Inverse Scattering for Soft Fault Diagnosis in Electric Transmission Lines

Qinghua Zhang, Michel Sorine and Mehdi Admane

INSTITUT NATIONAL
DE RECHERCHE
EN INFORMATIQUE
ET EN AUTOMATIQUE

INRIA

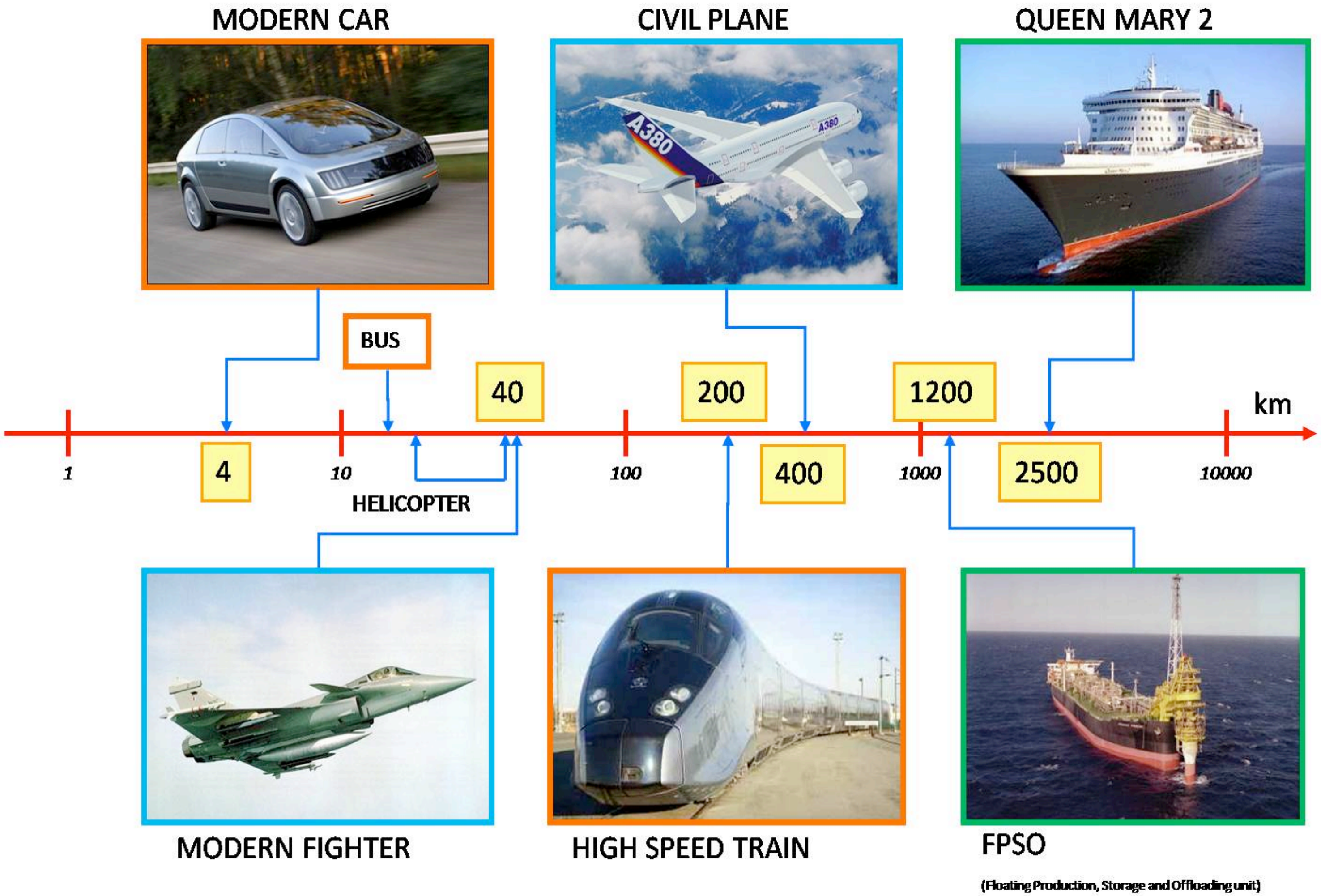
Motivation of the study

- In modern engineering systems, fault diagnosis is frequently an integrated functionality for various system components, but rarely for electrical cables.

- Though often considered reliable, electrical cables can fail, because of
  - aging
  - chemical attacks
  - mechanical and electrical accidents
  - etc.

- There are more and more electrical cables around us……

Total cable lengths in transportation equipments



Images by CEA-LIST

The signaling system of the French national raiway company (SNCF)

The total length of the signaling cables : more than 50 000 km.

Picture by SNCF

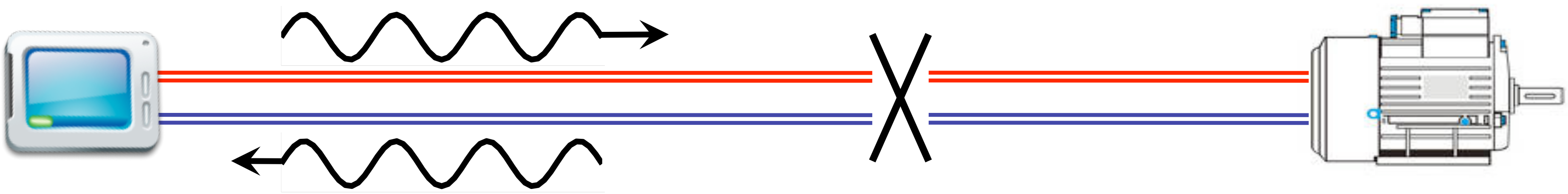
Ongoing projects on cable fault diagnosis in France

➢**ANR 0-DEFECT project**: On-board fault diagnosis for wired networks in automotive systems, with CEA LIST, Renault Trucks, Freescale, PSA, Delphi, Supelec-LGEP and INRIA.

➢**ANR INSCAN project**: Fault diagnosis for security critical long distance electric transmission lines, with SNCF, CEA LIST and INRIA.

➢**DIGITEO DIAGS platform**: Development and validation of diagnostic systems, with CEA LIST, Supelec LGEP and INRIA.

Reflectometry: a well known instrument for hard fault diagnosis



- Basic working principle: response time $\longrightarrow$ 2xdistance
- Efficient for hard faults (open or short circuits)
- Not suitable for soft faults (classical methods)

The proposed method for soft fault diagnosis

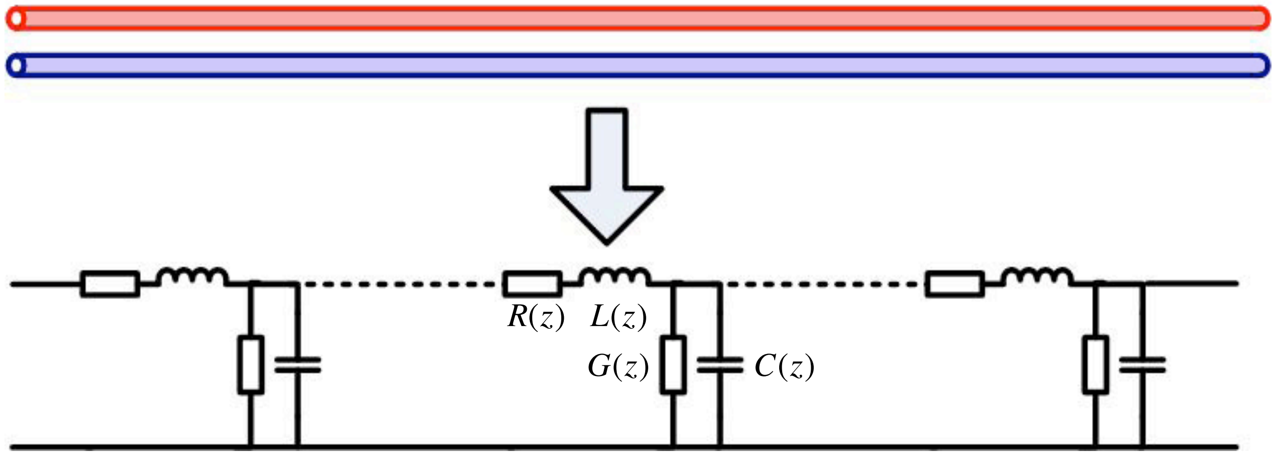
Reflectometry measurement

+

Inverse scattering

Estimation of distributed characteristic impedance

One dimensional model of transmission lines

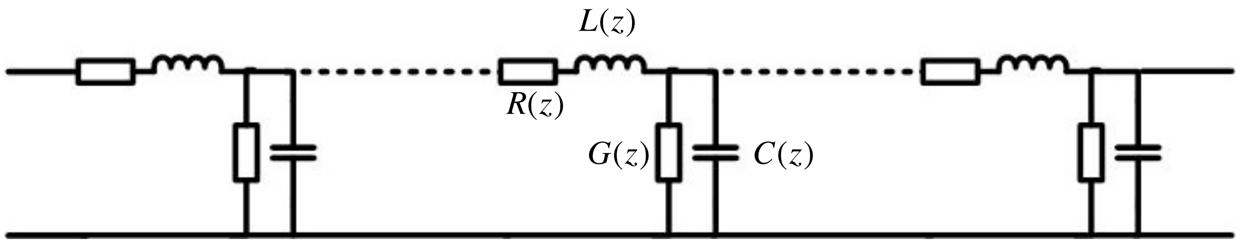


$$\frac{\partial U(t,z)}{\partial z} + L(z)\frac{\partial I(t,z)}{\partial t} + R(z)I(k,z) = 0$$

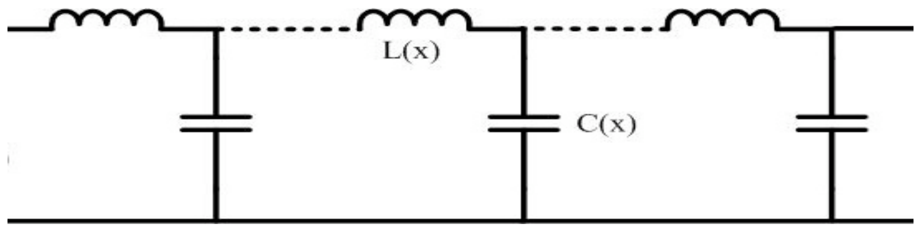
$$\frac{\partial I(t,z)}{\partial z} + C(z)\frac{\partial U(t,z)}{\partial t} + G(z)U(k,z) = 0$$

Telegrapher's equations

Scope of this talk: lossless transmission lines



$R(z) \equiv 0$ $G(z) \equiv 0$

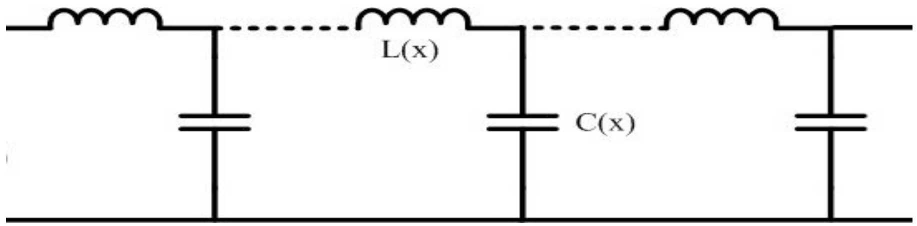


$$\frac{\partial U(t,z)}{\partial z} + L(z)\frac{\partial I(t,z)}{\partial t} = 0$$

$$\frac{\partial I(t,z)}{\partial z} + C(z)\frac{\partial U(t,z)}{\partial t} = 0$$

Good approximation for high quality lines

Frequency domain telegrapher's equations



$$\frac{\partial U(t,z)}{\partial z} + L(z)\frac{\partial I(t,z)}{\partial t} = 0$$

$$\frac{\partial I(t,z)}{\partial z} + C(z)\frac{\partial U(t,z)}{\partial t} = 0$$

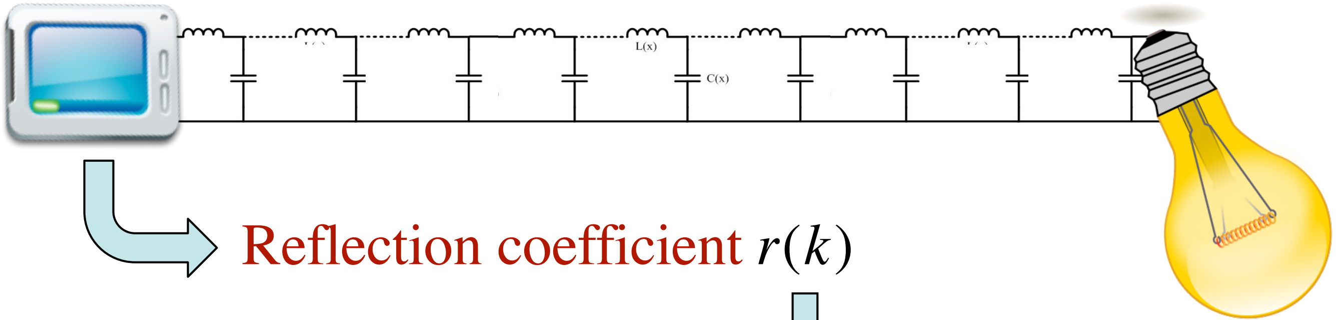
$$U(t,z) \longrightarrow U(k,z) = \int_{-\infty}^{+\infty} U(t,z)\exp(ikt)\,dt$$

$$I(t,z) \longrightarrow I(k,z) = \int_{-\infty}^{+\infty} I(t,z)\exp(ikt)\,dt$$

$$\frac{dU(k,z)}{dz} - ikL(z)I(k,z) = 0$$

$$\frac{dI(k,z)}{dz} - ikC(z)U(k,z) = 0$$

The transmission line inverse scattering problem

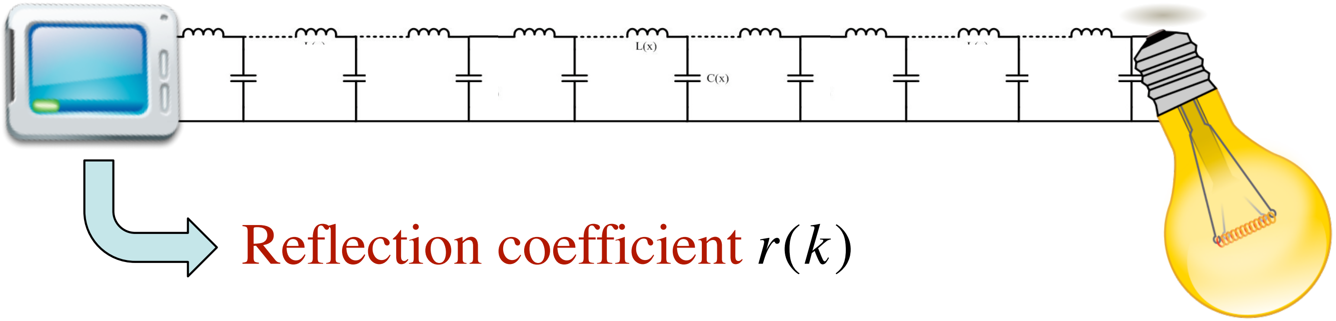


Reflection coefficient $r(k)$

Characteristic impedance $Z_0(x) = \sqrt{\dfrac{L(x)}{C(x)}}$ for all $x \in$ the transmission line

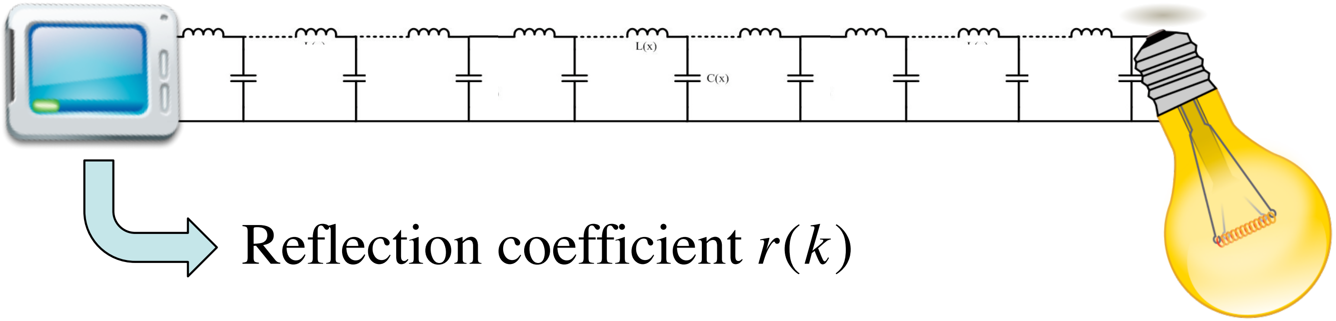
Assumption: soft faults affect $Z_0(x)$.

The reflection coefficient in frequency domain



$$r(k) = \frac{\overbrace{V(k,x_s) - Z_s I(k,x_s)}^{\text{Reflected wave}}}{\underbrace{V(k,x_s) + Z_s I(k,x_s)}_{\text{Incident wave}}} = \frac{Z(k,x_s) - Z_s}{Z(k,x_s) + Z_s}$$

Inverse scattering problem feasibility

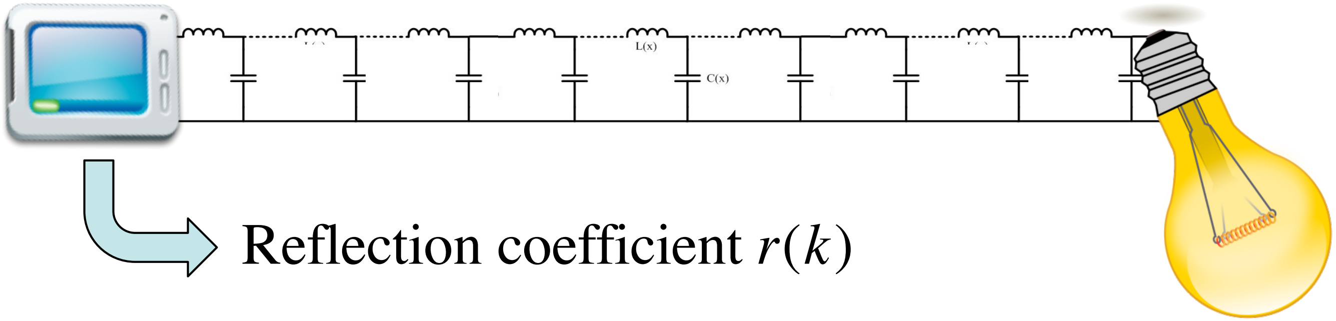


Reflection coefficient $r(k)$

From $r(k)$ measured at one end of the transmission line, is it possible to to compute the distributed $Z_0(x) = \sqrt{\dfrac{L(x)}{C(x)}}$ for all $x \in$ the transmission line?

Yes, if $r(k)$ is measured by scanning the frequencies k!

The distributed parameter system identifiability



Reflection coefficient $r(k)$

From the only measurement of $r(k)$,

the distributed $Z_0(x)=\sqrt{\dfrac{L(x)}{C(x)}}$ is identifiable for all $x \in$ the transmission line,

but $L(x)$ and $C(x)$ are not individually identifiable.

A few words about inverse scattering

- In physics, inverse scattering is the problem of determining the characteristics of an object from observation of radiation or particles scattered by the object.

- In mathematics, inverse scattering refers to the determination of differential equations based on known asymptotic solutions.

A few equations about inverse scattering

Zakharov–Shabat equations:
(similar to Schrödinger equation)

$$\frac{dv_1(k,x)}{dx} + ikv_1(k,x) = q(x)v_2(k,x)$$
$$\frac{dv_2(k,x)}{dx} - ikv_2(k,x) = q(x)v_1(k,x)$$

Jost solution:

$$\lim_{x\to+\infty} v_1(k,x) = 0$$
$$\lim_{x\to+\infty} v_2(k,x)\exp(-ikx) = 1$$

Reflection coefficient:

$$r(k) = \lim_{x\to-\infty} \frac{v_1(k,x)}{v_2(k,x)}\exp(2ikx)$$

$$r(k) \Rightarrow \boxed{\text{Inverse scattering}} \Rightarrow q(x)$$

Connecting the IS theory to transmission lines

Lossless telegrapher's equations

$$\frac{\partial U(t,z)}{\partial z} + L(z)\frac{\partial I(t,z)}{\partial t} = 0$$

$$\frac{\partial I(t,z)}{\partial z} + C(z)\frac{\partial U(t,z)}{\partial t} = 0$$

$$U(t,z) \longrightarrow U(k,z) = \int_{-\infty}^{+\infty} U(t,z)\exp(ikt)\,dt$$

$$I(t,z) \longrightarrow I(k,z) = \int_{-\infty}^{+\infty} I(t,z)\exp(ikt)\,dt$$

$$x(z) = \int_0^z \sqrt{L(s)C(s)}\;ds$$

$$v_1(k,x) = \frac{1}{2}\left(Z_0^{-\frac{1}{2}}(x)U(k,x) - Z_0^{\frac{1}{2}}(x)I(k,x) \right)$$

$$v_2(k,x) = \frac{1}{2}\left(Z_0^{-\frac{1}{2}}(x)U(k,x) + Z_0^{\frac{1}{2}}(x)I(k,x) \right)$$

Zakharov–Shabat equations

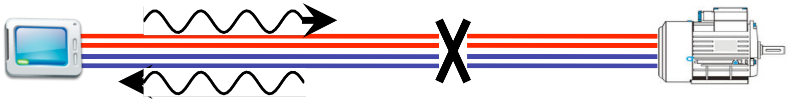
$$\frac{dv_1(k,x)}{dx} + ikv_1(k,x) = q(x)v_2(k,x)$$

$$\frac{dv_2(k,x)}{dx} - ikv_2(k,x) = q(x)v_1(k,x)$$

$$q(x) = -\frac{1}{2Z_0(x)}\frac{dZ_0(x)}{dx}$$

Main reference: Jaulent 1982

The gap between theory and practice



- Finite length lines
- $r(k)$ measured at an end of the line.

Zakharov–Shabat equations

$$\frac{dv_1(k,x)}{dx} + ikv_1(k,x) = q(x)v_2(k,x)$$
$$\frac{dv_2(k,x)}{dx} - ikv_2(k,x) = q(x)v_1(k,x)$$

- Defined for $x \in (-\infty, +\infty)$
- $r(k)$ defined at $x \to -\infty$

New results filling the gap:

- The finite line can be infinitely extended in an "equivalent manner".
- The practical and theoretic reflection coefficients $r(k)$ are equal.

(Now it is understood that, in historical references, the two $r(k)$ differ by a negative sign, because of an inconsistent notation choice.)

The inverse scattering computations

Fourier transform: $\rho(x) = \frac{1}{2\pi}\int_{-\infty}^{\infty} r(k)\exp(-ikx)\,dk$

Gel'fand-Levitan-Marchenko (GLM) equations:

$$A_1(x,y) + \int_{-y}^{x} A_2(x,s)\rho(y+s)ds = 0$$

$$A_2(x,y) + \rho(x+y) + \int_{-y}^{x} A_1(x,s)\rho(y+s)ds = 0$$

$$q(x) = 2A_2(x,x)$$

$$\frac{L(x)}{C(x)} = \frac{L(x_S)}{C(x_S)}\exp\left(-4\int_{x_S}^{x} q(s)ds\right)$$

Efficient numerical algorithms: (Frangos and Jaggard 1991), (Xiao and Yashiro 2002).

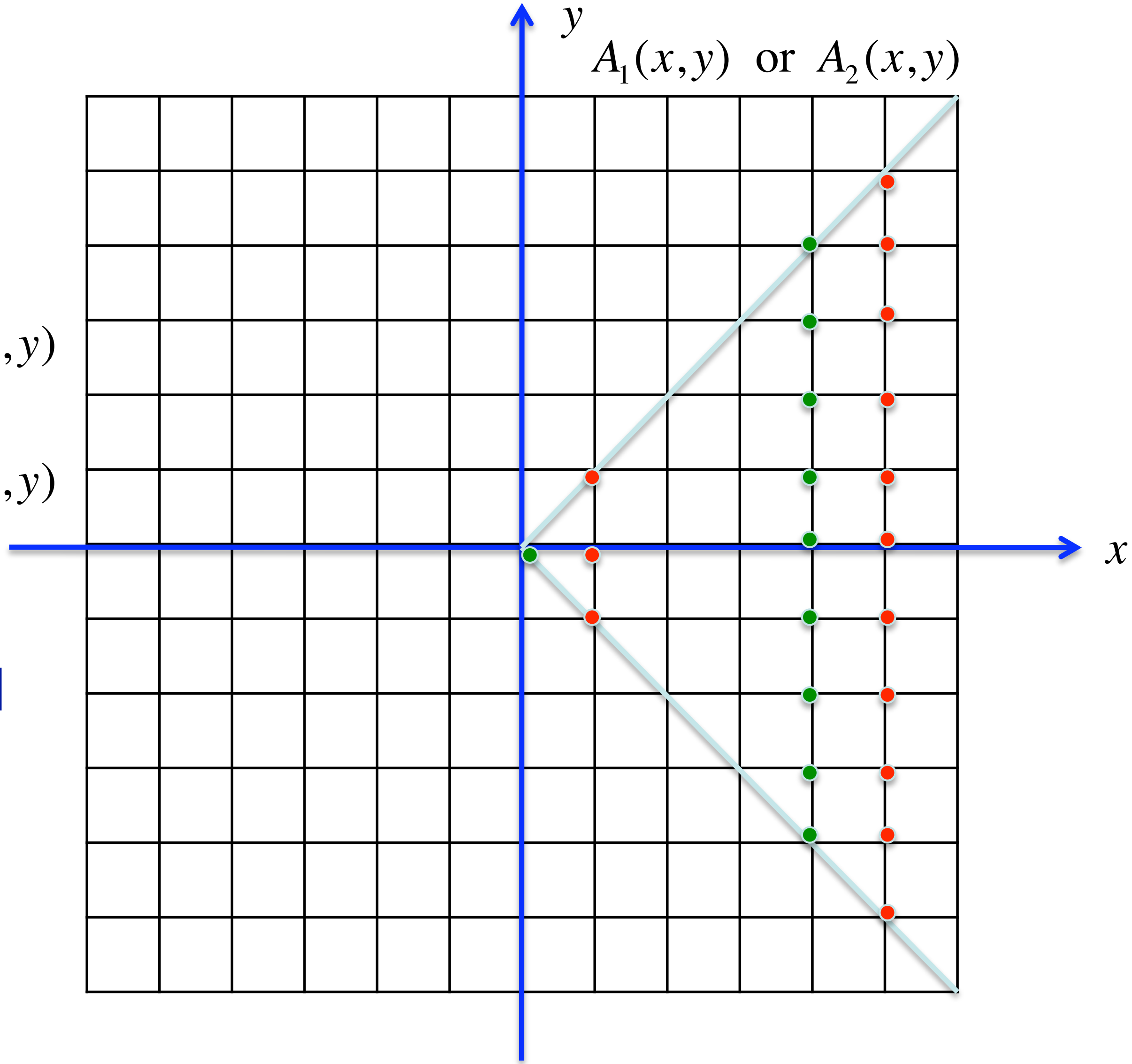
An efficient numerical algorithm

Make use of
extra equations

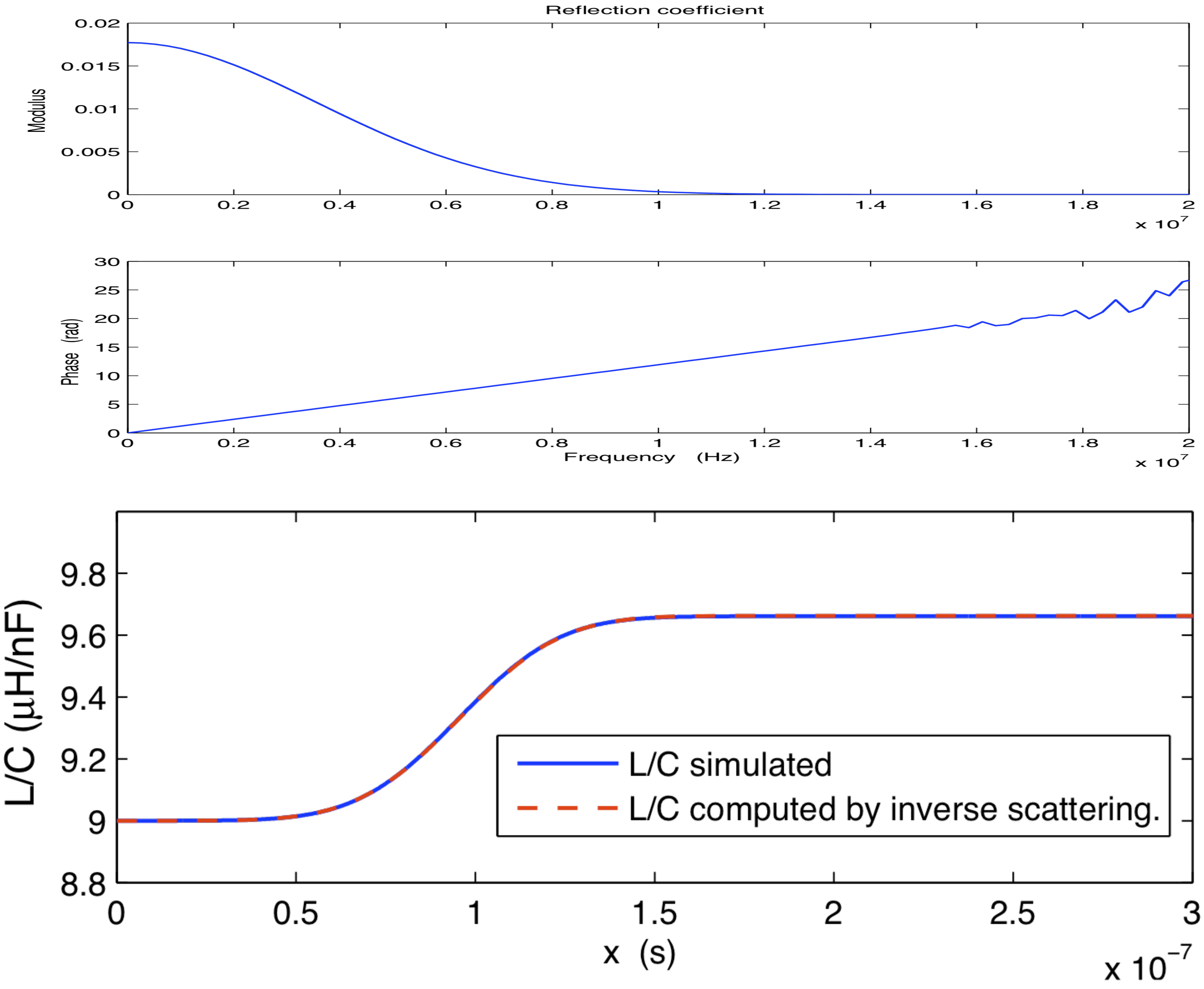
$$\frac{\partial A_1(x,y)}{\partial x} + \frac{\partial A_2(x,y)}{\partial y} = q(x)A_2(x,y)$$

$$\frac{\partial A_2(x,y)}{\partial x} - \frac{\partial A_2(x,y)}{\partial y} = q(x)A_1(x,y)$$

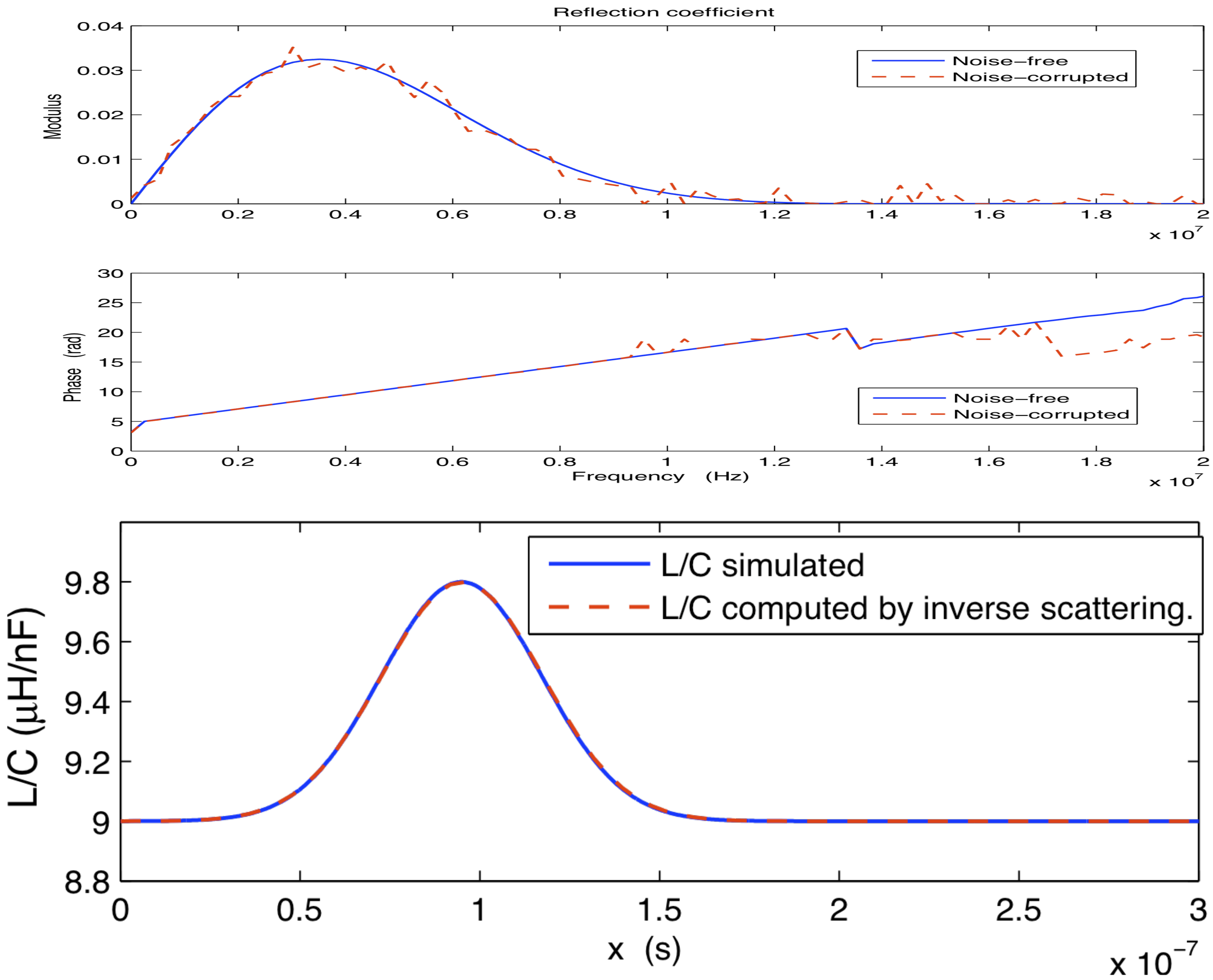
[Frangos and Jaggard 1991]
[Xiao and Yashiro 2002]



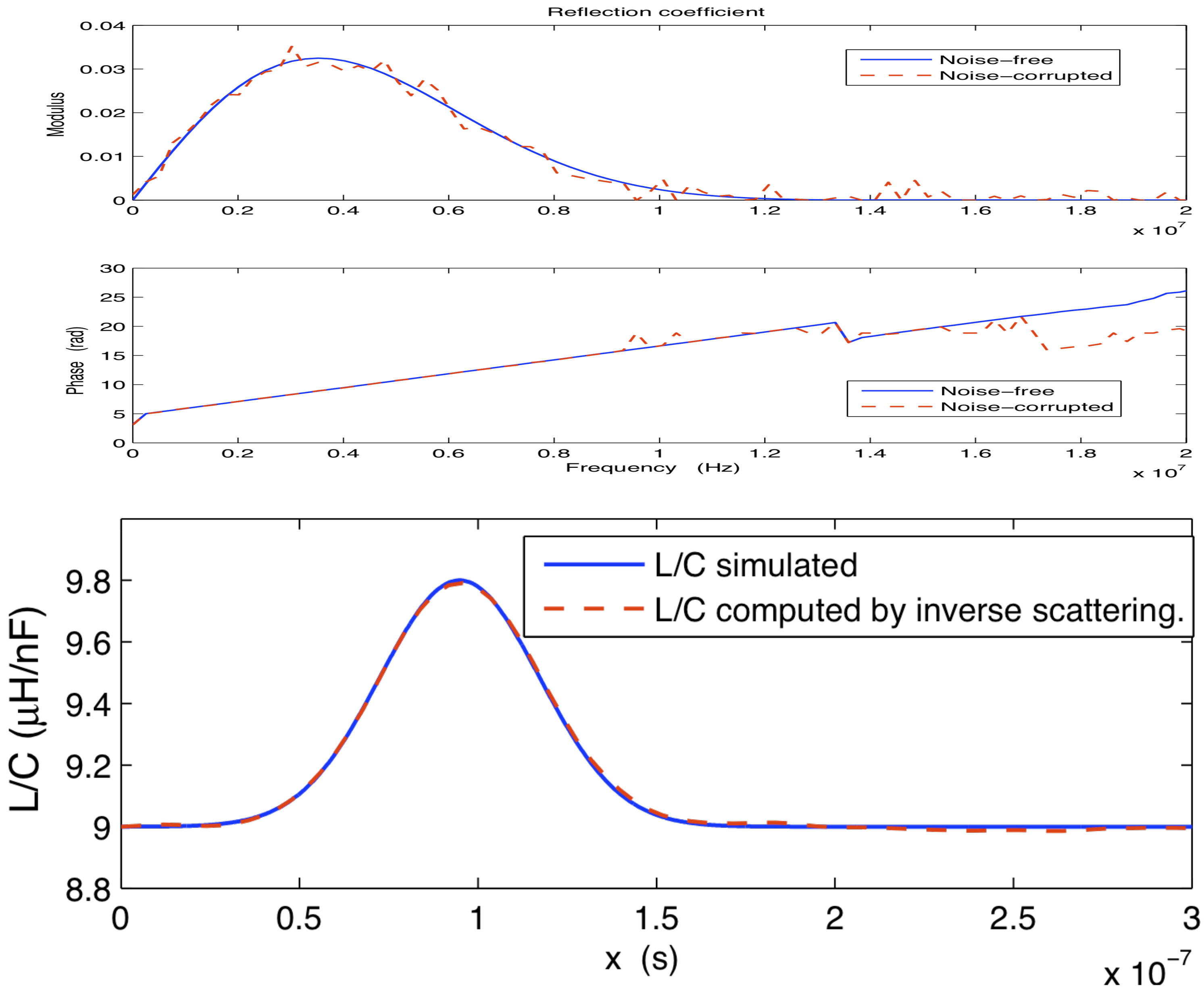
Numerical simulation 1



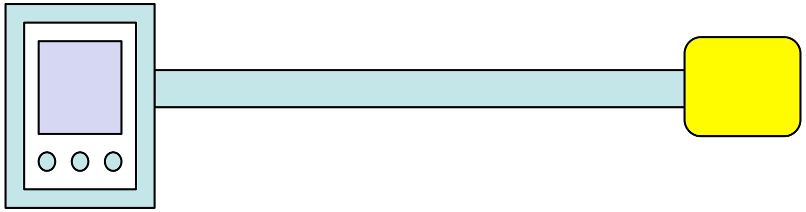
Numerical simulation 2 (noise-free)



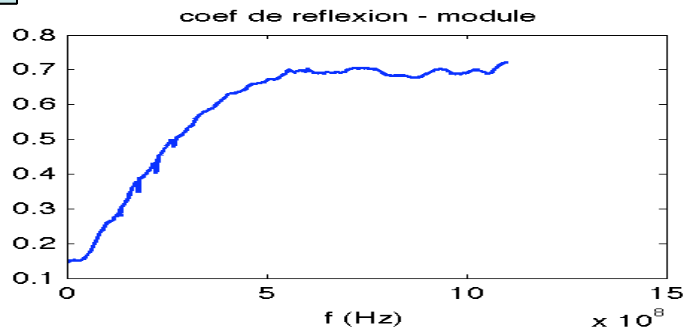
Numerical simulation 2 (noise-corrupted)

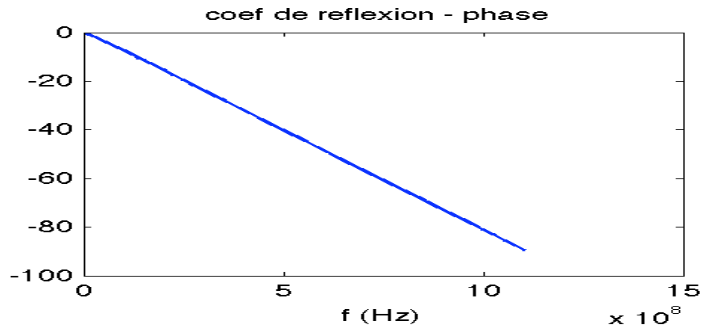


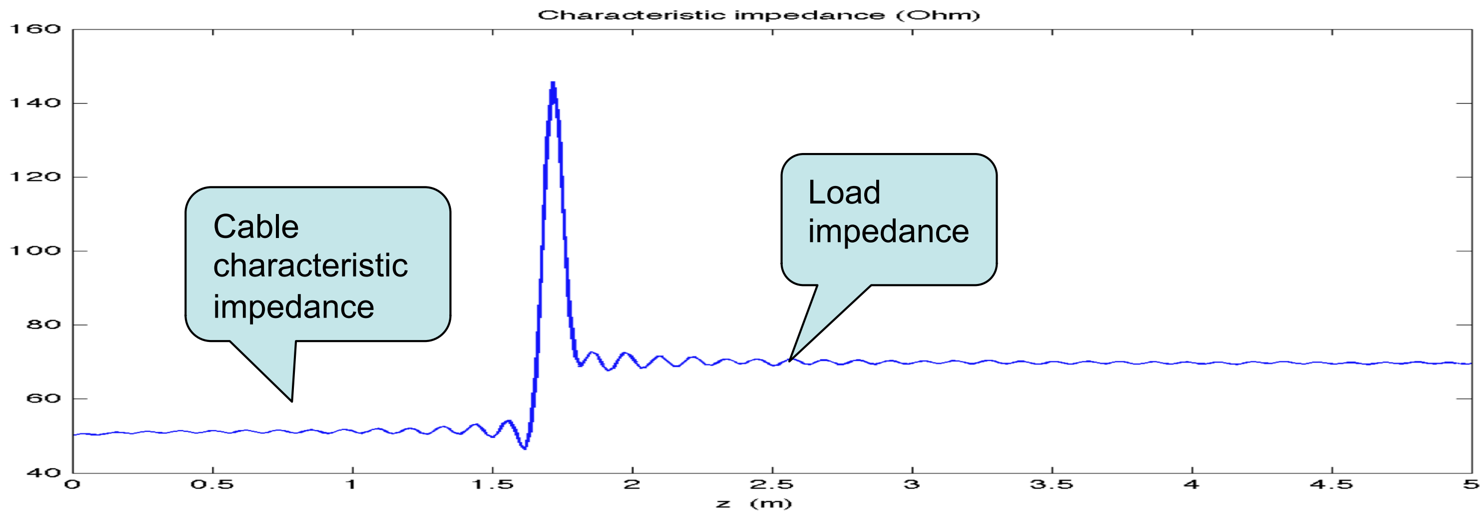
Laboratory experimentation 1



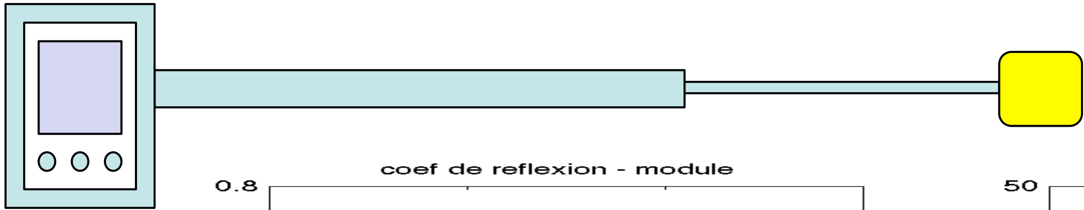
Data provided by Supelec-LGEP



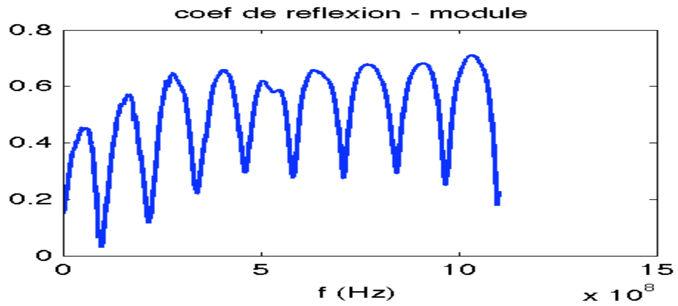


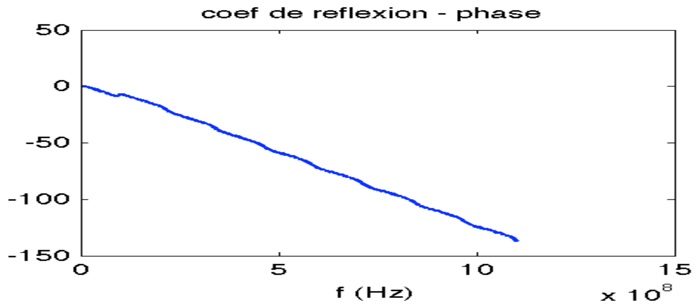


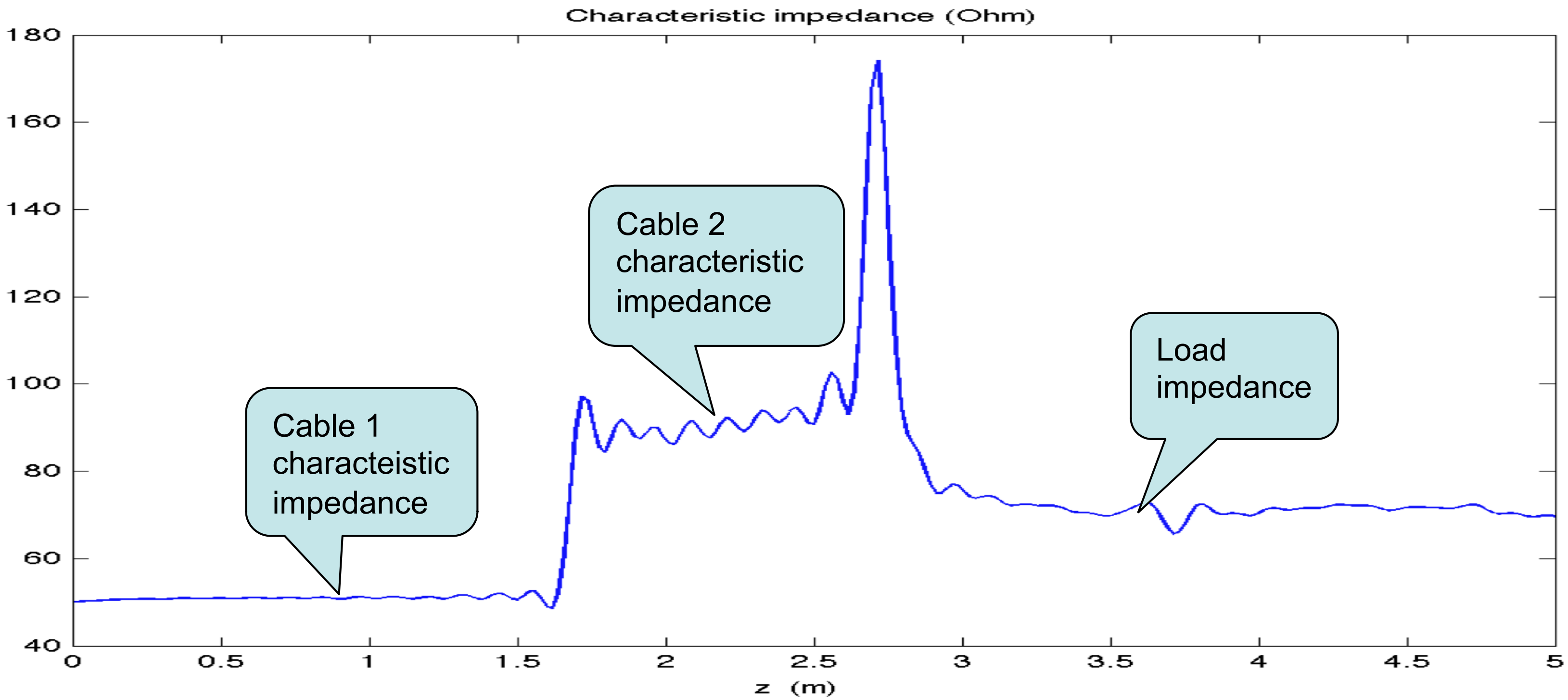
Laboratory experimentation 2



Data provided by Supelec-LGEP







Summary

- Inverse scattering applied to reflectometry is a powerful tool for soft fault diagnosis of transmission lines.

- New results:
  - Theoretical gap filled.
  - Promising simulation and experimental results.

Ongoing works

- Inverse scattering for lossy single transmission line: satisfactory theoretical and simulation results, experimentation currently under study.

- Multi-conducteur (multi-pair) transmission lines.

- Simple networks of transmission lines.

Acknowledgement

Thanks to CEA, SNCF and Supelec-LGEP partners for having provided pictures and experimental data.

Publications based on or related to this work

- Q. Zhang, M. Sorine, and M. Admane, “Inverse scattering for soft fault diagnosis in electric transmission lines,” accepted by *IEEE Transactions on Antennas and Propagation* in August 2010. http://hal.inria.fr/inria-00365991/

- H. Tang and Q. Zhang, “Lossy electric transmission line soft fault diagnosis: an inverse scattering approach.” http://hal.archives-ouvertes.fr/inria-00511353/en/. Presented at IEEE International Symposium on Antennas and Propagation, Toronto, July 2010.