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Mini-Tutorial: Advanced Computational Methods in Lightning Performance

The Lightning Induced Over-Voltage (LIOV) Code

C.A. Nucci

Dept. of Electrical Engineering

University of Bologna - 40136 Bologna, Italy

carloalberto.nucci@mail.ing.unibo.it

The presentation is based on work carried out as part of a collaborative project between the University of Bologna (C.A. Nucci), the University of Lausanne – EPFL (M.Ianoz, F. Rachidi) and and the University of Roma-La Sapienza (C. Mazzetti)

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

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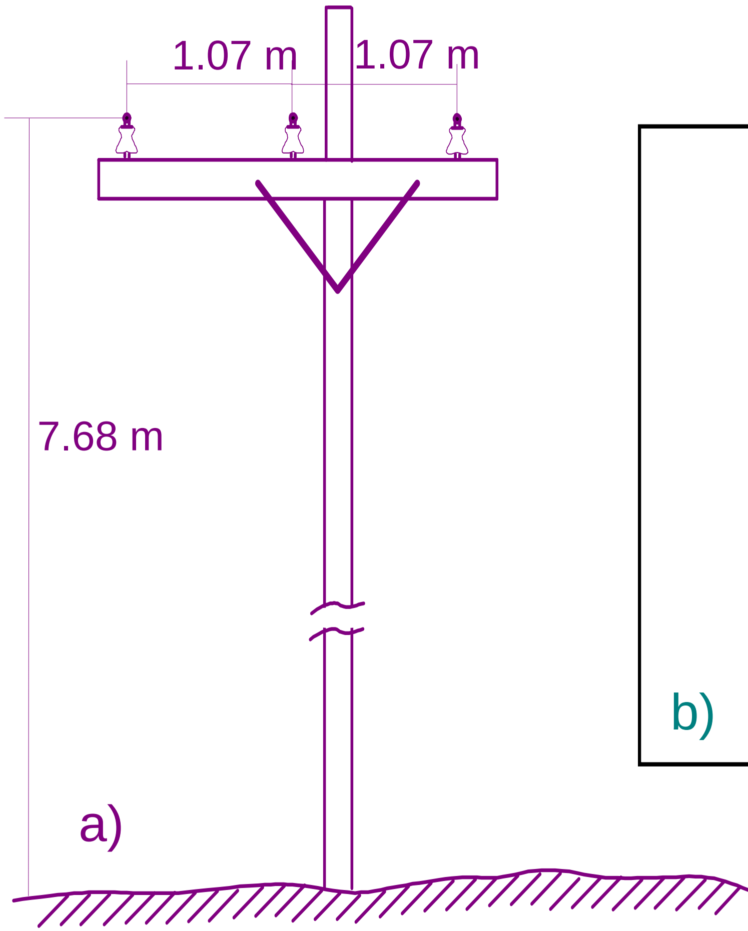
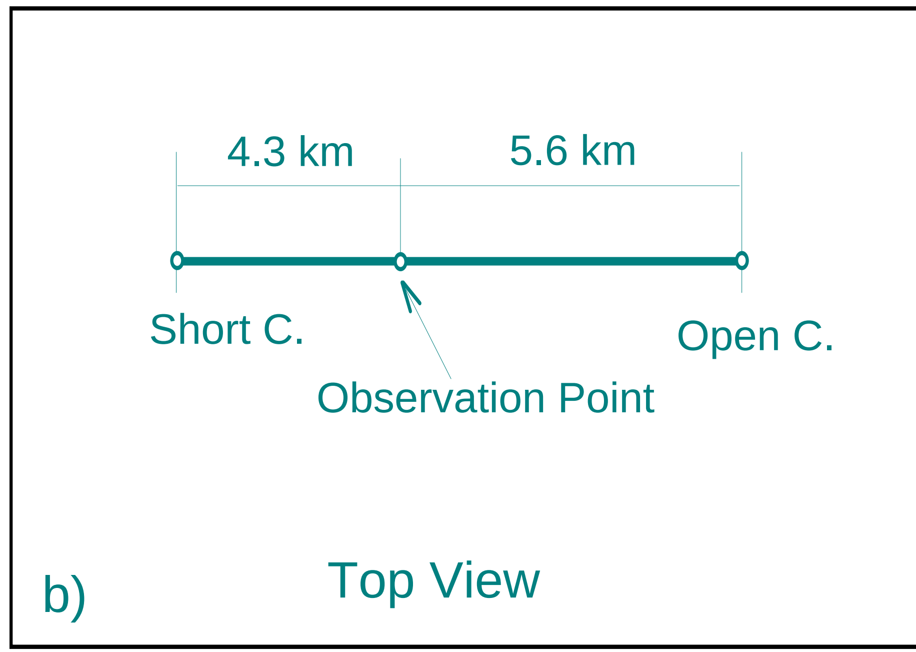
Introduction

Which are the main factors that may affect waveshape and intensity of lightning-induced voltages?

- Waveshape of lightning current (I_{peak}, dI/dt)
- Position of stroke location
- Ground (soil) resistivity
- Line construction
- Shielding wire (pole grounding)
- Presence of surge arresters
- Learder-induction effects
- Channel tortuosity and inclination
- Corona
- …

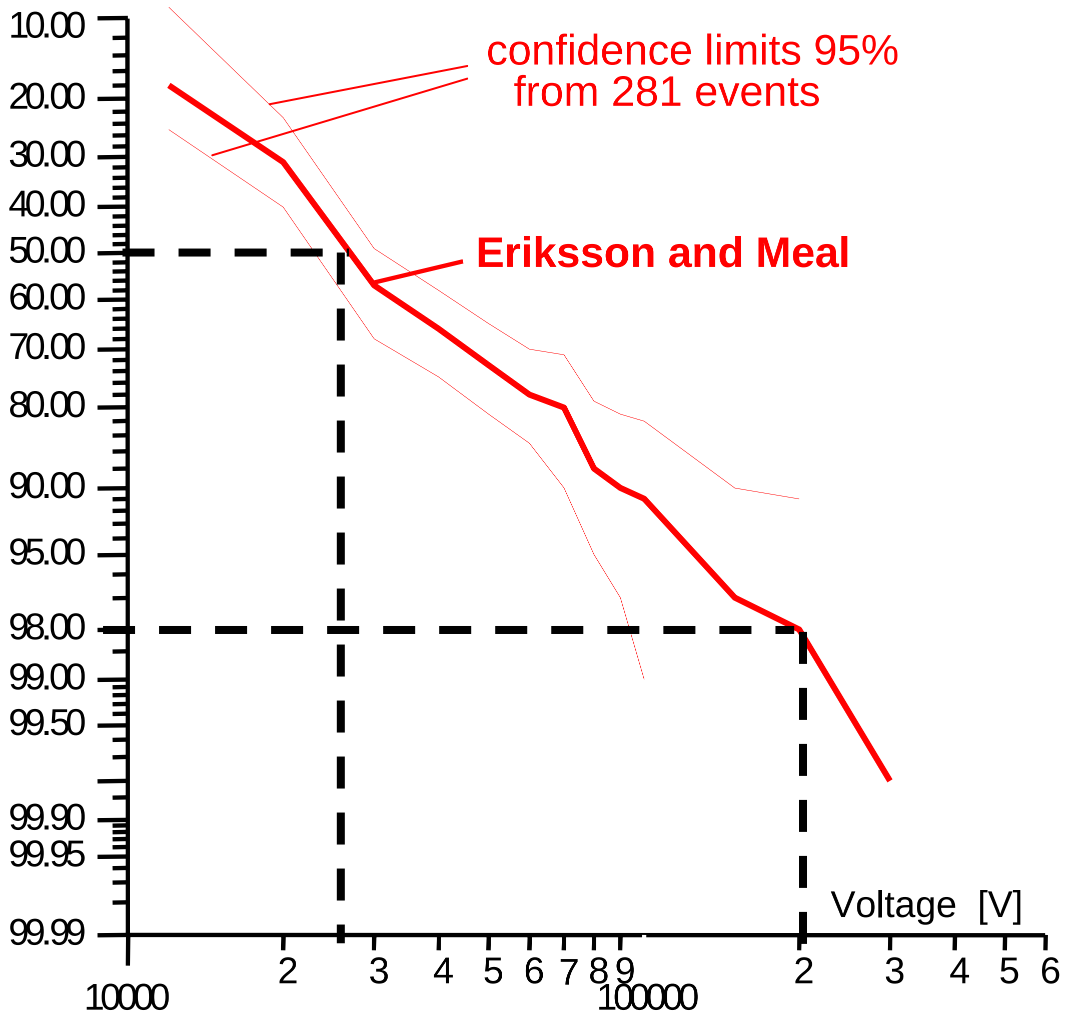
Introduction *Cont.*





Eriksson and Meal experiment
Trans. of IEE, 1982

Introduction *Cont.*



Introduction *Cont.*

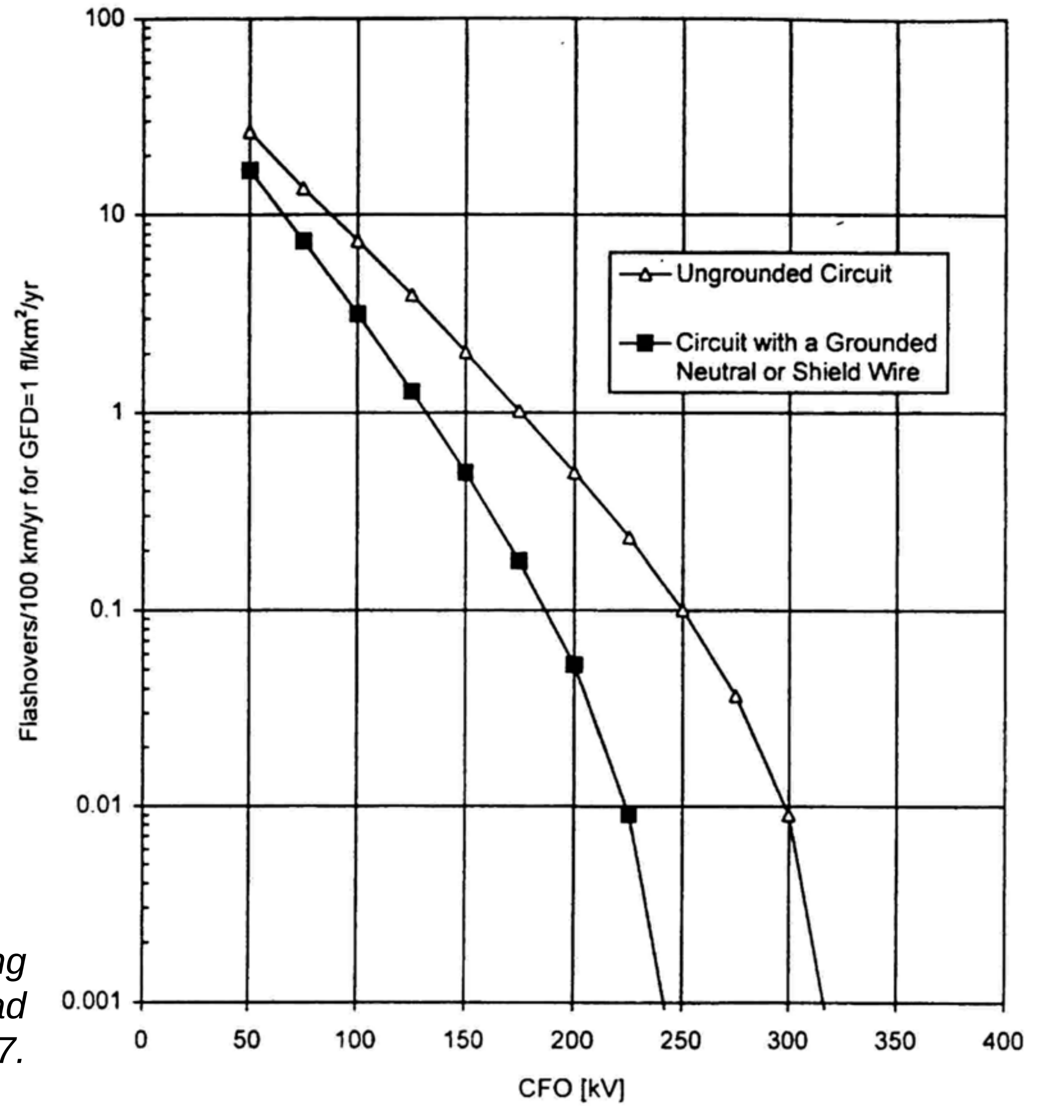
Using the Rusck simplified formula

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

where

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

which applies to infinitely long lines above perfectly conducting ground

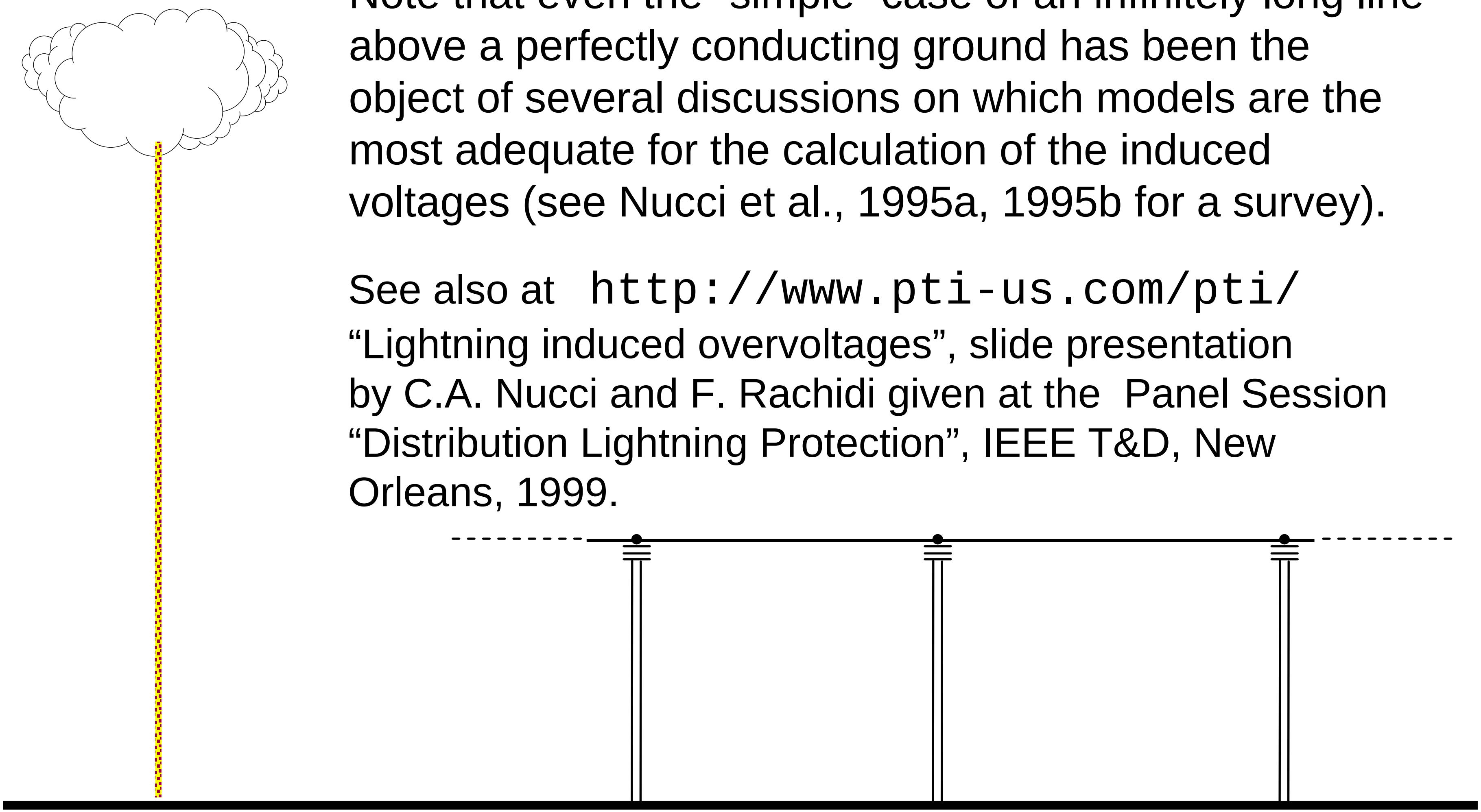


From: "IEEE Guide for Improving the Lightning Performance of Electric Power Overhead Distribution Lines", 1997.

Introduction *Cont.*

Note that even the “simple” case of an infinitely long line above a perfectly conducting ground has been the object of several discussions on which models are the most adequate for the calculation of the induced voltages (see Nucci et al., 1995a, 1995b for a survey).

See also at `http://www.pti-us.com/pti/`
“Lightning induced overvoltages”, slide presentation by C.A. Nucci and F. Rachidi given at the Panel Session “Distribution Lightning Protection”, IEEE T&D, New Orleans, 1999.



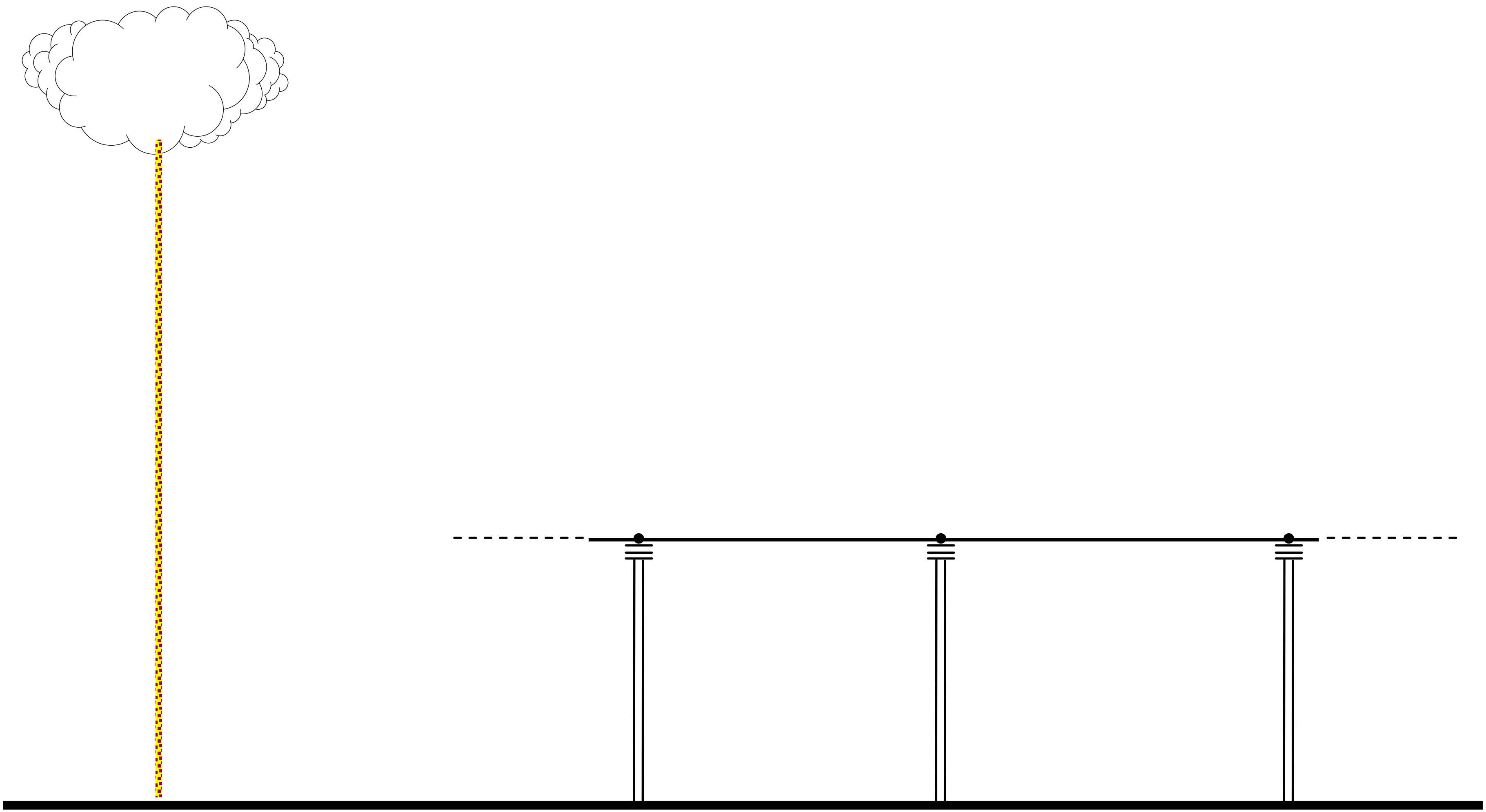
Introduction *Cont.*

The availability of a computer code for the calculation of lightning-induced disturbances on more relistic configurations of transmission lines

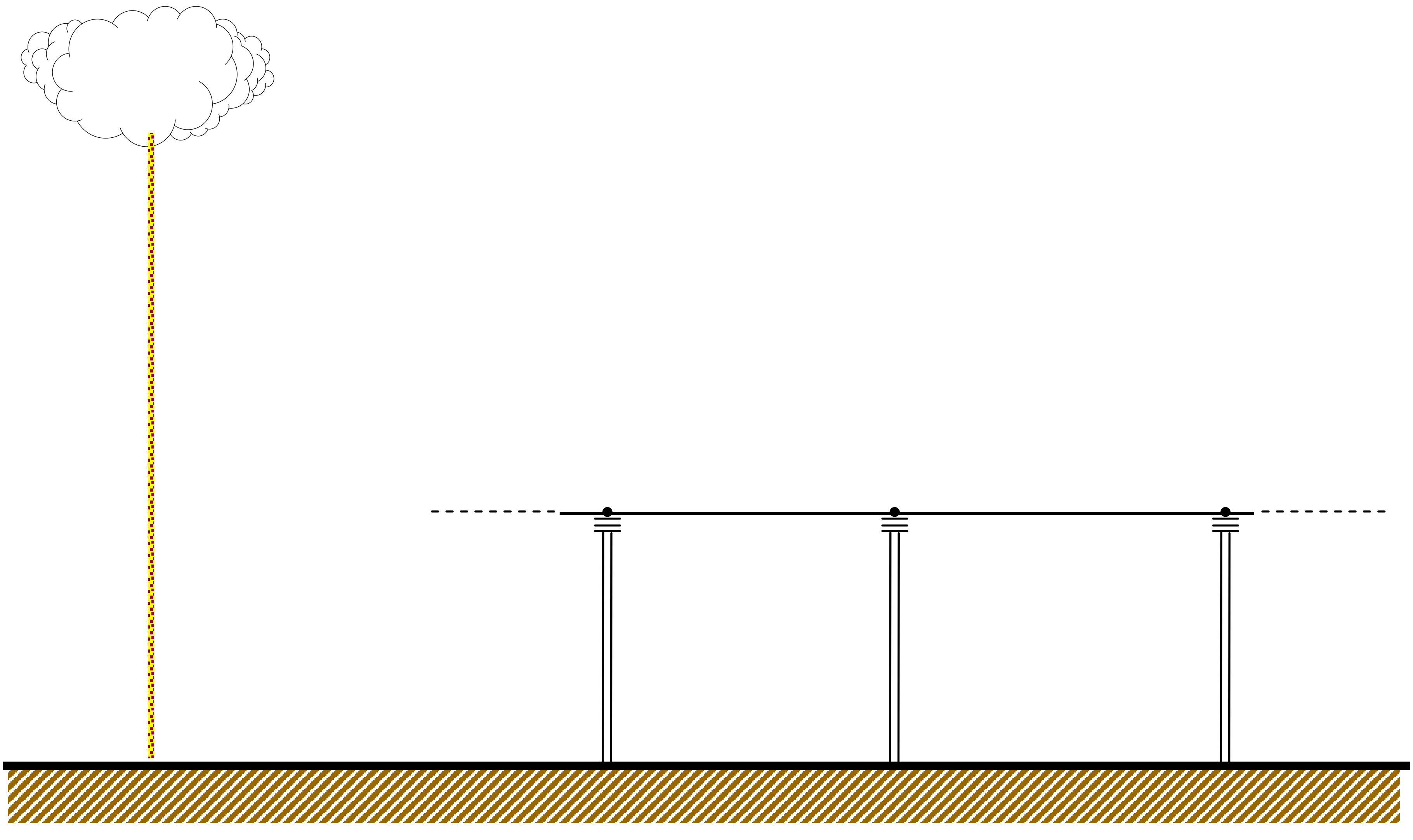
is of interest for solving problems of

- Power quality
- Electromagnetic compatibility (EMC)

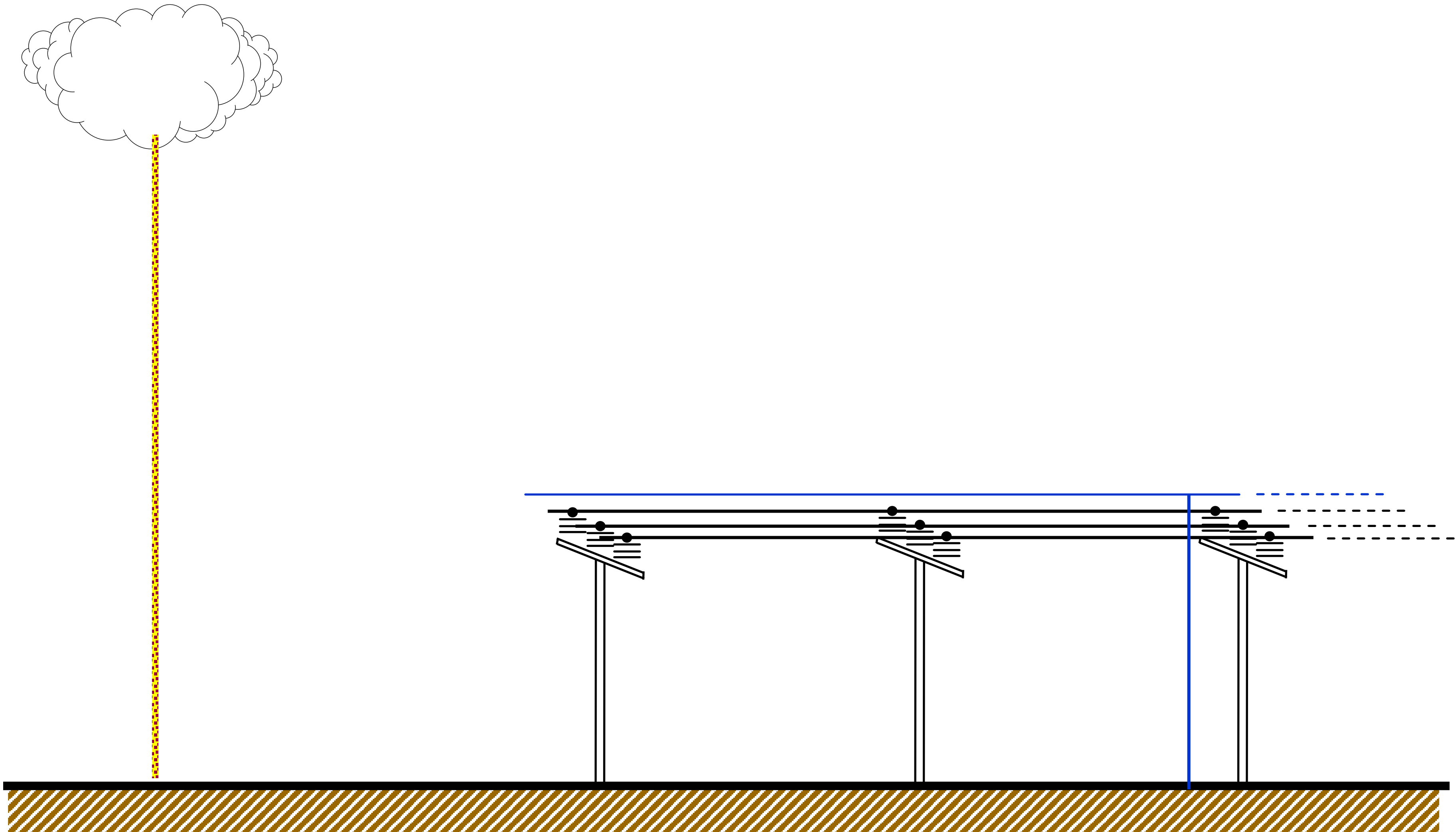
Introduction *Cont.*



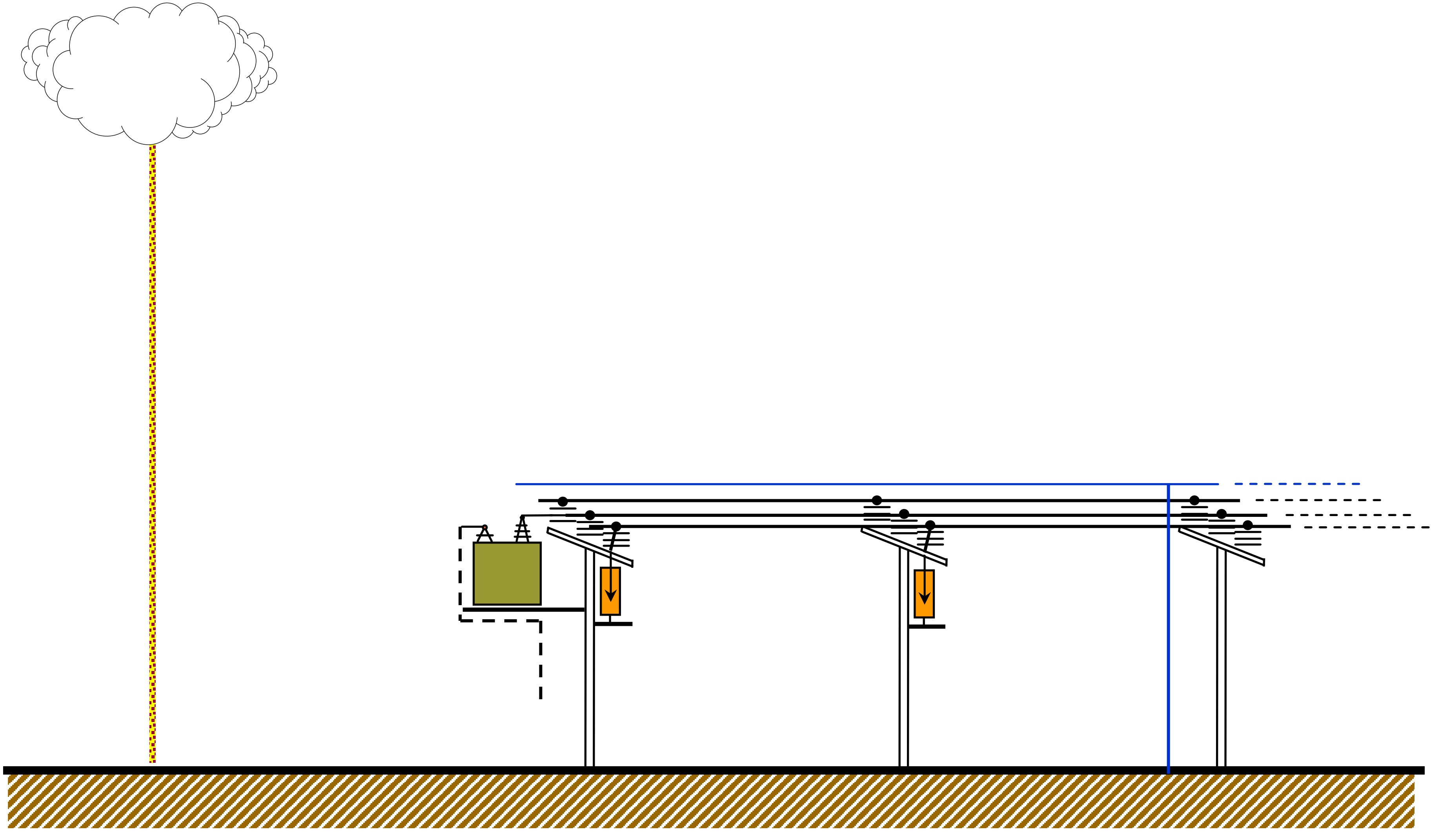
Introduction *Cont.*



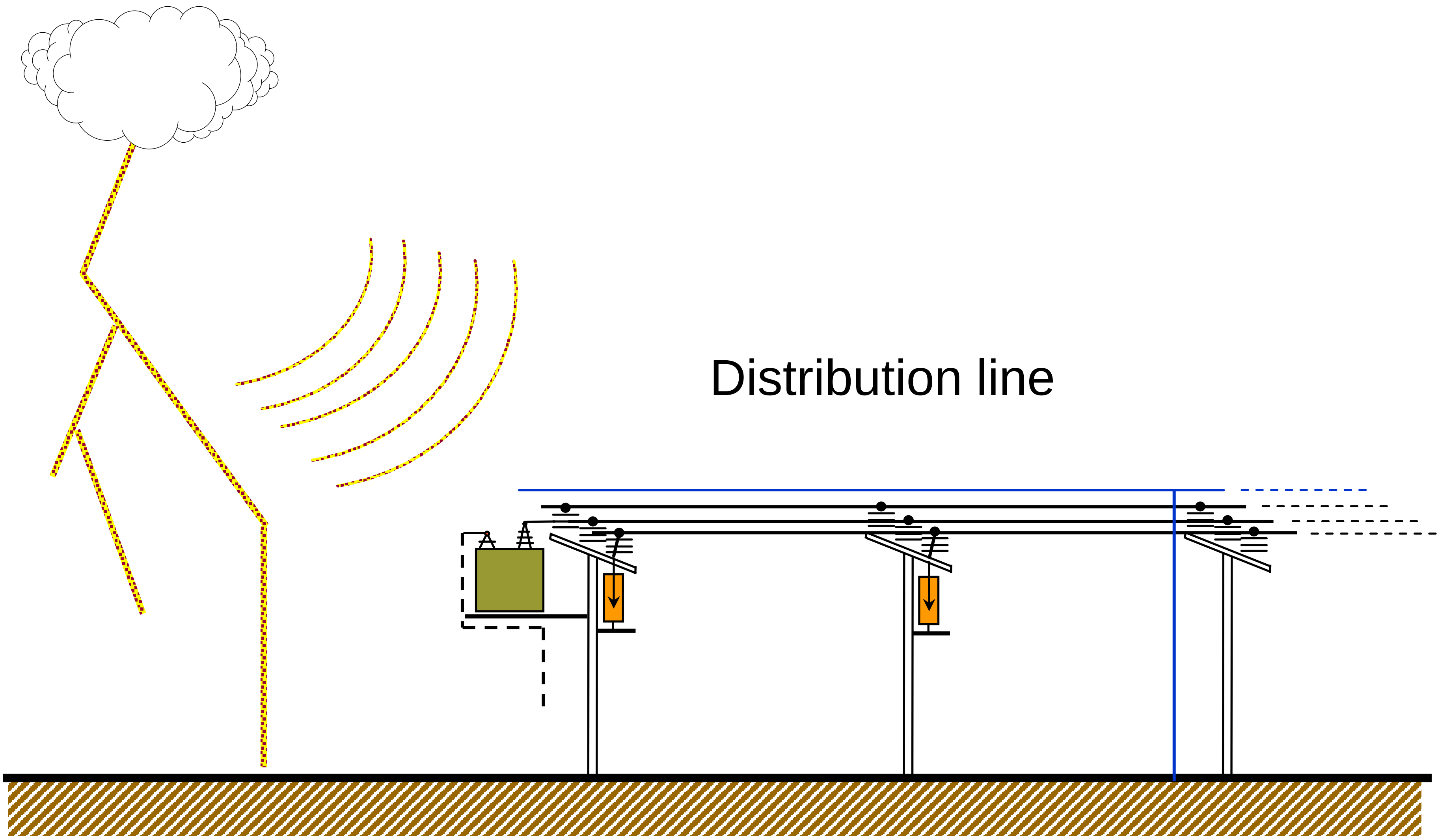
Introduction *Cont.*



Introduction *Cont.*



Introduction *Cont.*



Introduction *Cont.*

Three research groups of three different Universities

- Bologna (Faculty of Engineering, Dept. of Electrical Engineering)
- Lausanne (Swiss Federal Institute of Technology, Power Network Laboratory)
- Rome (Faculty of Engineering, Dept. of Electrical Engineering)

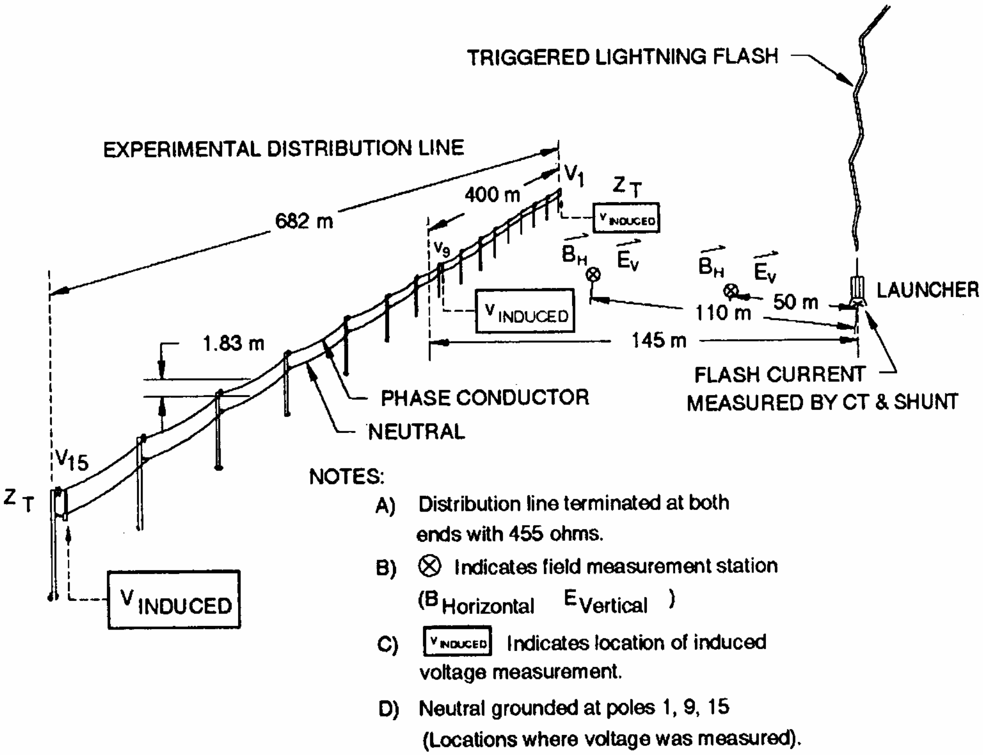
Started some years ago a program aimed at developing a computer code for the calculation of lightning-induced voltages on realistic line configurations using the most adequate models. → the **LIOV** code.

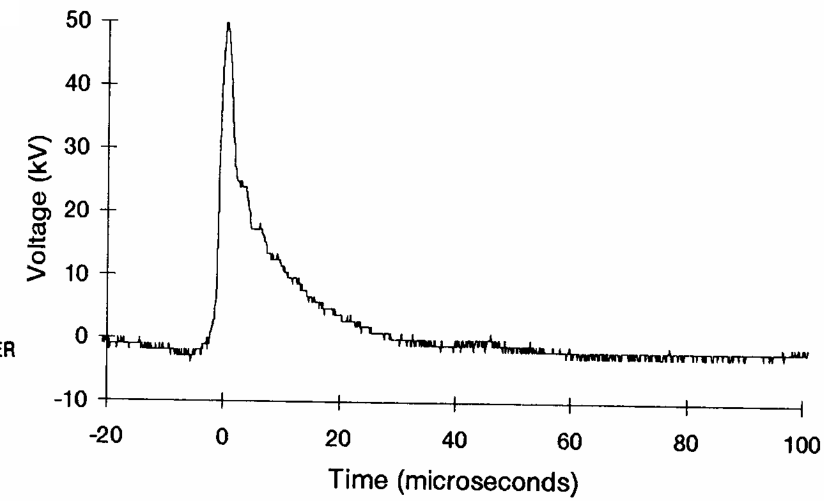
Introduction *Cont.*

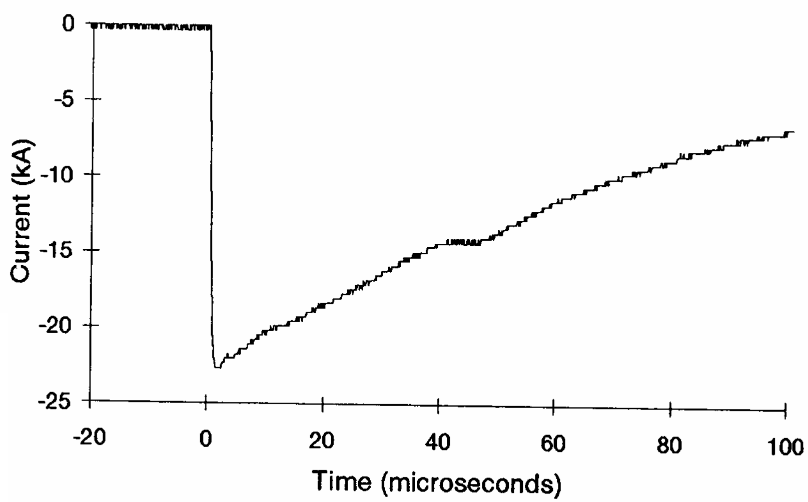
Based on previous studies on the subject (see References) and experimental data obtained by several researchers in the world

- Brasil (University of Sao Paulo)
- Colombia (National University of Colombia)
- France (St. Privat d'Allier)
- Japan (Criepi, University of Tokyo)
- Mexico (IEE)
- Norway (University of Trondheim)
- South Africa (Escom, NEERI)
- Sweden (Royal Institute of Technology, University of Uppsala)
- United States (University of Florida)

Introduction *Cont.*

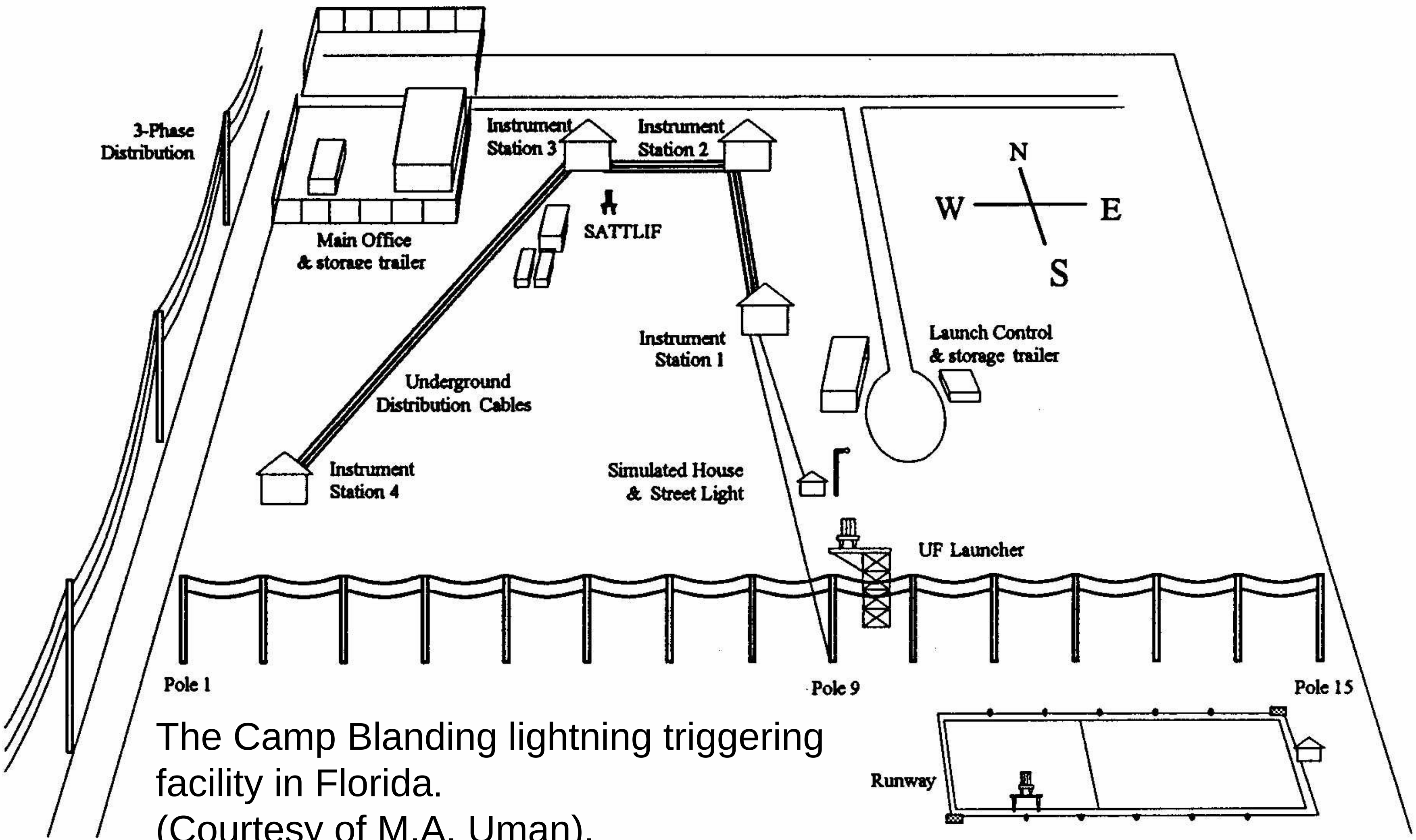






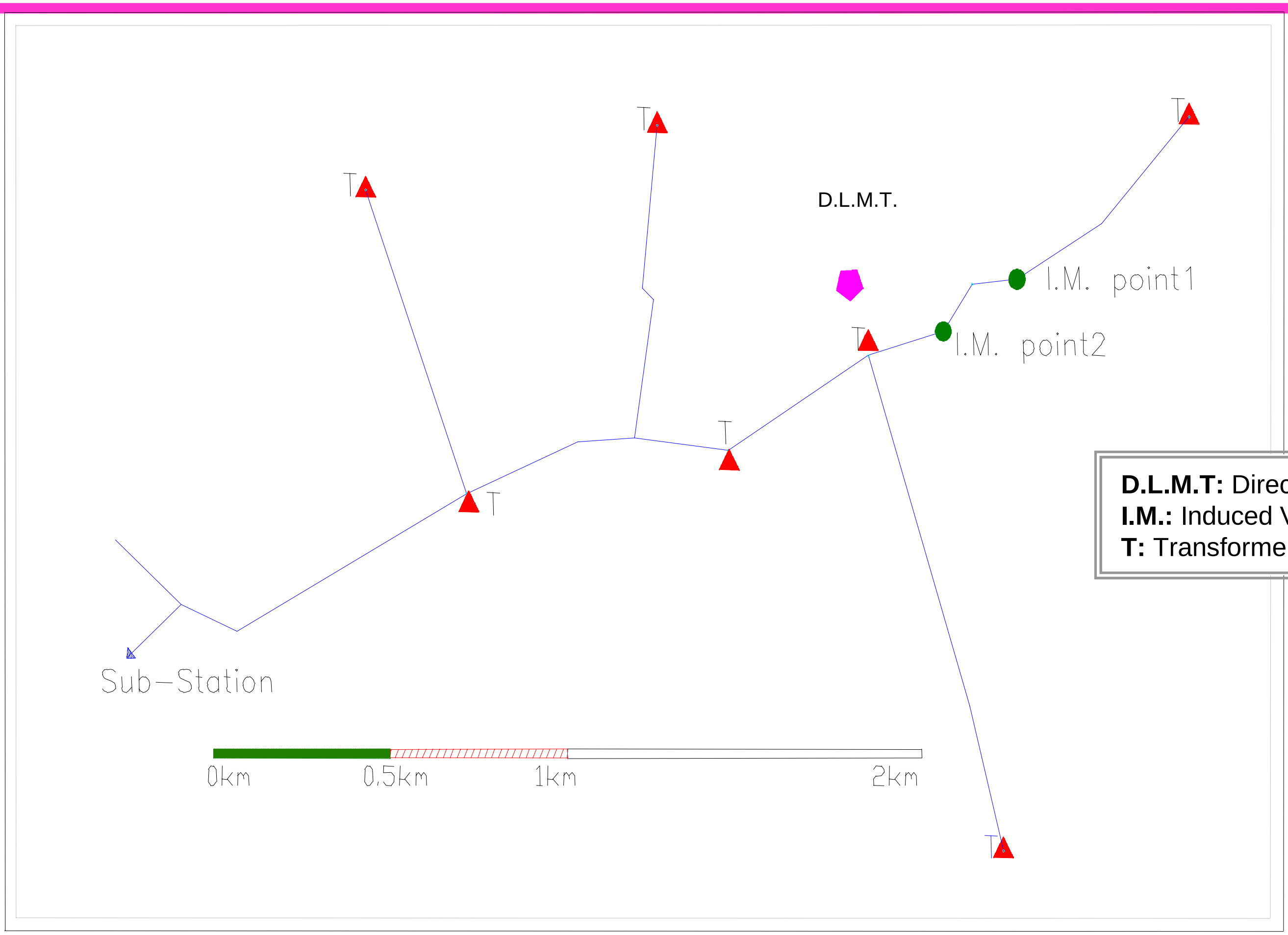
Adapted from Barker et al. IEEE Trans. on PWDR, Vol. 11, pp. 980-995, 1996.

Introduction *Cont.*



The Camp Blanding lightning triggering facility in Florida.
(Courtesy of M.A. Uman).

Introduction *Cont.*



D.L.M.T: Direct Lightning Measurement Tower
I.M.: Induced Voltage Measurement points
T: Transformer

Layout of the experimental station "Ilyapa" in Colombia (courtesy of H. Torres)

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2. Theoretical basis of the LIOV code

Return-Stroke Current

i (0,t) → **RSC** → i (z,t)

Lightning ElectroMagnetic Pulse

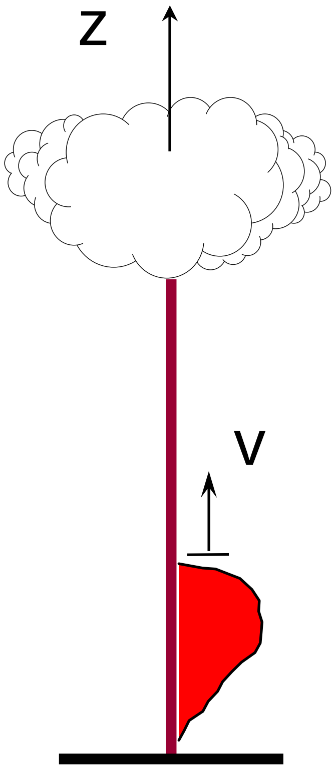
i (z,t) → **LEMP** → E, B

ElectroMagnetic Coupling

E, B → **EMC** → V, I

Return Stroke Current Model

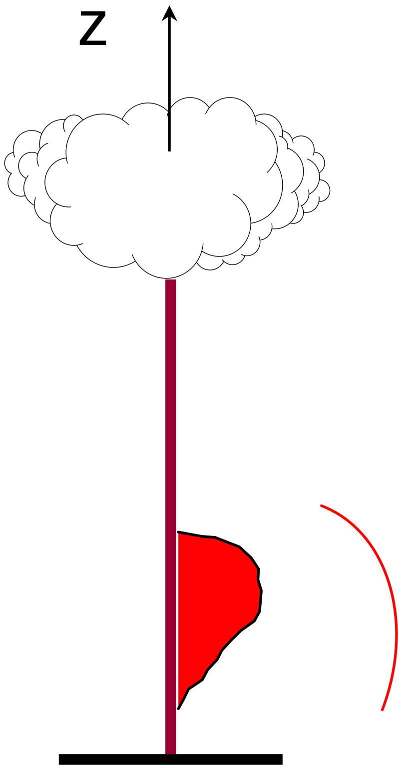
Transmission Line [*Uman and McLain, 1969*]



$$i(z,t) = i(0, t - z/v)$$

Return Stroke Current Model *Cont.*

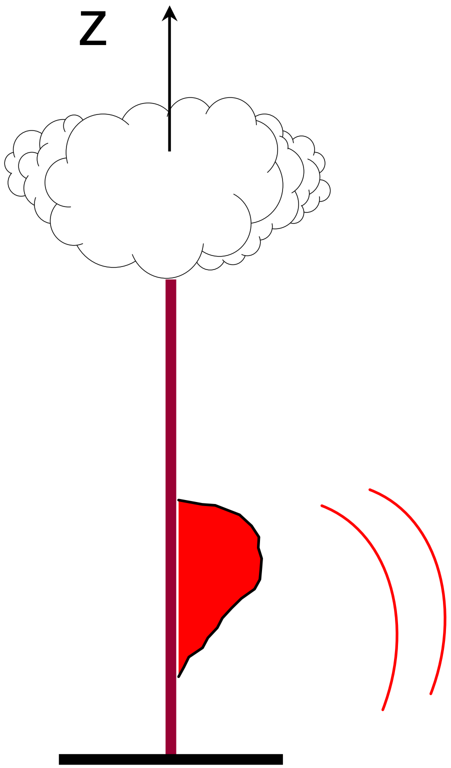
Transmission Line [*Uman and McLain, 1969*]



$$i(z,t) = i(0, t - z/v)$$

Return Stroke Current Model *Cont.*

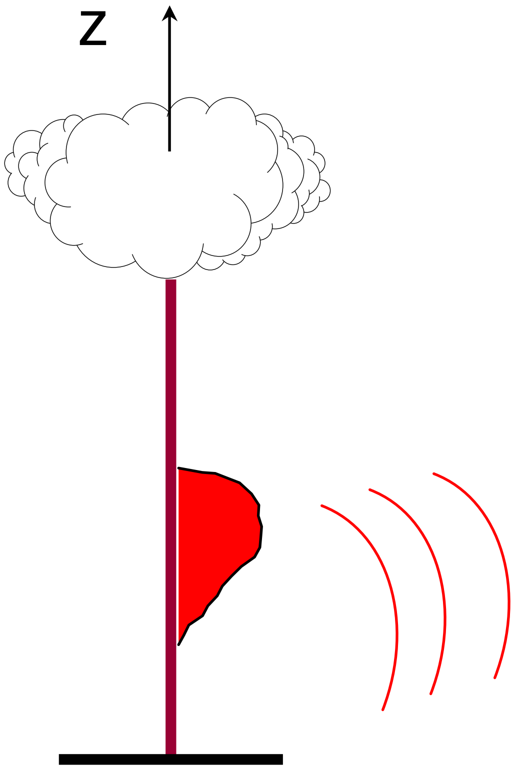
Transmission Line [*Uman and McLain, 1969*]



$$i(z,t) = i(0, t - z/v)$$

Return Stroke Current Model *Cont.*

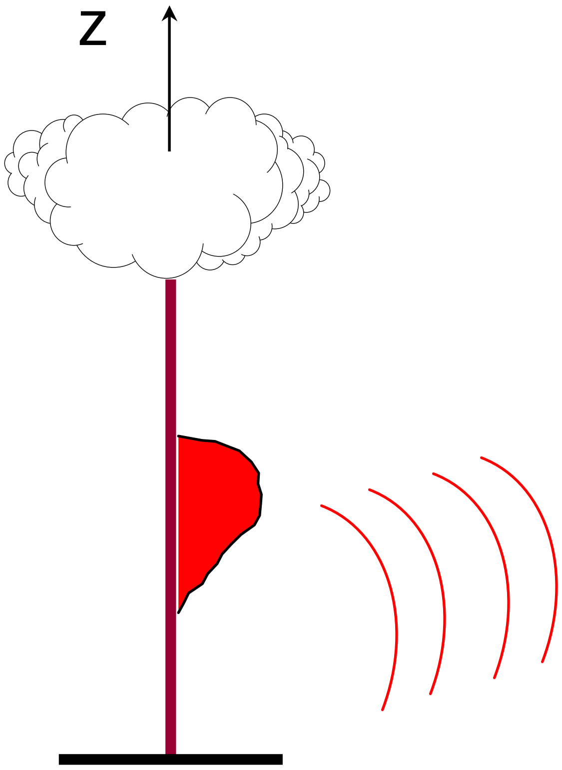
Transmission Line [*Uman and McLain, 1969*]



$$i(z,t) = i(0, t - z/v)$$

Return Stroke Current Model *Cont.*

Transmission Line [*Uman and McLain, 1969*]

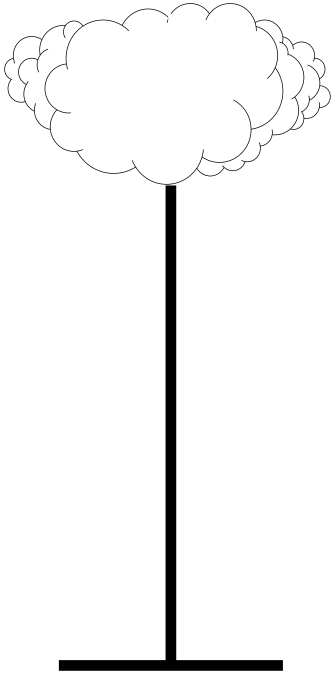


$$i(z,t) = i(0, t - z / v)$$

Return Stroke Current Model *Cont.*

Travelling Current Source [*Heidler, 1985*]

$$i(z,t) = i(0, t + z/c)$$



Modified TL [*Nucci, Mazzetti, Rachidi, Ianoz, 1988*]

$$i(z,t) = i(0, t - z/v)e^{(-z/\lambda)}$$

$$\lambda = 1 - 3 \ km$$

DU [*Diendorfer and Uman, 1990*]

Return Stroke Current Model *Cont.*

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)

Return Stroke Current Model *Cont.*

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

Return Stroke Current Model *Cont.*

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

Validation by means of triggered lightning

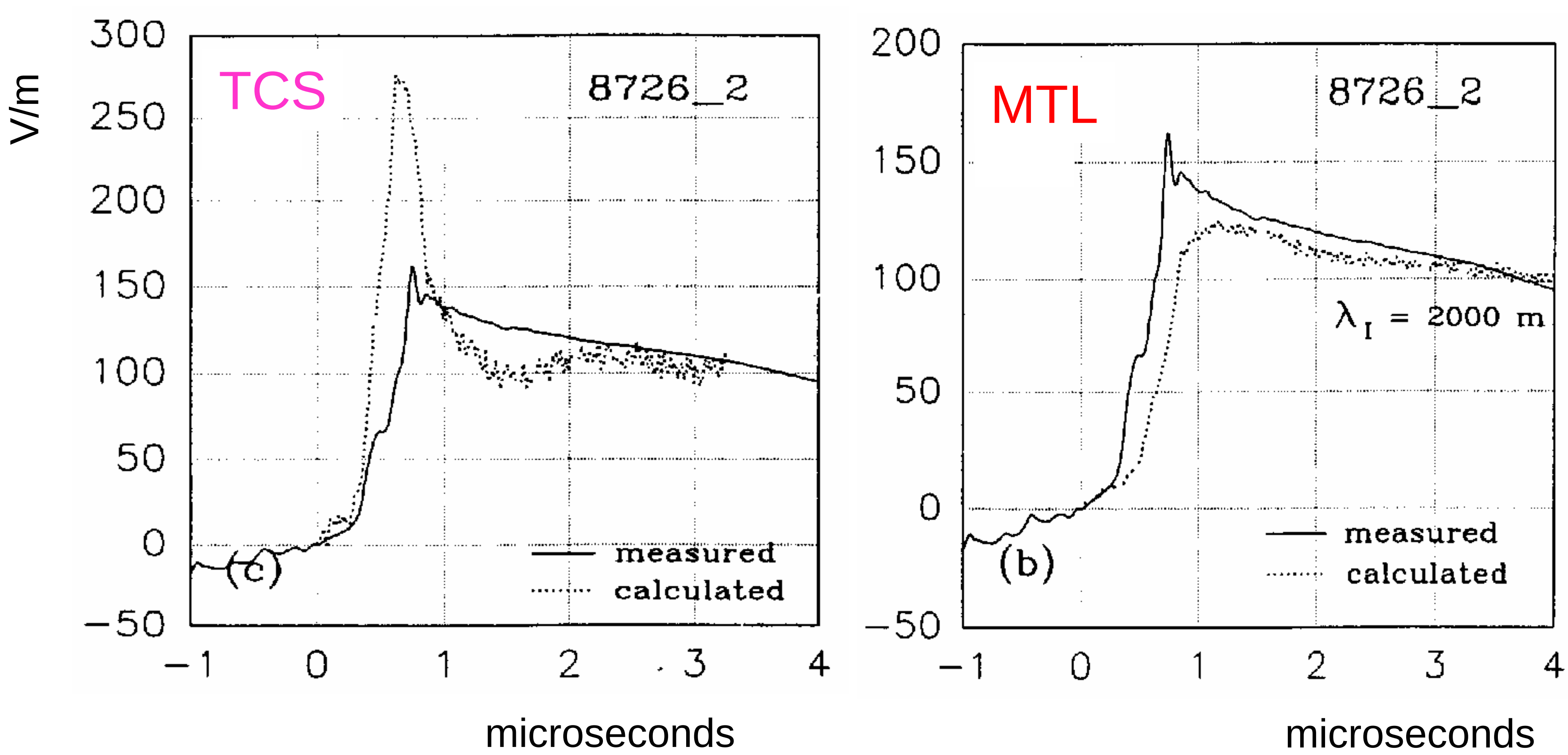
Return Stroke Current Model *Cont.*

Validation by means of triggered lightning *Cont'd*

Return-stroke current model *Cont.*

Camp Blanding experiments, 1999.
Courtesy of M.A. Uman

Return Stroke Current Model *Cont.*



Adapted by Thottappillil and Uman, 1993.

Validation by means of triggered lightning *Cont'd*

Return Stroke Current Model *Cont.*

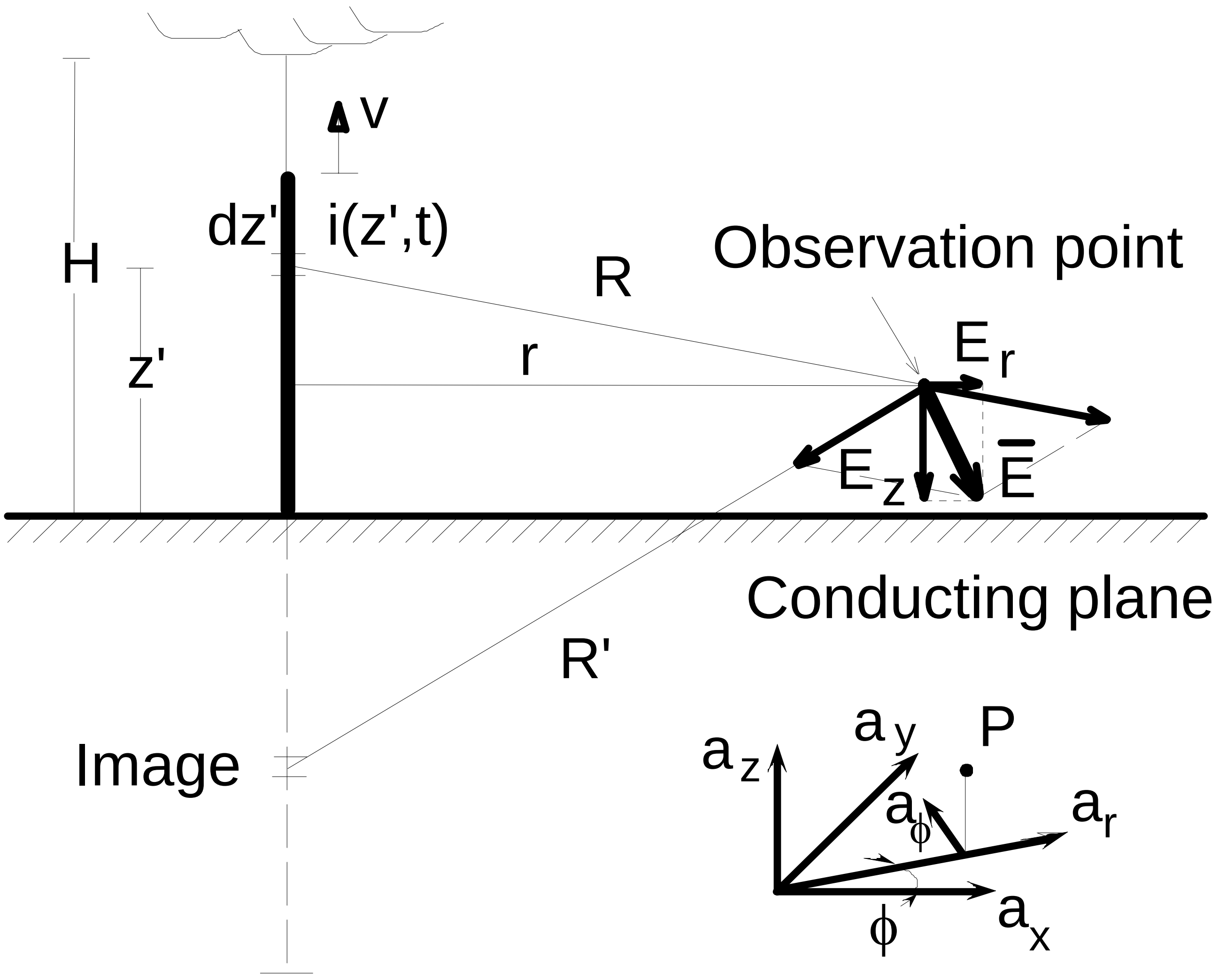
Summary of statistics on the absolute error of the model peak fields on the basis of triggerd ligthning **simultaneously measured currents, velocities and fields** (subsequent return strokes)

adapted from Thottappillil and Uman [1993].

Abs. Error $= \left| (E_{cal} - E_{meas}) / E_{meas} \right|$

	TL	MTL	TCS	DU	MDU
Mean	0.17	0.16	0.43	0.23	0.21
St.Dev.	0.12	0.11	0.22	020	0.19
Min.	0.00	0.00	0.14	0.00	0.02
Max.	0.51	0.45	0.84	0.63	0.60

LEMP Model



v
dz'
i(z',t)
H
z'
R
r
Observation point
E r
E z
E
Conducting plane
R'
Image
a z
a y
P
a φ
a r
a x
φ

LEMP Model *Cont.*

Vertical Electric Field:

Transverse Magnetic field:

can be calculated assuming the ground as perfectly conducting

M.A. Uman, D.K. McLain, E.P. Krider
"The electromagnetic radiation from a finite antenna",
Am. J. of Physics, Vol. 43, pp. 33-38, 1975.

LEMP Model *Cont.*

$$\mathrm{d}E_z(r,\phi,z,t) = \frac{dz'}{4\pi\varepsilon_o}\left[\frac{2(z-z')^2 - r^2}{R^5}\int_0^t i(z',\tau - R/c)\,\mathrm{d}\tau + \frac{2(z-z')^2 - r^2}{cR^4} i(z',t-R/c) - \frac{r^2}{c^2R^3}\frac{\partial i(z',t-R/c)}{\partial t} \right]$$

Vertical Electric Field

$$\mathrm{d}B_r(r,\phi,z,t) = \frac{\mu_o \mathrm{d}z'}{4\pi}\left[\frac{r}{R^3} i(z',t-R/c) \quad \frac{r}{cR^2}\frac{\partial i(z',t-R/c)}{\partial t} \right]$$

Transverse Magnetic field

LEMP Model

Cont.

$$\mathrm{d}E_r(r,\phi,z,t) = \frac{dz'}{4\pi\varepsilon_o}\Bigg[\ \frac{3r(z-z')}{R^5}\int_0^t \boxed{i(z',\tau-R/c)}\,\mathrm{d}\tau + \\ + \frac{3r(z-z')}{cR^4}\boxed{i(z',t-R/c)} + \\ + \frac{r(z-z')}{c^2R^3}\boxed{\frac{\partial i(z',t-R/c)}{\partial t}}\ \Bigg]$$

ε_o permittivity of the free space
c speed of light

Horizontal electric field … *however*

LEMP Model *Cont.*

… ground resistivity has to be taken into account =>
=> more complex approaches are needed

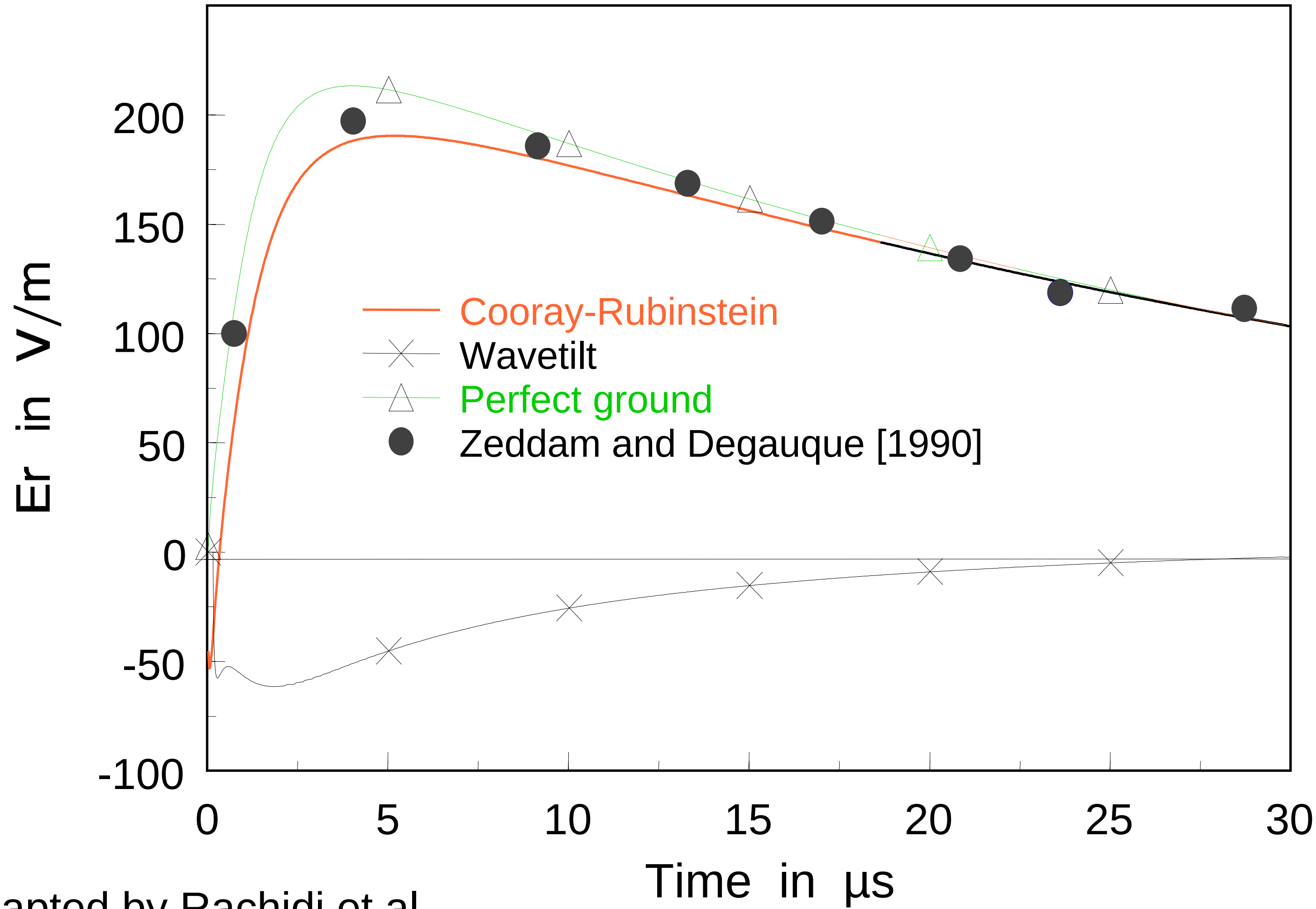
$$\underline{E}_r(r,z,j\omega) = \underline{E}_{rp}(r,z,j\omega) - \underline{H}_{\phi p}(r,0,j\omega)\frac{c\mu_o}{\sqrt{\varepsilon_{rg} + \sigma_g / j\omega\varepsilon_o}}$$

ε_{rg}, μ_{rg} relative permittivity and permeability of ground

$\underline{E}_{rp}(r,z,j\omega)$ $\underline{H}_{\phi p}(r,0,j\omega)$ Fourier-transforms of E(r,z,t) and of H(r,0,t) both calculated assuming a perfectly conducting ground

Cooray-Rubinstein expression - Correction by Wait

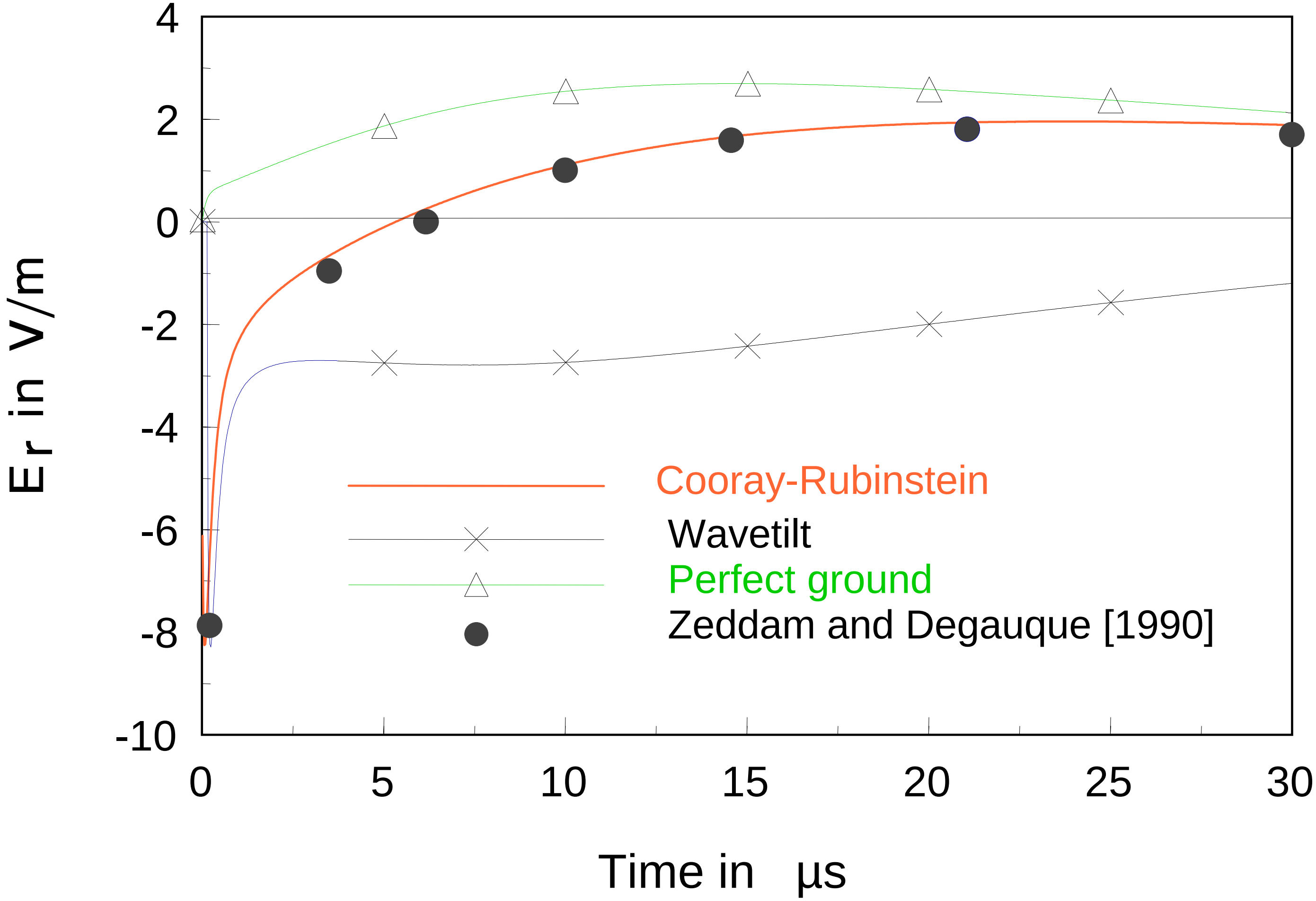
LEMP Model *Cont.*



Adapted by Rachidi et al,

r = 200m

LEMP Model *Cont.*



Adapted by Rachidi et al,

r = 1500 m

Coupling Model *Cont.*

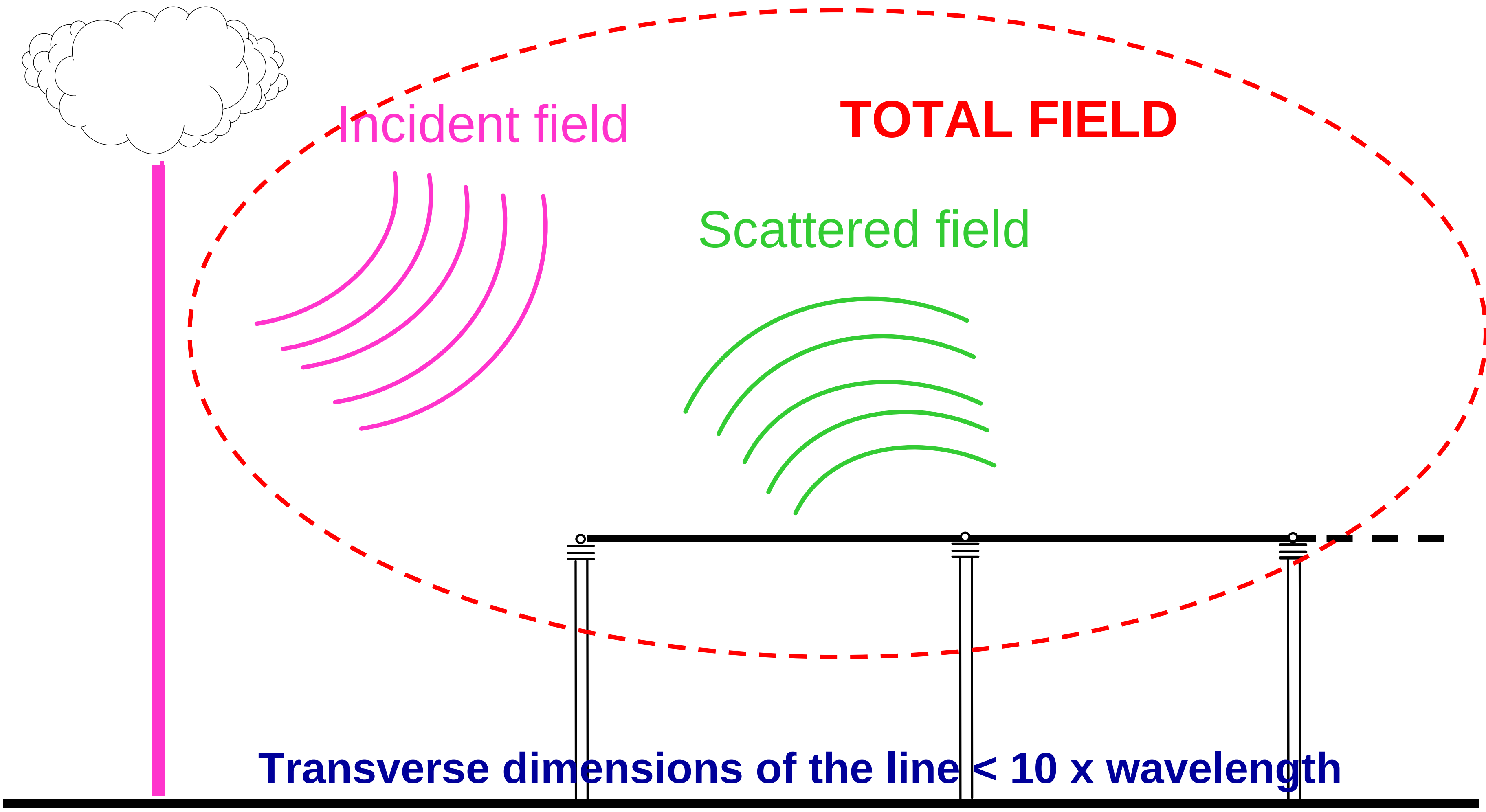
Three coupling models have been used so far:

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

Of the three models, the Agrawal one is considered the most adequate for a general external field excitation

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

Coupling Model *Cont.*



Transverse dimensions of the line < 10 x wavelength

Line response: quasi TEM

Coupling Model

Cont.

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

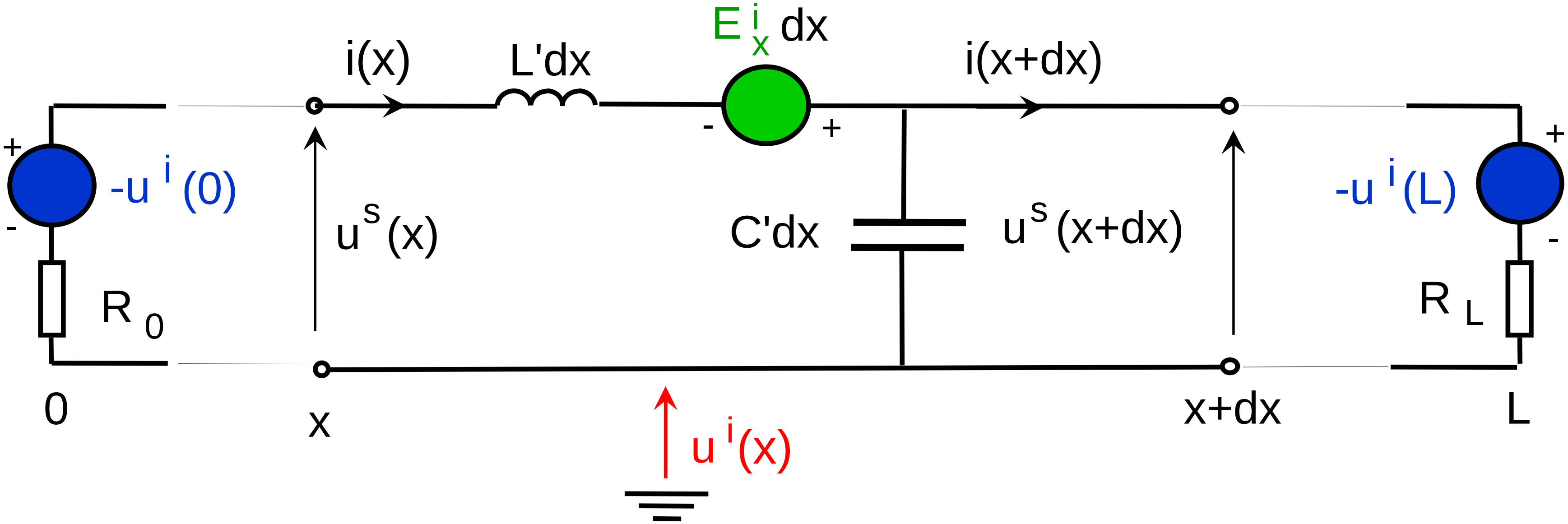
$$\frac{\partial i(x,t)}{\partial x} + C' \frac{\partial u^s(x,t)}{\partial t} = 0$$

$$u^s(x,t) + u^i(x,t) = u(x,t)$$

Transmission line Coupling equations by Agrawal et al.

(single-wire, perfectly conducting ground)

Coupling Model *Cont.*



Agrawal et al.

Coupling Model CONTROLLO RETICOLO

Cont.

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

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

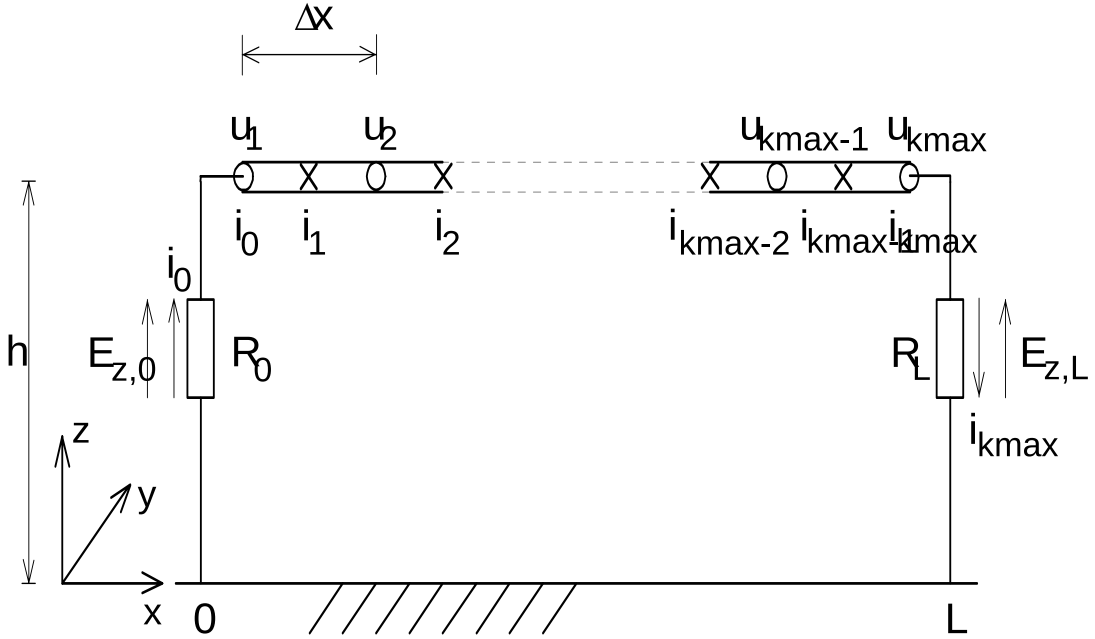
Equations

$$u^s(0,t) = -R_o i(0,t) - u^i(0,t) = -R_o i(0,t) + \int_0^h E_z^i(0,z,t)dz$$

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

Boundary conditions

Point-Centered Finite-Difference Method



Δx: spatial-integration step
Δt: time-integration step

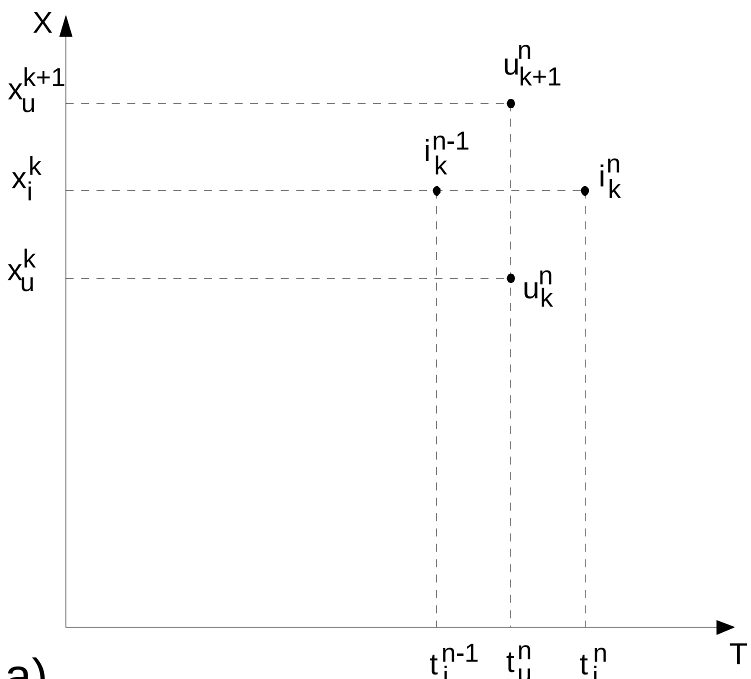
Coupling Model CONTROLLO RETICOLO Cont.

$$\frac{u_{k+1}^{n}-u_{k}^{n}}{\Delta x}+L\frac{i_{k}^{n}-i_{k}^{n-1}}{\Delta t}=\frac{us_{k}^{n}+us_{k}^{n-1}}{2}$$

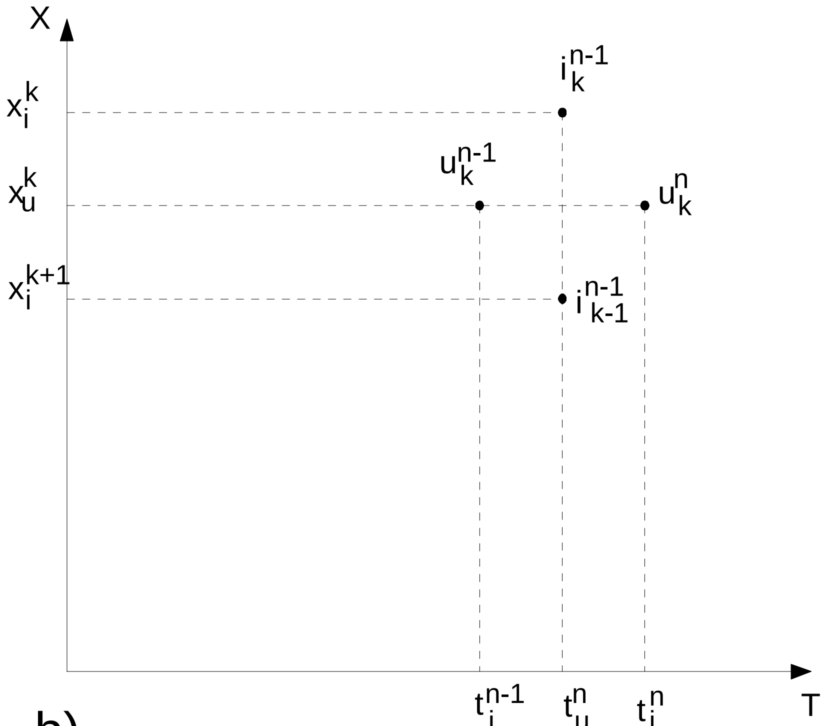
$$\frac{i_{k}^{n-1}-i_{k-1}^{n-1}}{\Delta x}+C\frac{u_{k}^{n}-u_{k}^{n-1}}{\Delta t}=0$$

$$\begin{cases} u_{k}^{n}=u^{s}\{(k-1)\Delta x,n\Delta t\} \\ i_{k}^{n}=i\{(k-0.5)\Delta x,(n+0.5)\Delta t\} \\ us_{k}^{n}=E_{x}^{i}\{(k-0.5)\Delta x,(n+0.5)\Delta t\} \end{cases}$$

k and *n* denote space and time increments



a)



b)

Coupling Model *Cont.*

Internal nodes:

$$u_k^n = A_1\left\{A_2 u_k^{n-1} - \frac{i_k^{n-1} - i_{k-1}^{n-1}}{\Delta x}\right\}$$

$$i_k^n = A_3\left\{\frac{us_k^n + us_k^{n-1}}{2} - \frac{u_{k+1}^n - u_k^n}{\Delta x} + A_4 i_k^{n-1}\right\}$$

with

$$\left.\begin{array}{l} A_1 = \left(\frac{C'}{\Delta t}\right)^{-1} A_2 = \left(\frac{C'}{\Delta t}\right) \\ A_3 = \left(\frac{L'}{\Delta t}\right)^{-1} A_4 = \left(\frac{L'}{\Delta t}\right) \end{array}\right\}$$

Boundary nodes:

$$i_0^n = \frac{3i_1^n - i_2^n}{2}$$

$$u_1^n = h \cdot E_z^i\Big|_0^n - R_o^n \cdot i_0^n$$

$$i_{K_{\max}}^n = \frac{3i_{K_{\max}-1}^n - i_{K_{\max}-2}^n}{2}$$

$$u_{K_{\max}}^n = h \cdot E_z^i\Big|_{K_{\max}}^n + R_L^n \cdot i_{K_{\max}}^n$$

Initial conditions (t=0):

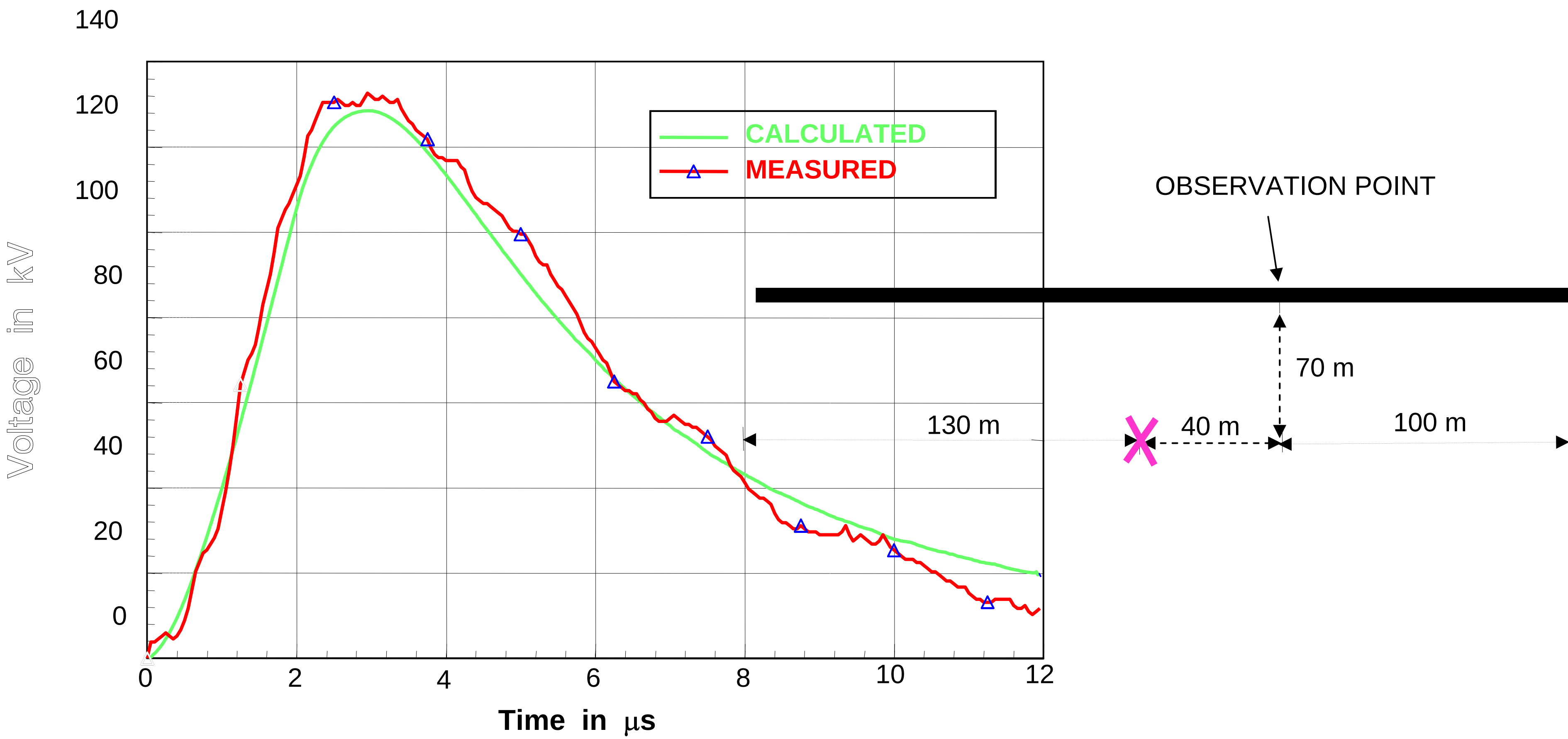
$$i_k^0 = 0 k = 0,1,\ldots,k_{\max}$$

$$u_k^0 = 0 k = 0,1,\ldots,k_{\max}$$

Coupling Model *Cont.*

Reduced scale model at the University Of São Paulo - Brazil

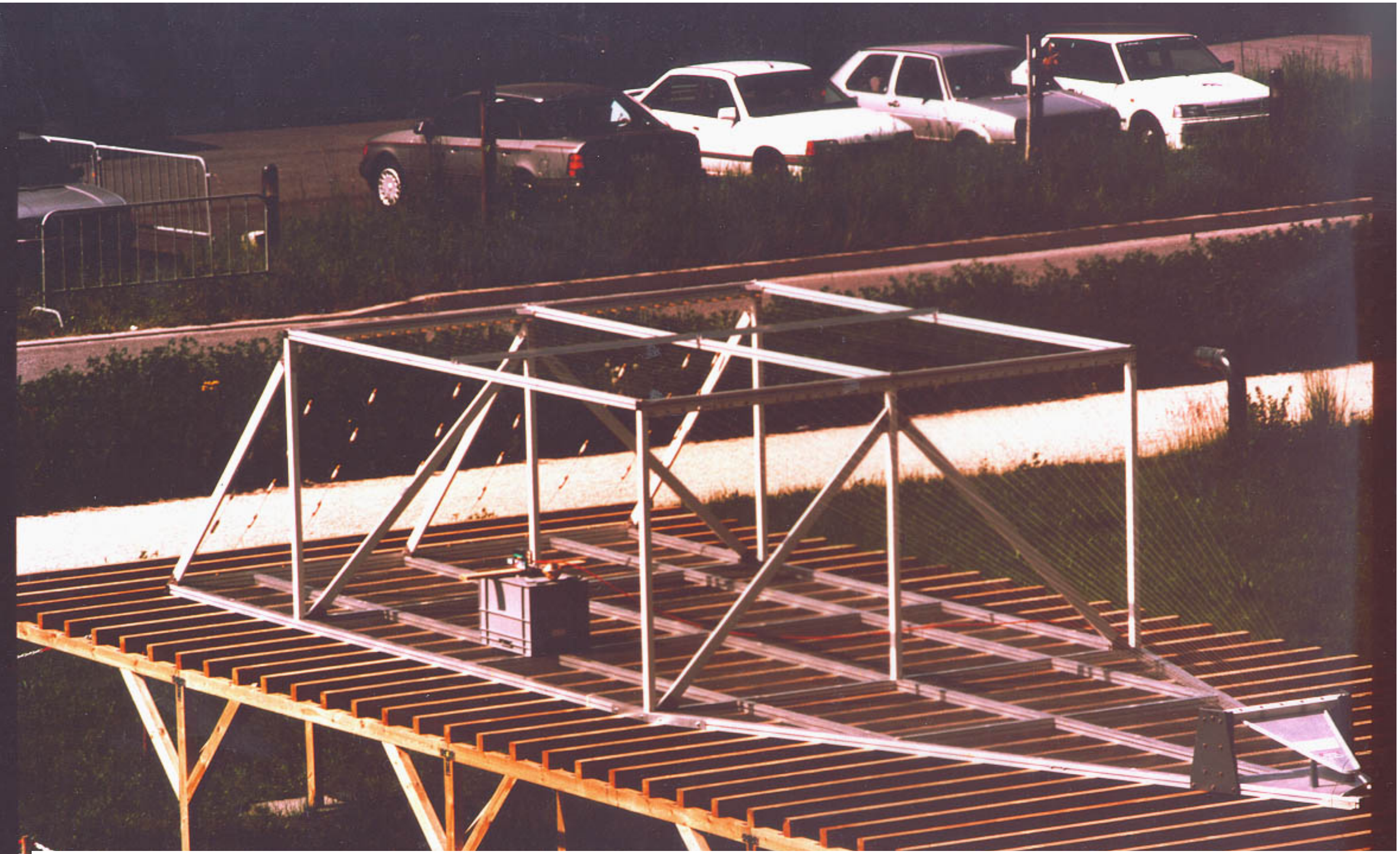
Coupling Model *Cont.*



Example of validation of the Agrawal coupling model

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

Coupling Model *Cont.*



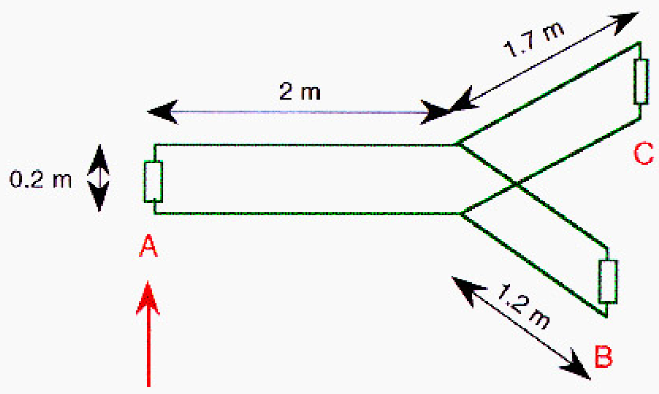
Using NEMP simulators (SEMIRAMIS, EPFL, Lausanne)

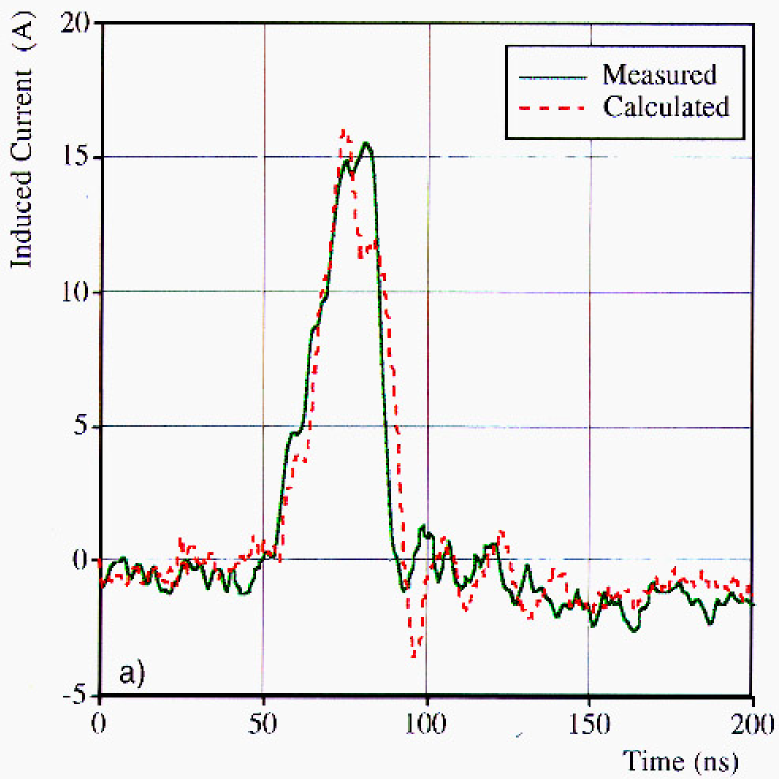
Coupling Model *Cont.*

Comparison with Experimental Results

(Line matched at A, B, C)

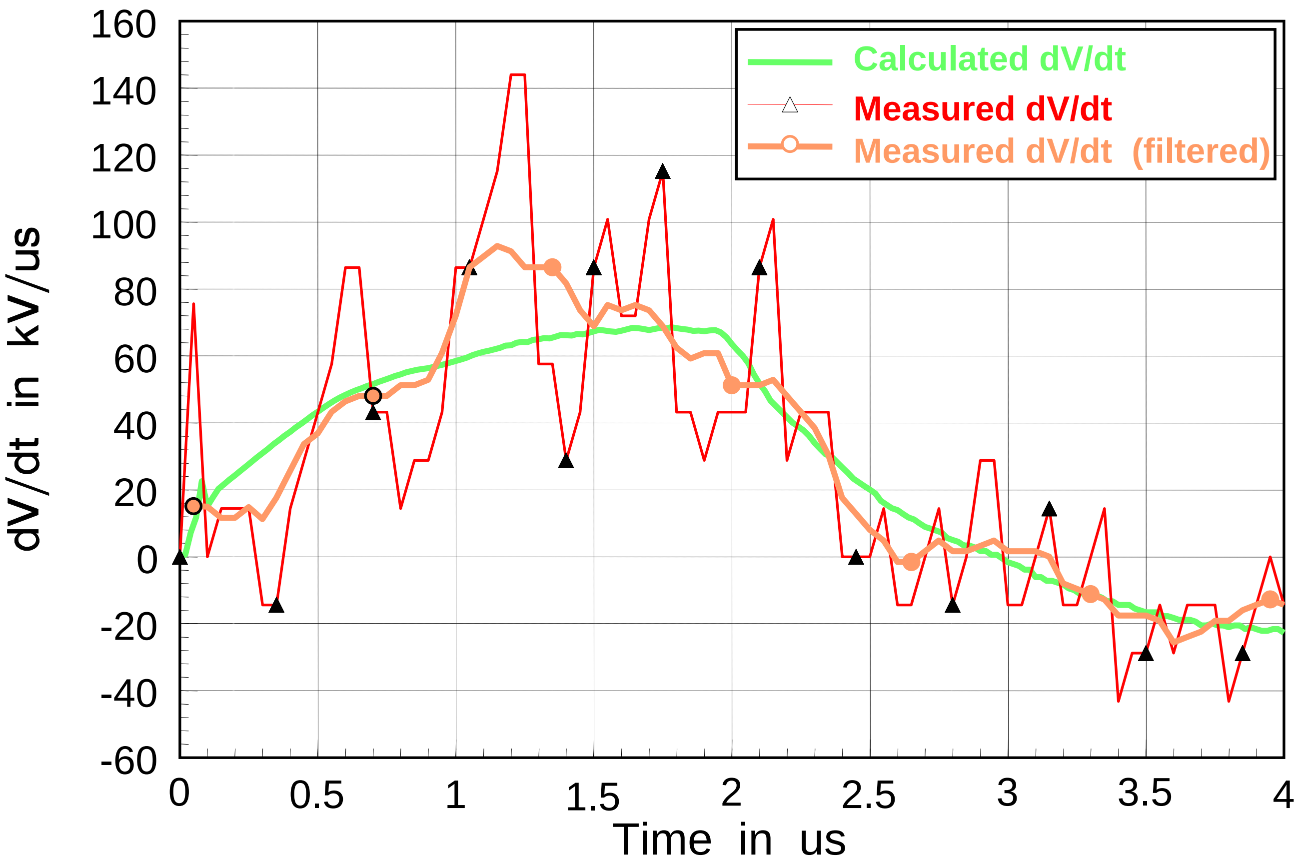
Using NEMP simulators





Adapted by Guerrieri et al., 19

Coupling Model *Cont.*



Using reduced-scale line model

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