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RECIPROCITY APPROACH FOR EM EMISSION OF CABLES IN A 3D GEOMETRY

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Abstract

The paper presents a numerical method for calculating EM emission of cables installed in a complex 3D geometry. This method based on the reciprocity principle relies on a field-to-transmission line coupling model. In a first part, the validation of the method is made on canonical configurations, performing calculations comparing the results with direct methods only. In a second part, the validation is made by comparing the calculated results with measurements on a satellite mock-up.

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1 INTRODUCTION

3D computer codes based on the resolution of Maxwell's equations, such as the wellknown FDTD codes, have the capacity to solve both EM coupling and EM emission problems. Nevertheless, those codes are unable to account for the complexity of multiconductor cables. However, cables are essential contributors for EM coupling on complex systems. In numerical simulations of cable EM-susceptibility, the field-to-transmission-line method [1] already offers an efficient operational methodology by proposing a resolution in two separate steps : the calculation of the incident fields on the wiring-routes with a 3D code and the calculation of the response of the wiring with a multiconductor cable network code. The coupling model favored at ONERA is Agrawal's model. Because of its simplicity, this model has many advantages compared to Taylor's or Rachidi's models. Making the approximation that the dielectric of the cables is negligible for the determination of the equivalent sources, the application of this model, here based on the chaining of an FDTD code (ONERA's ALICE code) and a cable-network code (ONERA's CRIPTE code), has been validated in many references ([2], [3]).

As far as an EM emission problem is now concerned, one might intuitively think of applying the same methodology in a reverse way. This one could be decomposed in 3 main steps :

- apply a perturbing source at the extremity of the wiring,
- calculate the current distribution along the cables with a cable computer code,
- make those currents radiate with a Maxwell-3D-code.
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For some specific geometry configurations, no 3D code is required and this approach can be applied when one has analytical expressions of Green's functions for the radiation of the currents along the cables. This is the case for a cable over an infinite ground plane [4]. Nevertheless, in a 3D configuration, and from the point of view of applying the technique with available numerical tools developed at ONERA, such an approach is not appropriate for a parametric study onto a given wiring topology. Indeed, for any modification of the topology of the wiring under study, concerning the terminal loads, the cable-bundle constitution, the height of the cable, a 3D calculation is required. One must realize that 3D calculations are generally time and memory requiring. Besides, one could think of directly applying the current distributions in the 3D solvers but the application of current conditions in adjacent cells requires the respect of Maxwell's equations and therefore this approach presents a real theoretical and technical difficulty; any error or current approximation of those currents is likely to introduce undesirable and not controlled numerical effects.

Finally, in the particular case of FDTD codes, problems related to the positioning of current elements anywhere in the structured mesh may occur. In the ALICE code for example, current generators are necessarily applied on wires, themselves positioned on the edges of the cells. Such a configuration barely fits with real cable routes. On the other hand, one might think that the use of a frequency domain 3D code (as an integral equation-based code) could overcome those drawbacks. However, such codes are generally more time and memory requiring than FDTD-like codes. In order to treat large dimension problems, such as the ones considered at the end of this article, they require large computer resources.

Hopefully, an appropriate reciprocity-formulation of the problem offers one the possibility to treat the EM emission problem by the resolution of an EM susceptibility problem. The way the reciprocity problem is formulated is exactly the one described in [1]. After some recalls on the reciprocity principle, the paper mainly focuses on the application of this formulation to build a methodology applicable to complex system models. The validation of the methodology is first presented on canonical configurations allowing us to validate the results with other direct methods. Then the demonstration is made on a complex 3D geometry on which reference measurements have been performed.

This article is mainly inspired from a French paper submitted to a French conference in 2002 [5].

2 NUMERICAL SIMULATION METHOD

Hereafter, we will recall how that the EM field radiated by a transmission line can be expressed by solving an EM coupling problem and by using the reciprocity theorem applied on an equivalent 2-port circuit [1]. We start from the reciprocity principle. We consider two EM-states characterized by their sources, their current and magnetic current densities, respectively (J_1, M_1) and (J_2, M_2). Those sources radiate and generate EM fields, (E_1, H_1) for EM-state 1 and (E_2, H_2) for EM-state 2. In a supposed infinite, linear and isotropic medium, both EM- states are related by the following volume integral :

$$\iiint_{volume}\left(E^1\cdot J^2 - E^2\cdot J^1 - H^1\cdot M^2 + H^2\cdot M^1\right)dv = 0 \qquad (1)$$

In the case where electric and magnetic sources are localized in space, for example, in the case of localized current or voltage sources, relation (1) which relates EM fields may be written under the form of a relation combining current and voltage of an n-port circuit.

In the particular case of a 2-port circuit (Figure 1), the reciprocity equation is given by :

$$V_a^1 I_a^2 + V_b^1 I_b^2 = V_a^2 I_a^1 + V_b^2 I_b^1 \qquad (2)$$

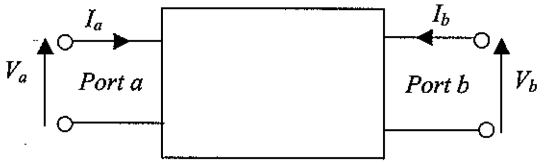

Figure 1 – 2-port circuit

By judiciously choosing EM-state 1 and EM-state 2 (Figure 2), relation (2) can be simplified :

- EM-state1 : a voltage generator $\tilde{V}_a^1$ is applied on port « a » with port « *b* » left in open circuit. The current I_b^1 on port b is therefore equal to zero.
- EM-state 2 : a current generator $\bullet_b^2$ is applied on port « b » and port « *a* » is left in open circuit. The voltage V_a^2 on port is therefore equal to zero.

The second reciprocity equation (2) is therefore reduced to :

$$\tilde{V}_a^1 I_a^2 + V_b^1 \tilde{I}_b^2 = 0 \qquad (3)$$

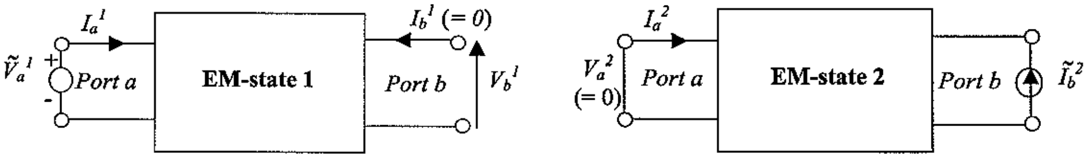

Figure 2 – Application of the reciprocity principle to the 2-port circuit. Choice of EM-state 1 and EM-state 2

2.1 Identification of the problem with a 2-port circuit

In the case of a localized EM electric field radiated by a wire on which a voltage source is applied, we can imagine a fictitious 2-port circuit whose 2 port are defined as followed :

- port « a » is located at the cable end where the voltage source is applied
- port « b » is located on a localized element *dl* where the E field is calculated (Figure 3).

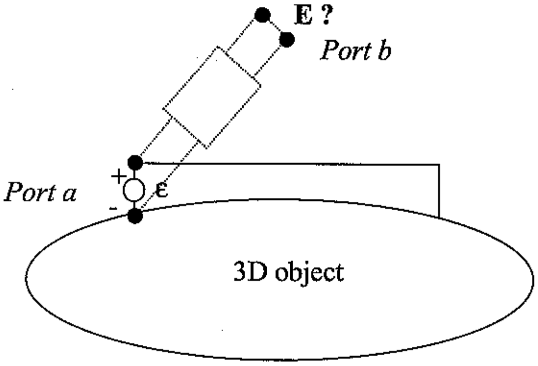

Figure 3- Identification of the problem with an equivalent 2-port circuit

2.2 Reciprocity problem formulation

The two EM-states are defined :

- EM-state 1 stands for the cable EM emission problem under study (Figure 4),
- EM-state 2 stands for the EM susceptibility of the same cable submitted to the radiation of a current element on port « *b* » (Figure 5).

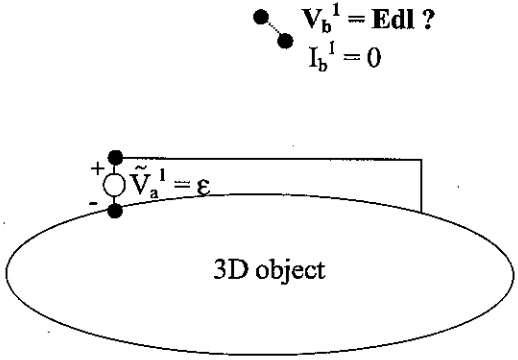

Figure 4 – Reciprocity method – EM-state-1's definition

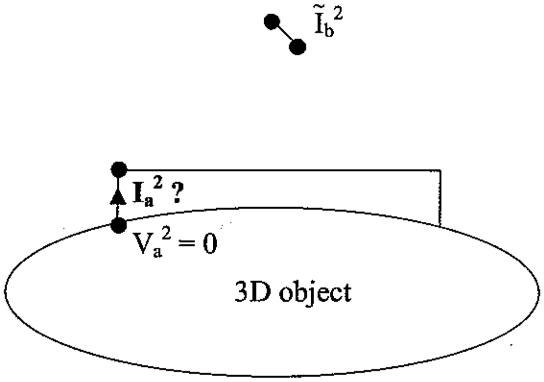

Figure 5 – Reciprocity method – EM-tate-2's definition

Consequently, the resolution of EM-state 2 by a field-to-transmission-line technique and the application of relation (3) allow one to determine entirely state-1's solution from state-2's solution.

$$E.dl = -V_a^1 \frac{I_a^2}{I_b^2} = -\varepsilon \frac{I_{LT}}{I_{source}} \qquad (4)$$

2.3 Application with a 3D solver

As mentioned in the introduction, an efficient method to solve EM-state 2 relies on the chaining of a 3D computer code and a cable network computer code. At ONERA, this chaining is already entirely operational and is fully validated ([1], [3], [6]). The ALICE code (operating in the time domain) provides the calculated incident electric fields tangent to the wiring routes (in the absence of the cable) as required in Agrawal's formalism. Those fields are induced by the application of a current source $\bullet_b^2$ onto an element of length *dl* (port « b »). Those electric fields are then introduced in the cable computer code as voltage sources distributed along the cable models. The CRIPTE code operates in the frequency domain. A calculation of the current I_a^2 generated by the application of the tangent electric fields on the wiring is made at the same position as the position of the voltage generator in state 1. The reciprocity relation (4) enables us to solve EM-state-1.

In this calculation, one will note that the electric fields produced by the current generator do not go to zero at late time . On the contrary, they stabilize around a constant value. This phenomenon can be explained by the fact that the capacitance existing between the current element and the 3D structure is charged. Therefore, precautions are required in the chaining of ALICE (time domain) and CRIPTE (frequency domain) when the Fourier transforms of each electric field component, tangent to the wiring routes, is made. In the past, we have shown the possibility to perform a time domain filtering of the responses (Hanning windows) before performing FFTs ([6], [7], [8], [9]).

In the application examples described hereafter, despite the increase of the calculation time, we have used a discrete Fourier transform (DFTs) providing more precise results while removing the problem of Hanning filtering.

The technique used is presented in Figure 6. Unlike with the FFT technique, the constant part of the signal is rigorously taken into account by decomposing the signal in two parts (time varying and constant parts). The Fourier transform is then obtained by :

$$F(\omega)=\int_0^{t_0} f(t)e^{-j\omega t}dt+\frac{A}{j\omega}e^{-j\omega t_0} \qquad (5)$$

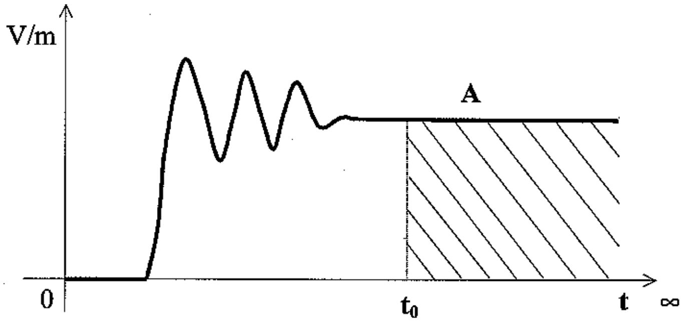

Figure 6 – Decomposition of the field signal in order to account for the constant late-time part

3 RESULTS

3.1 Numerical validations

In a first step, the reciprocity method is compared with direct methods (treatment of the emission problem in a single step). One must note that the ALICE code, as most of the 3D codes, accounts for simple wire structures (thin wire models) and that the cable radiation module in CRIPTE is valid only if the cable is considered onto an infinite metallic ground plane ([7], [8], [9]). Consequently, a first and natural validation case dealt with considering a one-wire transmission line on a ground plane. Figure 7 presents the calculations of the radiated electric field obtained by the 3 methods at a test-point located vertically to the line and at a 1-meter height.

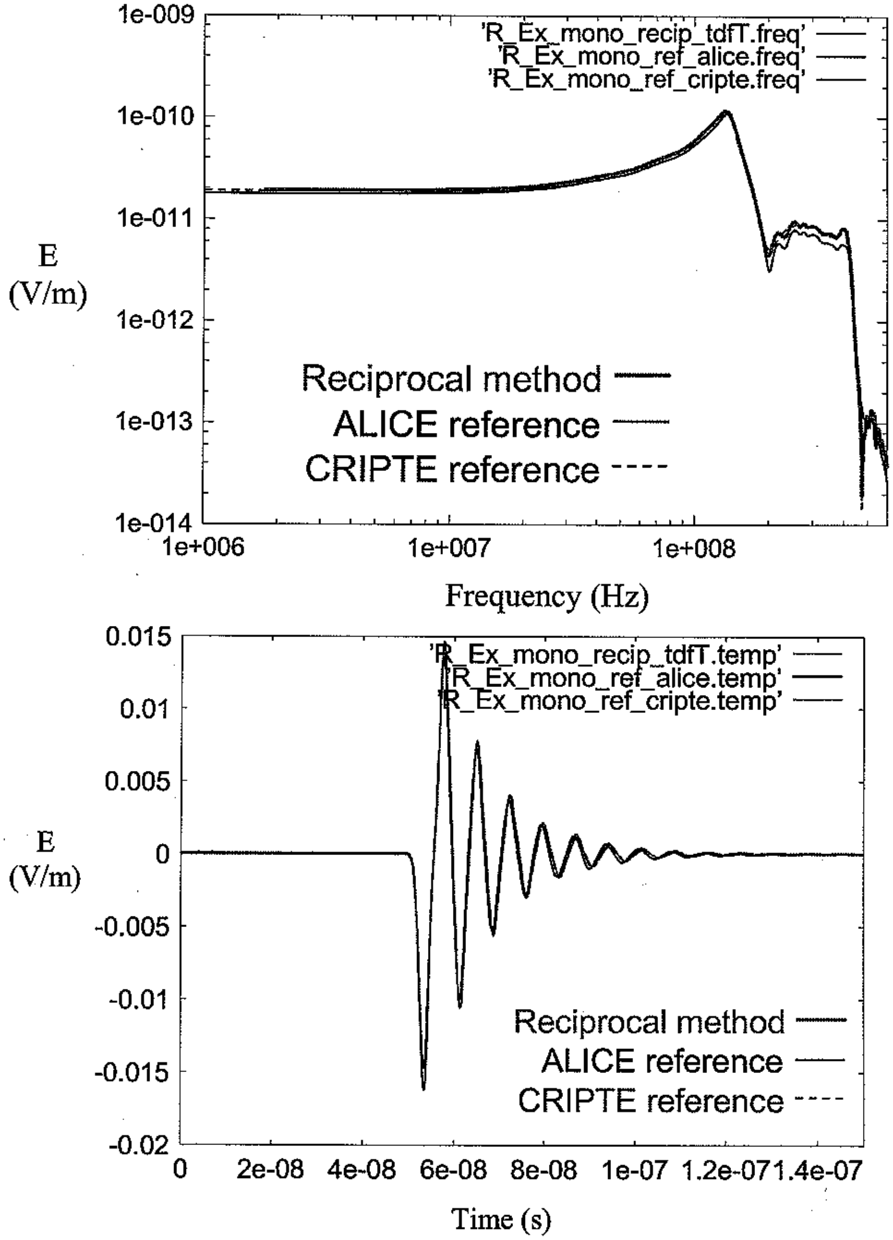

Figure 7 – Electric field radiated at one test-point by a one-wire transmission line over an infinite ground plane. Comparisons between the reciprocity approach and direct reference methods.

3.2 Experimental validations

In a second time, the reciprocity calculation method is applied on a satellite mock up (Spacebus-300A-type, Figure 8) for which the FDTD mesh is represented in Figure 9. . The volume of the satellite is approximately 16 m^3. The number of cells is equal to 11647152 (calculation volume : Ni=228,Nj=198,Nk=258) (2080000 for the satellite mock up volume : Ni=130,Nj=100,Nk=160). The size of a cube-cell is equal to 2 cm. The 3D calculation on EM-state 2 was made on a Pentium III (550 MHz Xeon) Dell PC with 1 Gb of memory and took approximately 14 hours (for 8192 iterations – time step = 3.10^{-11} s). The calculation time for the cable network response is negligible compared to the 3D calculation time. Note that ONERA had already used this mock-up in past studies to analyze and model the susceptibility of electric wiring to ESDs ([6],[8]). Calculated results are compared against experimental results (Figure 10, Figure 11 and Figure 12).The calculation of the incident fields being made once and for all for a given location of the current element injection, different types of cables could be tested on the same routes.

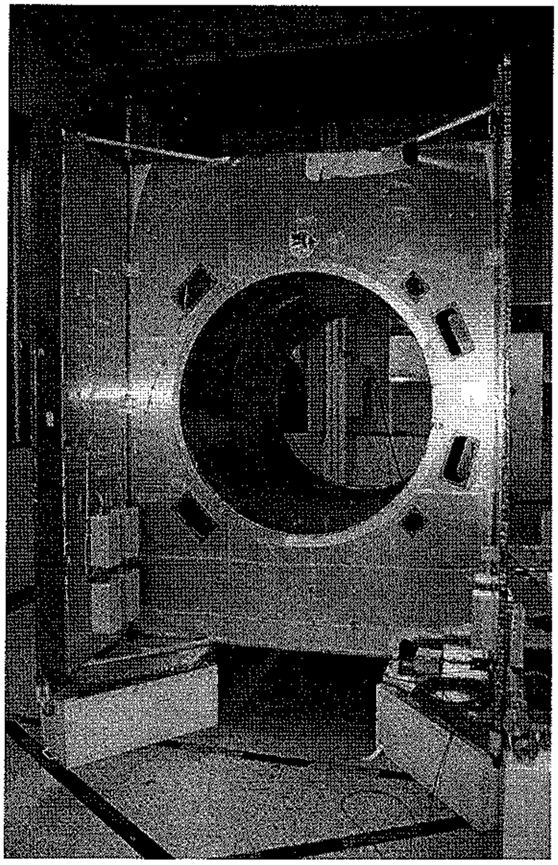

Figure 8 – Satellite mock-up – view of North panel, South panel and « internal deck »

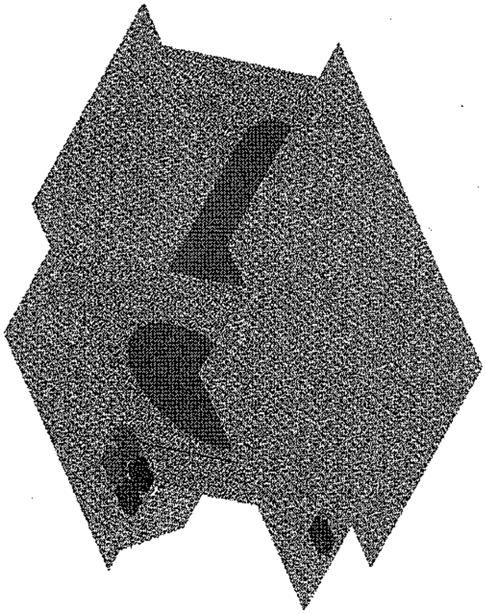

Figure 9 – Mesh of the satellite mock-up.

In order to obtain a good quality in the comparisons, all the characteristics of the measuring apparatus used during the experiment had to be precisely taken into account (amplifiers, measurement cables ...).

In the two first configurations of a one-wire cable and an unshielded twisted pair (Figure 10 and Figure 11), we verify that the field levels are higher than in the second configuration of the shielded twisted pair (Figure 12). In this last case, the sensitivity of the measurement apparatus being too low, only fields for frequencies higher than 10 MHz could be measured.

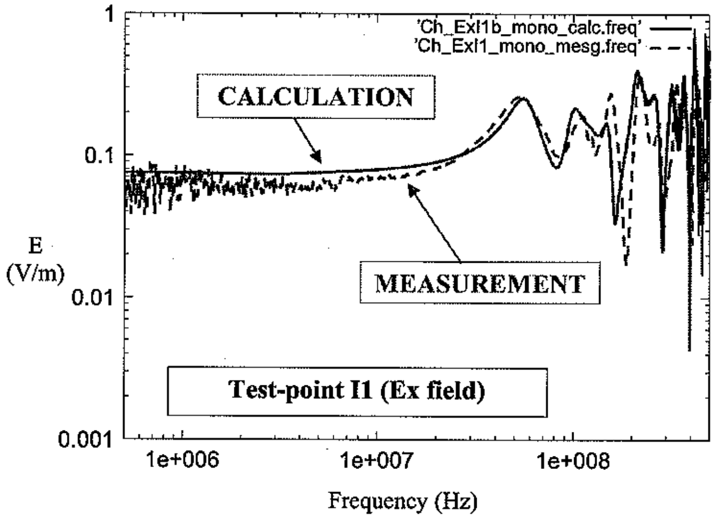

Figure 10 – Electric field radiation of a one-wire cable on the satellite mock-up at test-point I1

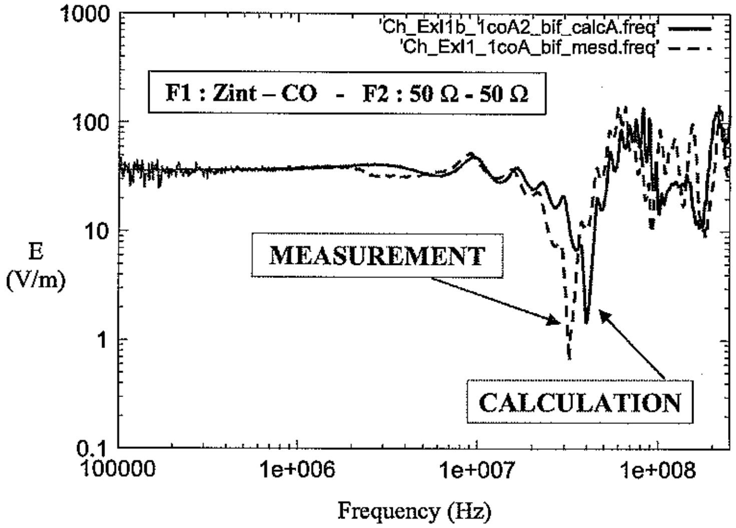

Figure 11 – Electric field radiation of an unshielded twisted pair on the satellite mock-up at test-point I1

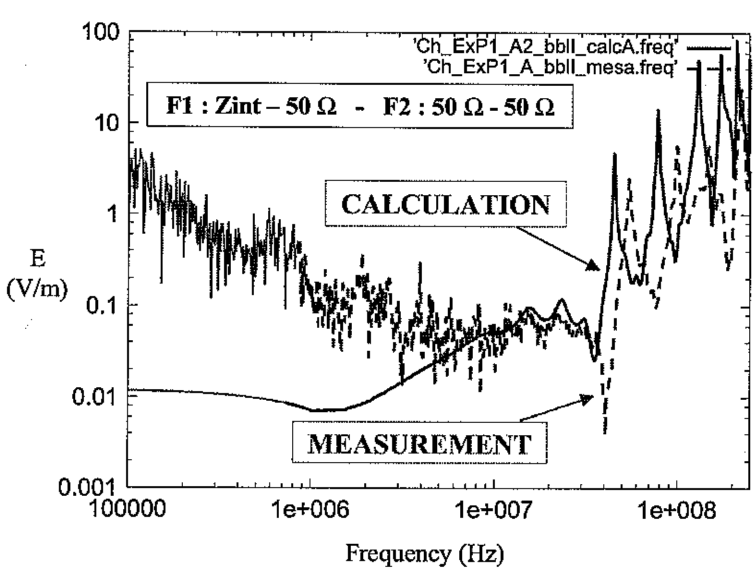

Figure 12 - Electric field radiation of a shielded twisted pair on the satellite mock-up at test-point P1

4 ACCOUNTING FOR THE RADIATION OF NEIGHBORING CABLES

The field measurements on the mock-up have demonstrated the importance to account for cables close to the "emitting" cable (combined EM coupling and radiation of neighboring cables phenomenon). In Figure 13, we see that the field simulation is comparable to the measurement only when the neighboring cable 5 is disconnected [7].

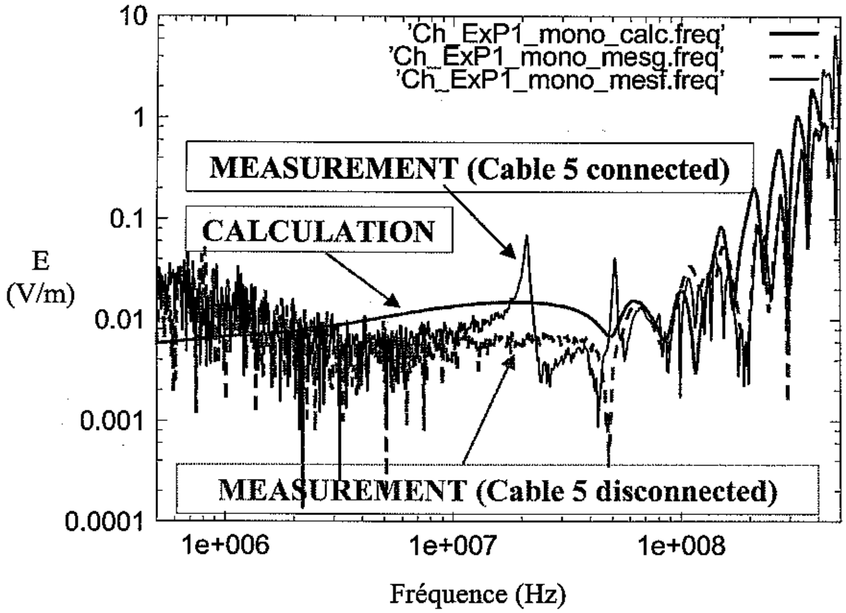

Figure 13 – Radiation of the one-wire cable at test-point P1 on the satellite mock-up. Influence of a neighboring cable

However, when the topology of the neighboring wires is controlled precisely enough, such a phenomenon can be taken into account in numerical simulations. Again, let us take the example of the radiation of a one-wire cable on an infinite ground plane. The geometrical configurations of this cable, first alone then close to an other perturbing cable are given in Figure 14 (A et B).

In both cases, a 1 Volt voltage generator is placed on the vertical wire of the line. We want to know the electric field at test-point P. The perturbing line has the same per-unit-length parameters as the "emitting" line. The perturbing line (length = 1.6 m) runs along the "emitting" line on a 20-cm length. Along this length, the distance between the two lines is constant and equal to 0.5 mm. Then, towards its remote end, the perturbing line runs close to test point P (at a10-cm distance). Both lines are placed at 5 cm above the ground plane. Their terminal loads are equal to 50 Ω.

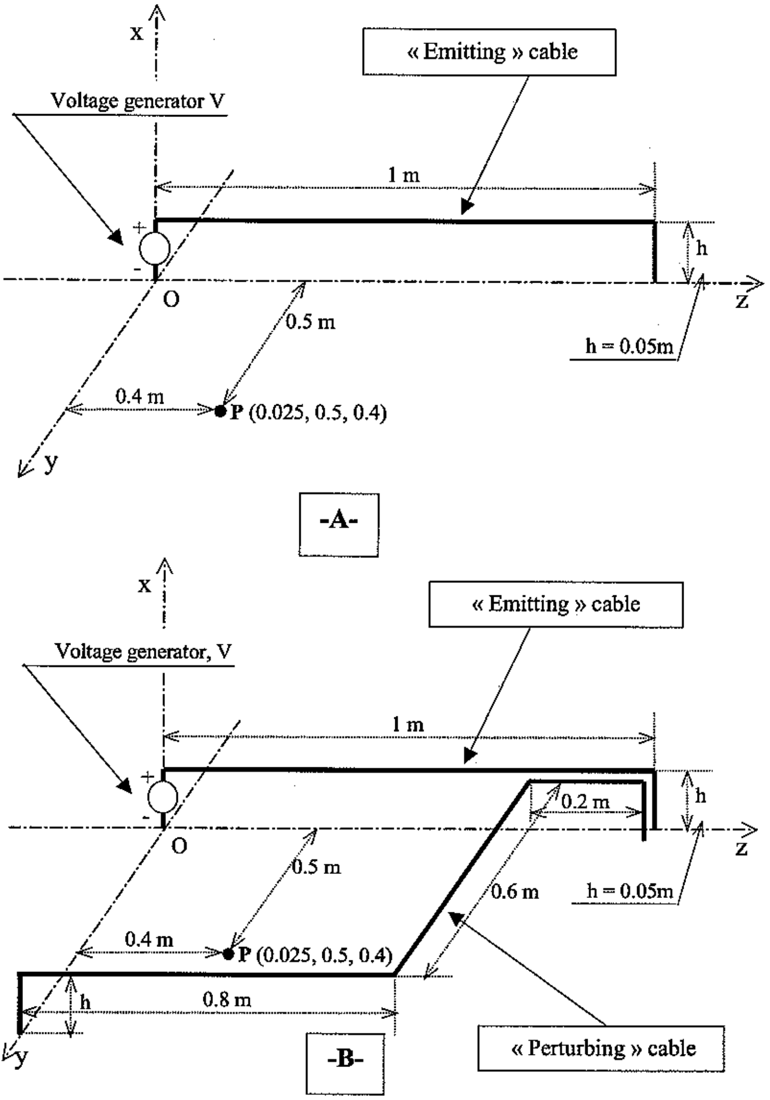

Figure 14 – One-wire line alone and presence of a perturbing line

In the reciprocity resolution of the problem, the whole wiring must be taken into account. In the ALICE 3D code, the tangent electric fields of state 2 are calculated on the routes of the two lines ("emitting" line and "perturbing" line). Then, those fields are introduced as distributed source terms in the CRIPTE code. Both lines are modeled in the same topological network including the cross coupling on the 20-cm distance. The electric field radiated at test-point P by the transmission-line excited by the 1-Volt generator, in the absence, or the presence, of the "perturbing" line are presented in Figure 15. The amplitude of the radiated field is higher in the case of the presence of the "perturbing" line. Indeed, the current circulating on the "emitting" line couples onto the "perturbing" line. This one also radiates and therefore modifies the E field produced by the "emitting" line alone at test-point P.

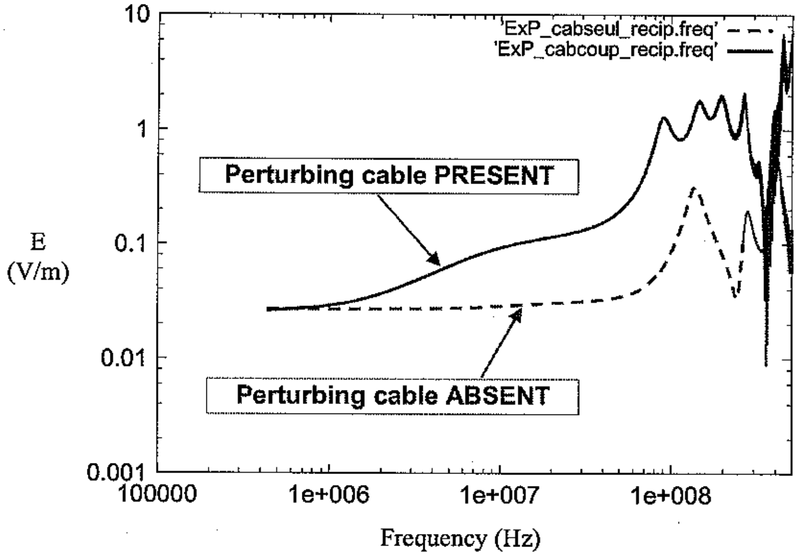

Figure 15 – Electric field radiated at test-point P by a one-wire cable installed on an infinite metallic ground plane in the absence or the presence of a perturbing cable (calculation with the reciprocity approach)

5 CONCLUSION

The encouraging results obtained in this numerical and experimental investigation showed how the reciprocity method can be applied on large-dimensions 3D systems. The only calculation to perform concerns an EM susceptibility calculation. Therefore, the same calculation chain ALICE/CRIPTE, developed at ONERA, allows us to study EM susceptibility and EM emission problems at the same time.

In the experimental validations, the importance of neighboring cables have clearly been demonstrated. Indeed, for several test-points, neighboring cables may have a non negligible influence of the field radiated by a "suspected" cable. In order to demonstrate this relevance, this "perturbing" phenomenon has been reproduced numerically on a geometry, simpler than the satellite mock-up.

In this article, only electric field calculations have been showed. The proposed method remains applicable to the determination of magnetic fields. Indeed, in the resolution of EM-state 2, the current injection segment could be replaced by a current loop (principle of magnetic sensors). Nevertheless, the implementation and the validations of this configuration remain to be done.

Besides, one will note that the rectangular shape of the satellite presented in this paper is appropriate for the use of an FDTD computer code. However, in the case of a more conform geometry, it would be more appropriate to apply an hybrid technique allowing one to better account for the surface of the object, while maintaining FDTD performance in most of the calculation volume, and to make easier the description of the cable routes [3].

Finally, the reciprocity relation applied in the article between cable-ports and field-sensor ports could be easily generalized to a "multiple port –multiple field " problem. Nevertheless this one still requires small modifications in the current available calculation chains. Especially, the use of a frequency domain 3D technique allowing one to solve a linear system with several right-hand-sides is clearly indicated for future applications of this kind of problem.

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