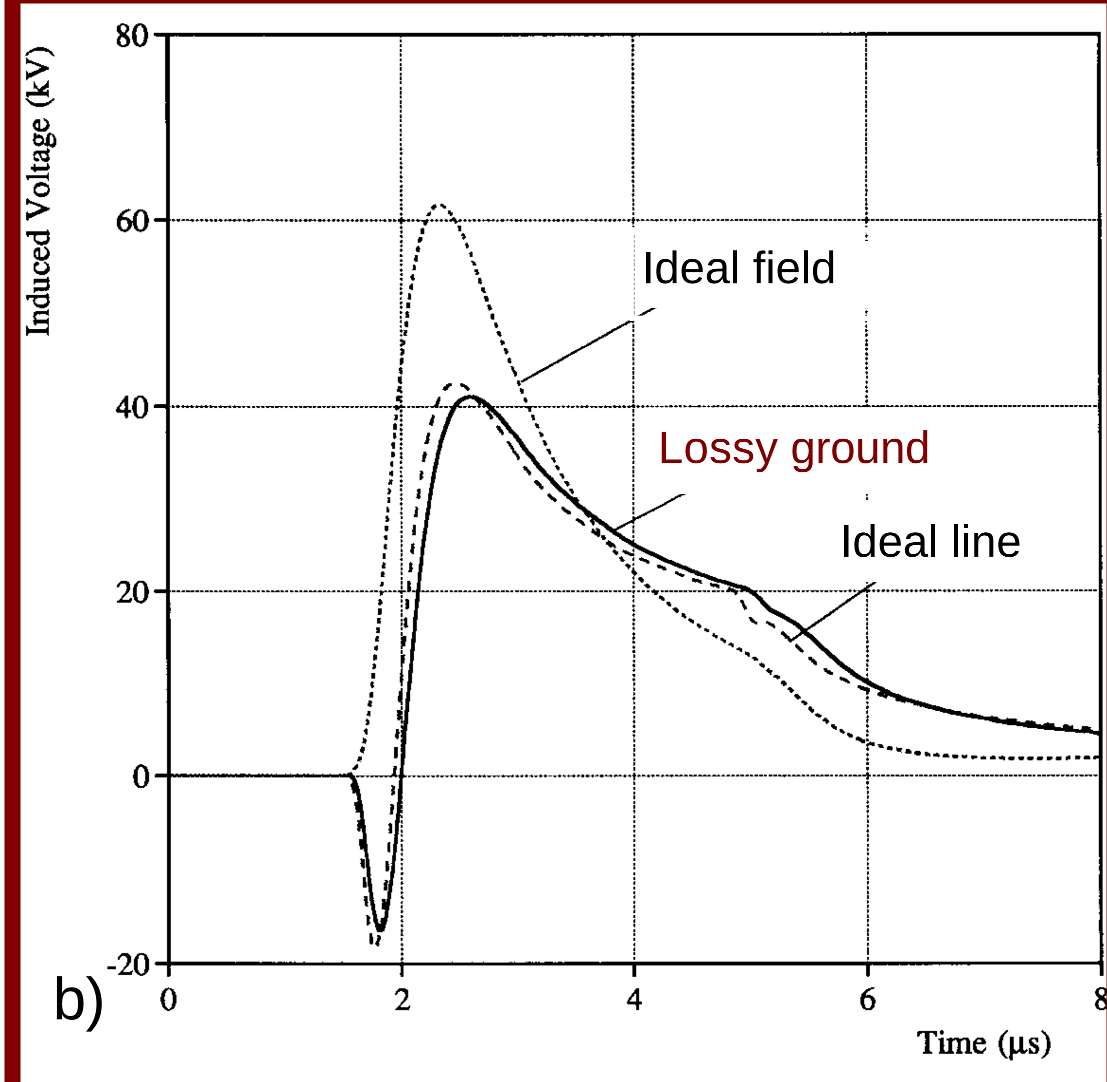
Lossy ground:

σ = 0.001 S/m



11. What effect does pole grounding and ground resistivity have ? *Cont.*

Influence of ground resistivity *Cont.*



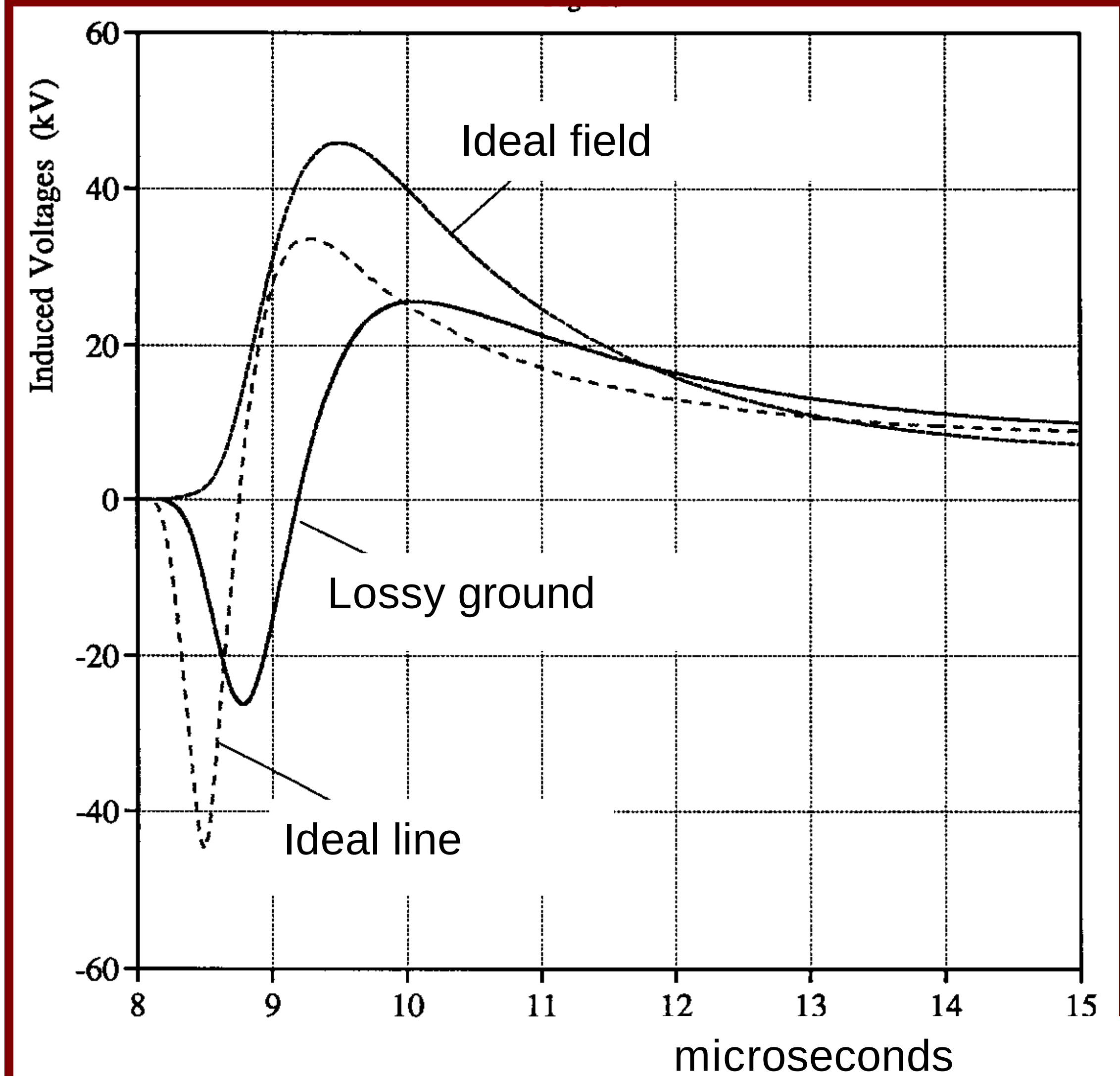
Lossy ground
(σ = 0.001 S/m)

Ideal field:
ground resisitivity only in the expression of the ground impedance

Ideal line:
ground resistivity only in the expression of the incident field

11. What effect does pole grounding and ground resistivity have ? *Cont.*

Influence of ground resistivity *Cont.*



Lossy ground
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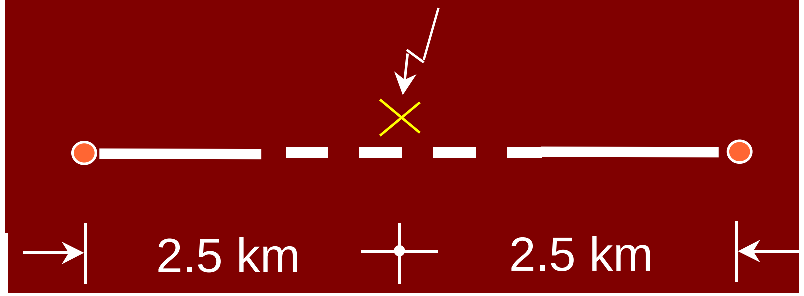


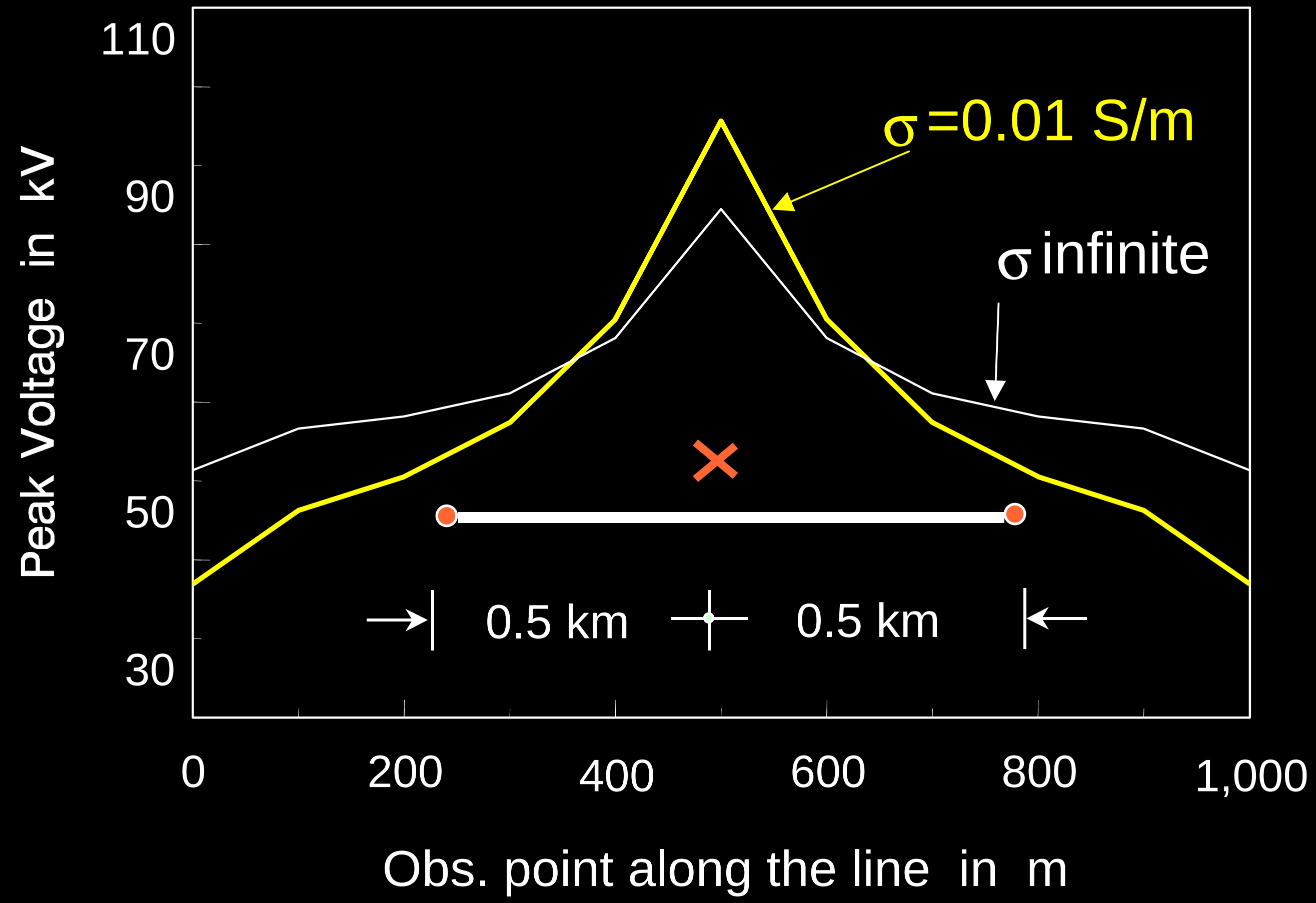
11. What effect does pole grounding and ground resistivity have ? *Cont.*

Influence of ground resistivity

How does the ground resistivity affect magnitude and shape of the induced voltages?

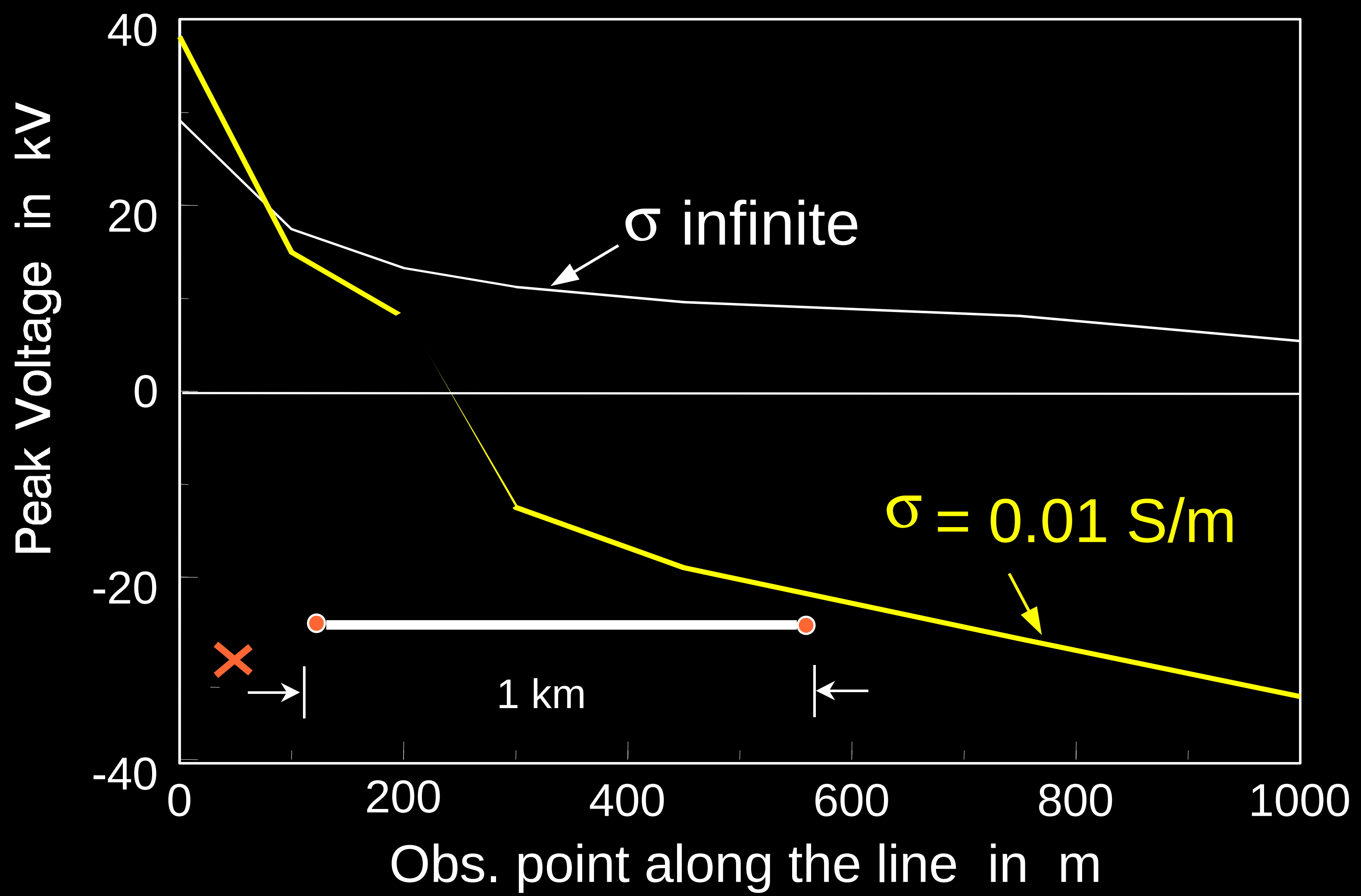
11. What effect does pole grounding and ground resistivity have ? *Cont.*

Influence of ground resistivity *Cont.*



11. What effect does pole grounding and ground resistivity have ? *Cont.*

Influence of ground resistivity *Cont.*



11. **What effect does pole grounding and ground resistivity have ?** *Cont.*

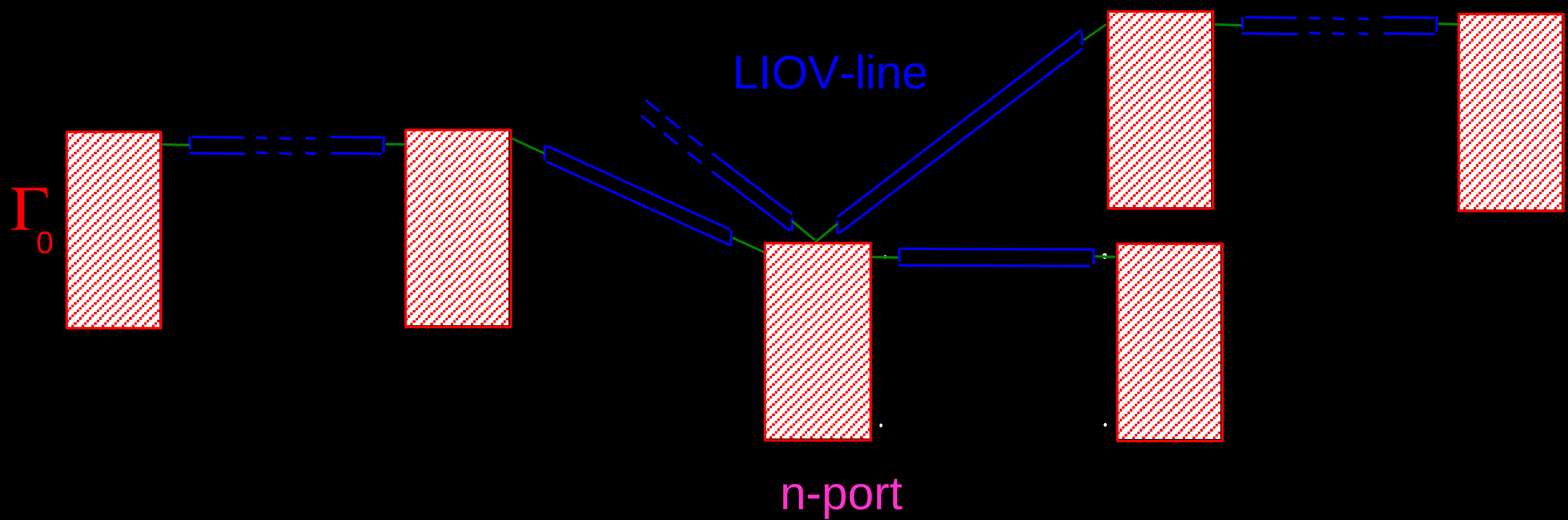
Influence of ground resistivity *Cont.*

The ground resistivity can increase or decrease the magnitude of the induced voltages depending on the stroke location and the observation point along the line

=> the calculation is not trivial

12. Some of the current researches which are being done on induced voltages

- Lightning electromagnetic field characterization using natural and artificially-initiated lightning
- Experimental validation of field-to-transmission line coupling models
- Development of engineering tools for the protection of power networks against lightning-induced overvoltages
- Leader-induction effect
- Effect of ground conductivity on lightning-induced overvoltages



The LIOV code calculates:

- **LEMP (using the MTL model and Cooray-Rubinstein expr.)**
- **Coupling using the Agrawal model.**

The EMTP :

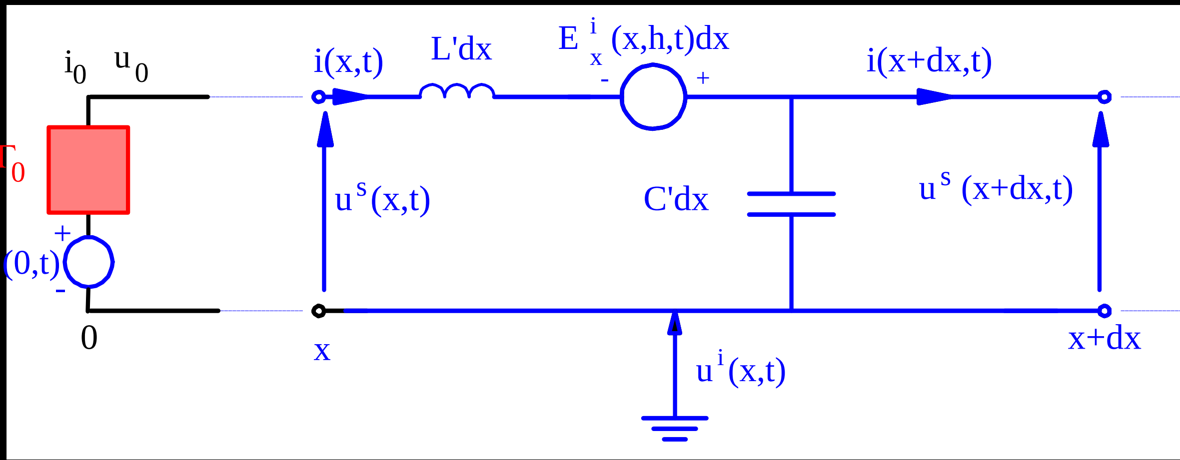
- **calculates the boundary conditions**
- **makes available a large library of power components**

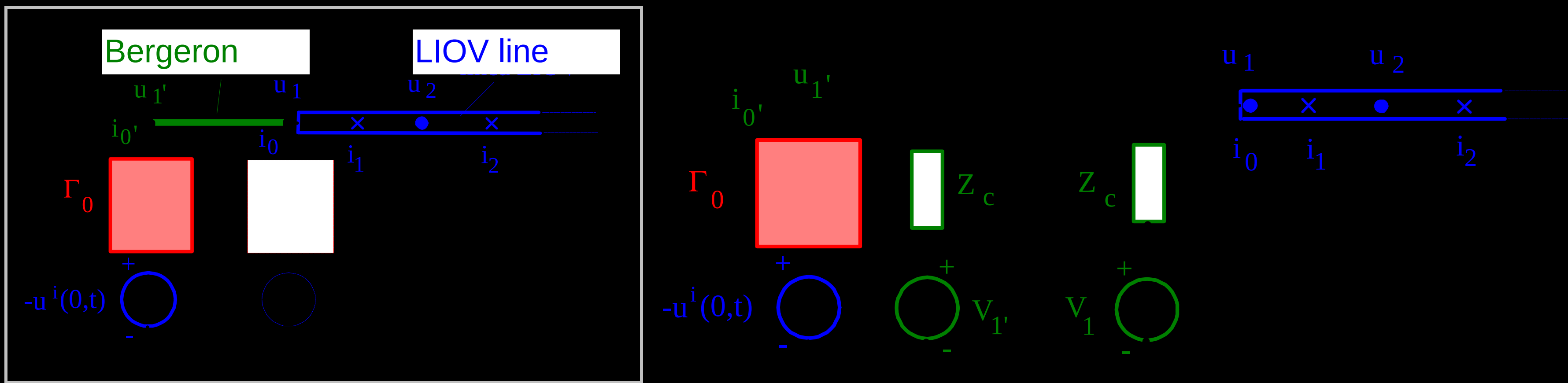
LIOV has been developped within the framework
of an international collaboration involving

- **University of Bologna**
- **Swiss federal Institute of Technology (EPFL, Lausanne)**
- **University of Roma 'La Sapienza'**

Its link with EMTP has been realized in collaboration with
ENEL-CESI (Univ. Bologna)

Other methods have been proposed
EdF (EPFL)





Link between LIOV and EMTP

$$\frac{\partial u^{s}(x,t)}{\partial x} + L' \frac{\partial i(x,t)}{\partial t} = E_{x}^{i}(x,h,t)$$

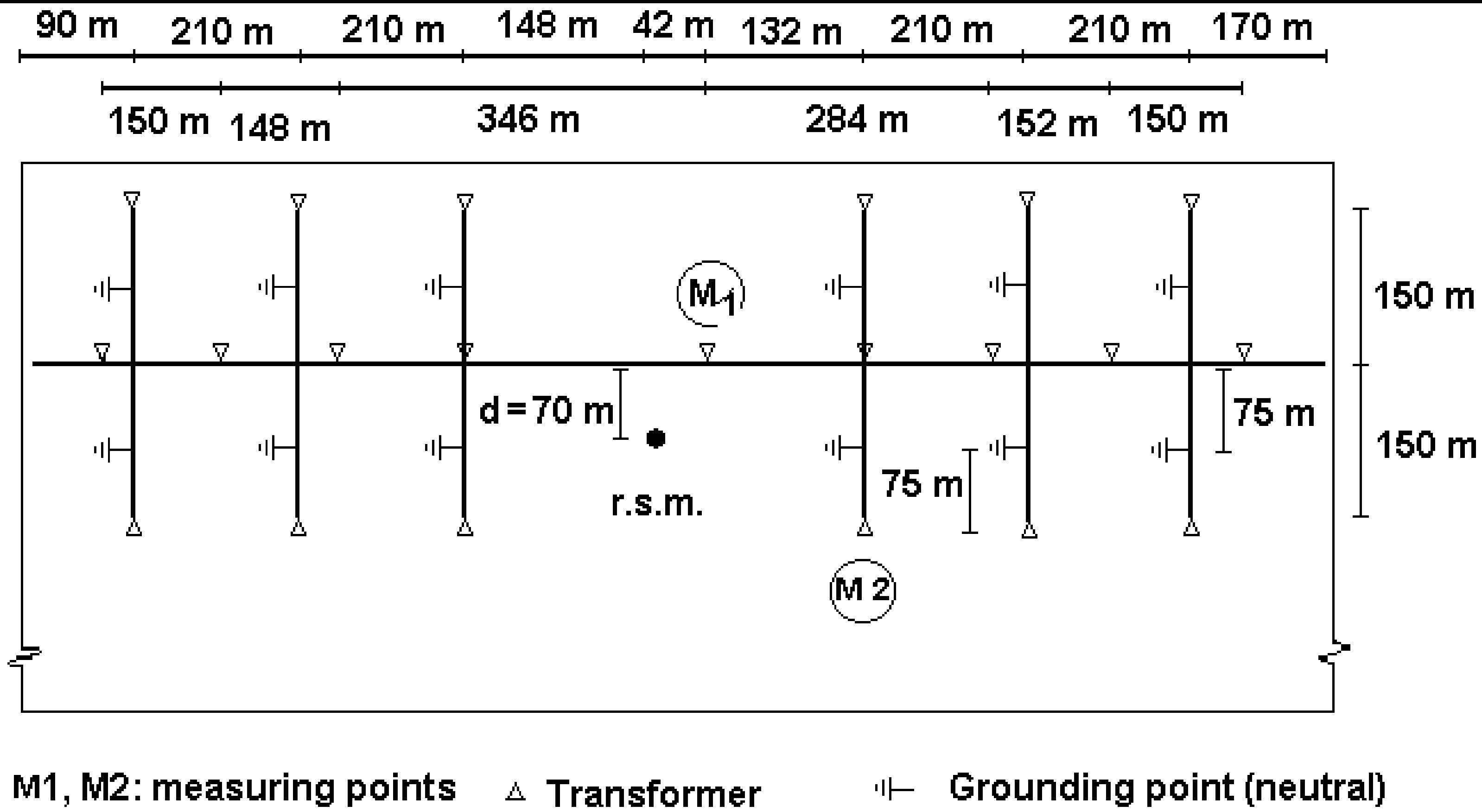
$$\frac{\partial i(x,t)}{\partial x} + C' \frac{\partial u^{s}(x,t)}{\partial t} = 0$$

$$u^{s}(0,t) = u_{1}(t) = -\Gamma_{o}\left(i(0,t)\right) + \int_{0}^{h} E_{z}^{i}(0,z,t)\,dz$$

$$\begin{aligned} u_{1}(t) &= -Z_{c}\, i_{0}(t) + \left[u_{1'}(t-\Delta t) + Z_{c}\, i_{0'}(t-\Delta t)\right] \\ &= -Z_{c}\, i_{0}(t) + V_{1}(t-\Delta t) \end{aligned}$$

$$\begin{aligned} u_{1'}(t) &= Z_{c}\, i_{0'}(t) + \left[u_{1}(t-\Delta t) - Z_{c}\, i_{0}(t-\Delta t)\right] \\ &= Z_{c}\, i_{0'}(t) + V_{1'}(t-\Delta t) \end{aligned}$$

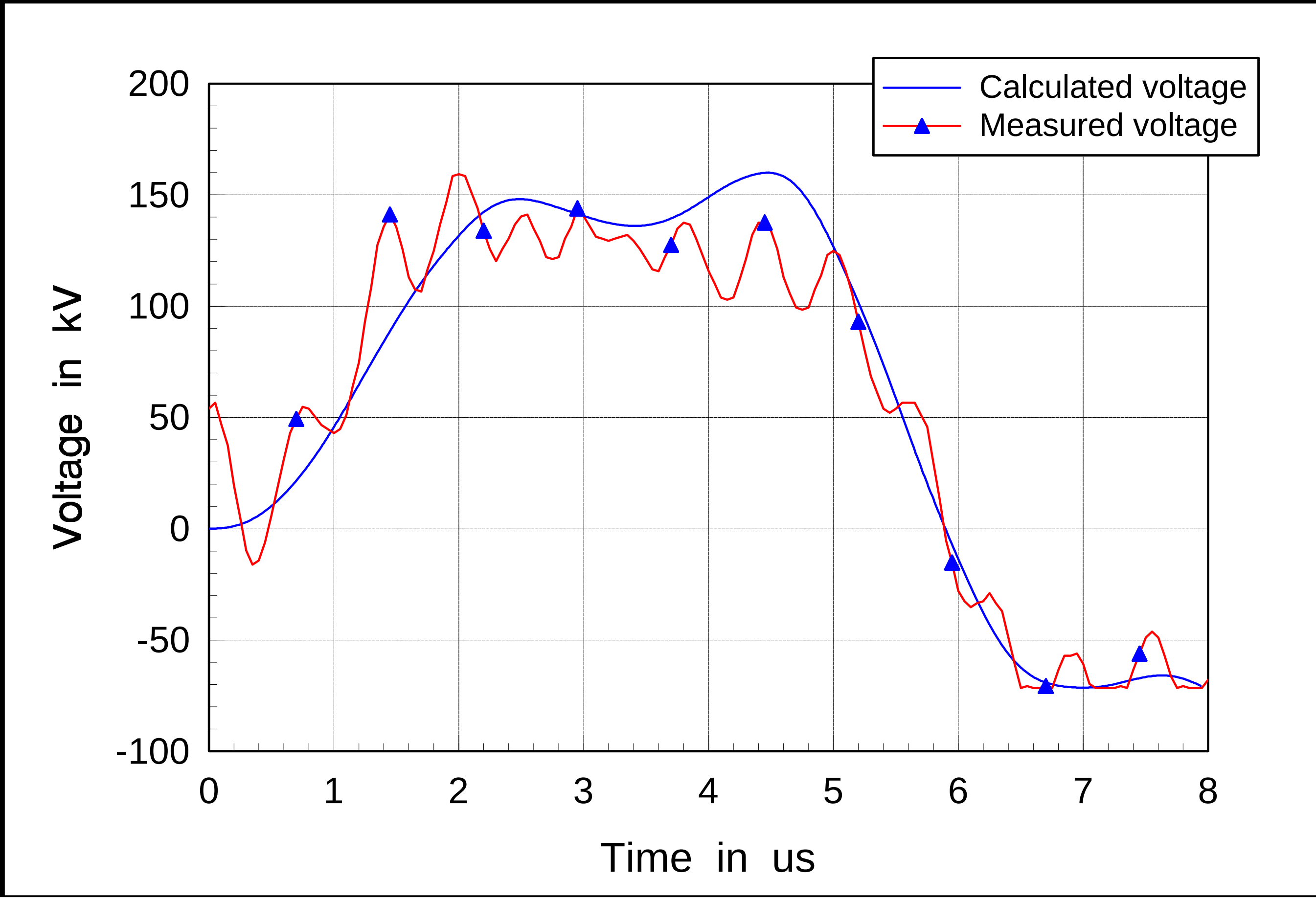
12. Some of the current researches which are being done on induced voltages *Cont.*



Validation using data from a more complex system

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

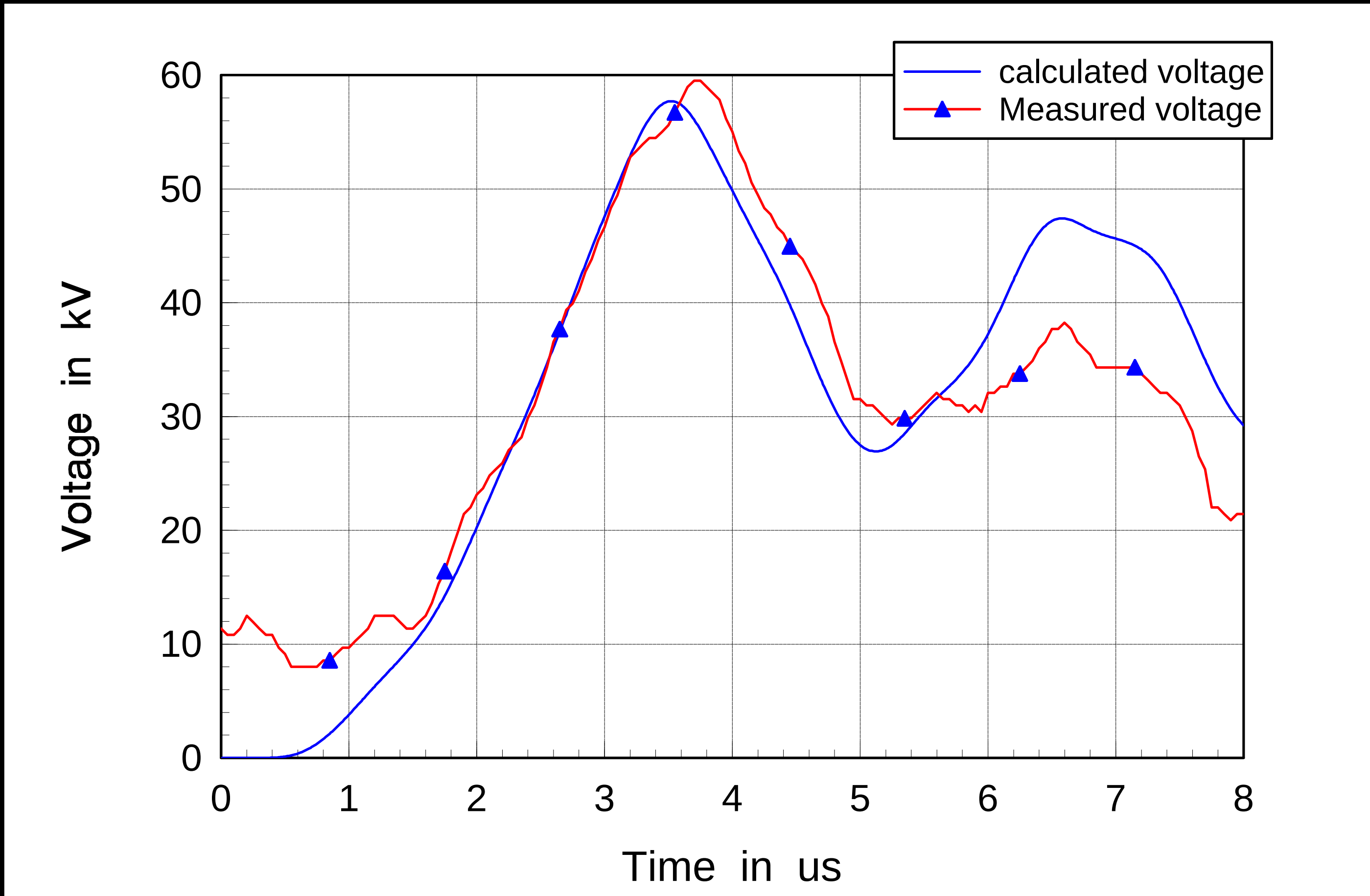
12. Some of the current researches which are being done on induced voltages *Cont.*



Validation using data from a more complex system

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

12. Some of the current researches which are being done on induced voltages *Cont.*



Validation using data from a more complex system

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

12. Some of the current researches which are being done on induced voltages *Cont.*

- Return stroke modeling and influence of elevated strike objects on lightning current and radiated fields
- Adequacy of the available lightning return stroke current statistical data
- Effect of corona on lightning-induced voltages
- Lightning detection and location systems
- Lightning channel tortuosity and inclination

13. What is the CIGRE working group doing on induced voltages ?

Within the framework of
CIGRE working group WG 33.01 "Lightning",

Task Force 33.01.01 "Lightning induced voltages" established some years ago.

C.A. Nucci (responsible member), **P. Chowdhuri, G. V. Cooray, M.T. Correia de Barros, M. Darveniza, F. De la Rosa, G. Diendorfer, F. Heidler, M. Ishii, W. Janischewskyj, T. Kawamura, C. Mazzetti, P. Pettersson, F. Rachidi, V. Rakov, M. Rubinstein, T. Short, J.V. Shostak, M.A. Uman, S. Yokoyama**

13. What is the CIGRE working group doing on induced voltages ?

TF 33.01.01 has already produced two papers published in Electra dealing respectively with lightning return stroke models (August 95) and lightning electromagnetic field-to-transmission line coupling models (October 95).

A third paper, dealing with a sensitivity analysis and aimed at providing ranges of overvoltage values to be expected in the different typical line configurations, is in preparation.