Computation of an ESD-induced E-field environment and Definition of a current injector test set-up at equipment level

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Abstract

The ESD-induced electromagnetic field on a S/C is computed using the 3D PIC code GEODE. Typical E-field waveforms are deduced and a new susceptibility test at equipment level is proposed as an alternative to the plane wave approach.

1. Introduction

The objective was to replace the radiated field excitation of systems by a current injector excitation. A current injector acts on the cable as a voltage transformer. The test consists in applying a voltage generator which is equivalent to the field to wire interaction.

2. Definition of the Environment

The electromagnetic environment is computed using our computer code GEODE in the case of a linear surface discharge [1]. The blowoff current determines the electron emission rate from the charged patch with $V_d = -5$ kV : $I(t) = I_{max}(1-e^{-\frac{t}{\tau}})$ with Imax = 8.56 Amp and $\tau = 48.9$ ns for a total duration equal to 212 ns.

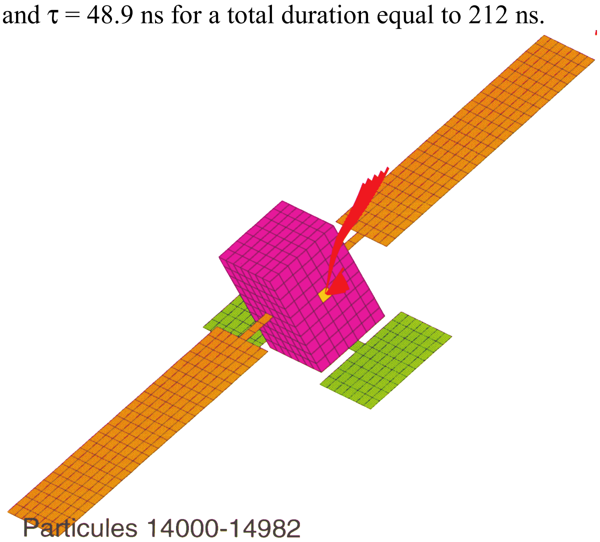


Figure 1: View of the meshed Spacecraft (Δx = 30 cm) and electron trajectories at the end of the discharge.

Two typical waveforms are deduced from the analysis of the E-field normal to the discharge's panel, one example is shown on figure 2.

They are one low frequency and one high frequency triangular pulses which characteristics are shown in the table below (Fig.3).

	Peak value	Rise time	Fall time
waveform 1	20 kV/m	70 ns	10 ns
waveform 2	10 kV/m	10 ns	10 ns

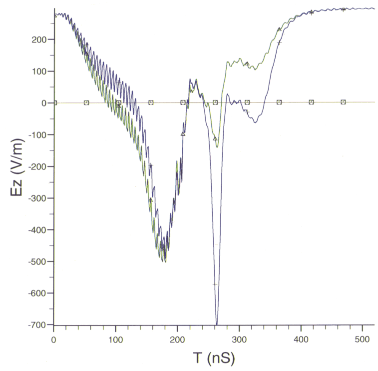


Figure 2: Electric Field pulse at the left edge of the panel (1.5 m from discharge site) which emphasises a narrow peak at the end of the propagation.

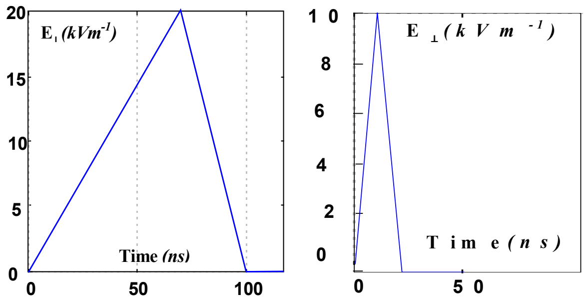


Figure 3: ESD induced E-field waveforms #1 and # 2

3. Definition of the test

The objective of ONERA's experiment was to apply, with a set of current injectors, the time waveforms defined as the elementary ESD field stress on an equipment. The injection has to be applied to a wiring connected to the equipment under test. This wiring has to be chosen as a representative one, but no real specification on the wiring is precisely mentioned in the standards.

3.1 The exact approach

The equivalent generators induced by the exposition to each pulse are determined in the following way :

- Modelling of the test set-up,
- Computation of the Thevenin generators,

Then, the validation of the test procedure was obtained on a reference test device (a 3 wires cable connected to 2 arbitrary loaded boxes).

- step 1 : Thevenin equivalent generator due to plane wave excitation.

We modelled the wiring system, that is to say, the wiring and its conventional termination, called *the "Line Impedance Stabilisation Network, LISN"* further on, the other terminal equipment being called *"Device Under Test", DUT.* In this model, the equipment was replaced by an open circuit for the calculation of Thevenin generators. A 1 V/m plane wave was applied on the wiring. The polarisation is similar to the one provided by usual TEM field injector devices (such as "CRAWFORD" cells). The characteristics of such an ''*hybrid''* plane wave are the following :

- direction of propagation parallel to the cable,
- electric field perpendicular to the reference metallic plane,
- magnetic field perpendicular to the surface made by the cable and its projection on the metallic plane.

The computation was carried out in the frequency domain by the CRIPTE code. The time domain response is then deduced by a transfer function with the field pulse.

- step 2 : Experimental injection of the computed Thevenin generators with a current injector.

In fact, a current injector should be called an "equivalent voltage transformer" or an "equivalent voltage generator injector". We used this property to apply the two Thevenin generator waveforms computed at step 1. In the Thevenin equivalent model, it is important not to forget to take into account the input impedance of the source. In the experiment, this was done by letting the wiring under study connected. A numeric-to-analog converter is used to synthesise the given waveform at the input of a suitable amplifier to obtain the given amplitude. The resulting voltage pulse is applied to the current injector at DUT input (Fig.4).

3.2 Description of the experimental procedure

The validation system we used is composed of a 3-twisted-wires cable connecting two pieces of terminal equipment, modelled as black boxes. These boxes are shielded and contain shielded 50 Ω coaxial cables with terminal SMA loads which can be easily connected typically , 50 Ω, short circuit (sc) and open circuit (oc) (Fig.4).

The voltage injection with the so-called ''current injector '' is applied at the DUT. The line impedance stabilisation network (LISN) is generally 50 Ω loaded but extra sc and oc configurations have also been considered.

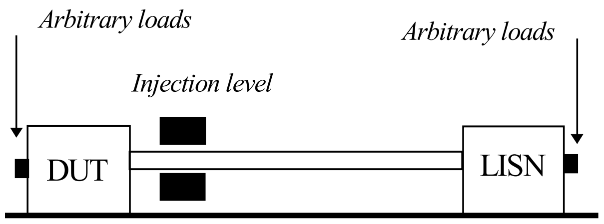


Figure 4 :Schematics of the validation set-up

Beside, the modelling of the set-up (network + cable + boxes) has been done using the CRIPTE code [2]. S-parameters have been computed and compared to measurements as a circuit validation of the model. Several configurations of the wiring have been studied considering :

- the load configurations (open or short circuit and 50 Ω loads),
- the cable configurations (shielded or unshielded cables with different heights above a ground plane)

No special optimisation of the models have been carried out. After these numerical simulations, the accuracy of the model was declared sufficient for further treatments.

3.3 Validation experiments

Figure 5 displays, in the frequency domain, the open circuit voltage computed at the DUT input, when a 1V/m plane wave is applied on the validation set-up. This simulated voltage is equal to the Thevenin equivalent voltage generator. This generator is in fact a vector. When all the loads of the LISN are equal, all the components of the vector are almost equal. But if the loads of are different, the components of the vector may be themselves very different. Generally, the LISN is chosen with symmetric load values.

All these results presented in this section were obtained with a 50 Ω loaded LISN. The result on figure 5 is classical and can be easily explained. According to Agrawal [3], the equivalent model of the field-to-wire coupling is made of two generators, equal to the perpendicular field at the extremities of the wiring. At low frequency, their amplitude is similar, and they only differ with their phase shift, due to the propagation direction of the plane wave. Consequently, the open circuit voltage, equal to the difference between these two generators presents a 20 dB per decade slope. At high frequency, the open circuit voltage is driven by the resonance of the wiring and depends on the length of the cable.

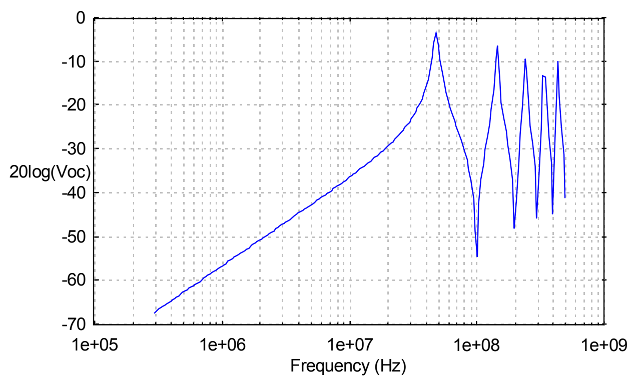


Figure 5 : Thevenin equivalent generator computed with CRIPTE code at the input level of the DUT (1 V/m hybrid plane wave injection).

The time domain equivalent generator when waveform 1 is applied is shown on figure 6. This result is simply obtained by multiplying the transfer function presented on figure 5 by the spectrum of "waveform 1" and then, by taking the inverse FFT of the result. One will notice that the multiple oscillations observed on the curve are mainly due to the resonance of the line (close to λ/4 in this configuration).

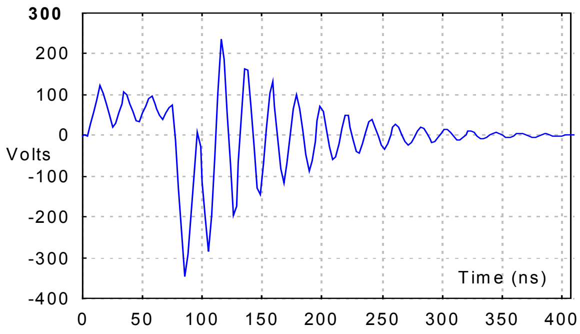


Figure 6 : Time domain Thevenin generator computed with the CRIPTE code at the input level of the DUT (1 V/m hybrid plane wave injection).

In a first step of analysis, no amplifier was used. Figure 7 shows the low amplitude waveform which was applied on the validation set-up. The shape of the waveform is respected very closely. The time domain response of the DUT is then measured directly on a 50 Ω load.

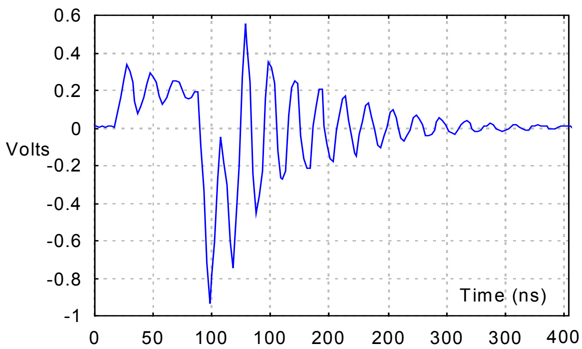


Figure 7 : Time domain Thevenin generator at the output of the digital/analog converter and injected on the experimental set-up at the input level of the DUT (1 V/m hybrid plane wave injection)

This experimental configuration has been simulated in parallel by CRIPTE code. This is done either starting from the response to a 1V generator at the DUT input or taking into account the whole problem from the plane wave irradiation.

The results obtained in time domain on a DUT 50 Ω load are synthesised on figure 8. The superimposition of both curves coming from CRIPTE code demonstrate the reliability of the Thevenin concept.

Because of an insufficient amplitude, the measured curve had to be multiplied by a suitable gain to be superimposed with the two other curves. Nevertheless, we observe that the three results are very similar.

The amplitude of the negative pulse is somewhat too large. This may come from the fact that the transfer function of the probe was not introduced in our treatment (assumed flat over the frequency range).

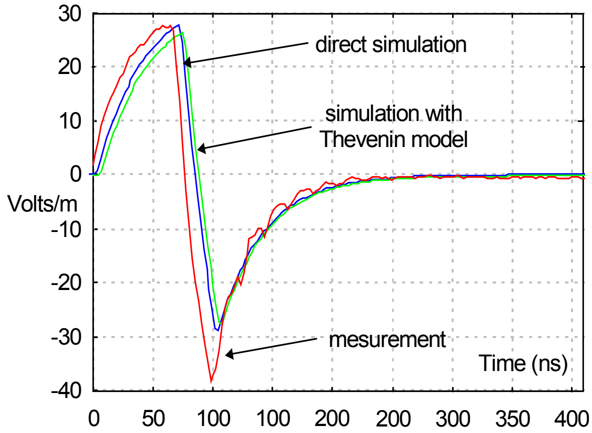


Figure 8: Time domain voltage measured on a 50 Ω load on the DUT (all loads equal to 50 Ω)

4. Definition of a modified procedure

One may think that the rigorous procedure presented in the previous section, couldn't be applied in standard tests because of the requirement of a computer code calculation. Also, the shape of the Thevenin generator depends on the length of the line and on the LISN loads. This is the reason why we tried to define a modified test procedure with a limited use of the computer.

Figure 5 shows that the transfer function of the Thevenin generator is derivative at low frequency. We take advantage of this property by injecting a generator which is the derivative of the generic waveform. The following section will demonstrate how such an idea can be applied in our case. Of course the only requirement of a computer code will be to compute the real level on an arbitrary load and the level obtained for a localised excitation. The adjustment of the level will be obtained by the amplifier. But no extra Thevenin generator calculation has now to be done.

4.1 Frequency analysis

The objective is to replace the actual excitation of the wiring system, by a single generator. To make the test simpler, we propose to apply the generator in the middle of the wiring.

Figure 9 represents the ratio between the response to a plane wave and the response to a localised generator in the middle of the wiring for each of the three load configurations (DUT 50 Ω).

At low frequency, the ratio is similar only for short-circuit and 50 Ω loads. But, from 10 MHz to 100 MHz this ratio is the same for the three loads and we observe a -20 dB slope per decade. The fact that the real excitation (the plane wave) is the derivative of a constant injection is confirmed in this frequency range. At higher frequency, we observe quite the same resonance for the three load configurations.

For these reasons we considered that the injection of the derivative of the generic waveform could be a relevant idea.

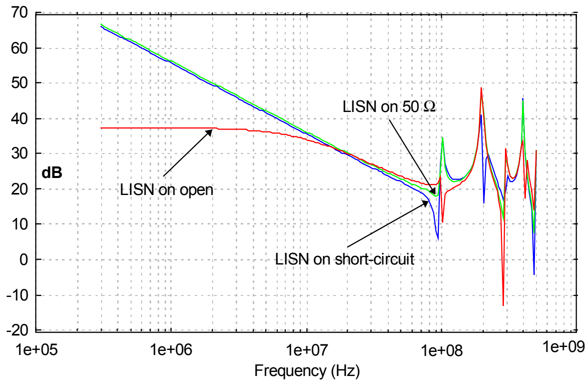


Figure 9: Ratio between the voltage computed on a 50 Ω DUT when a 1 V localised generator is applied in the middle of the wiring and the voltage on the same load for an hybrid plane wave excitation.

4.2 Case of Waveform #1

The generic waveforms 1 and 2 are triangles. Consequently, their derivative is made of two square signals with opposite sign. Figure 10 shows such a signal, related to the derivative of waveform 1, generated with the numeric-analogic converter. Let us precise that now, such an costly device is not required any more in the test because such a signal can be generated easily.

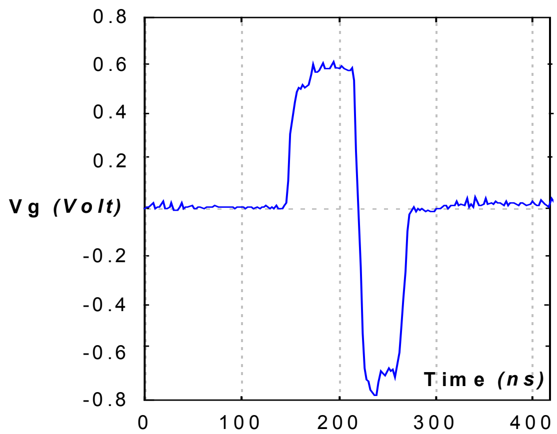
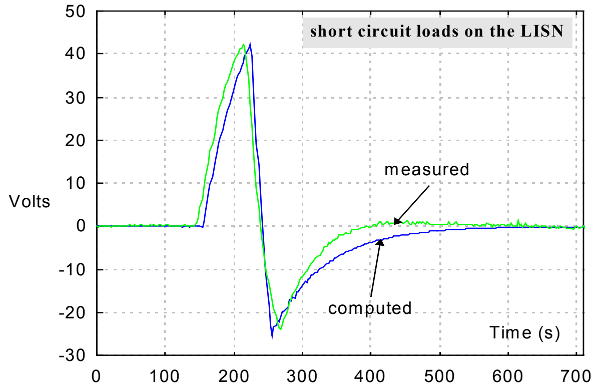
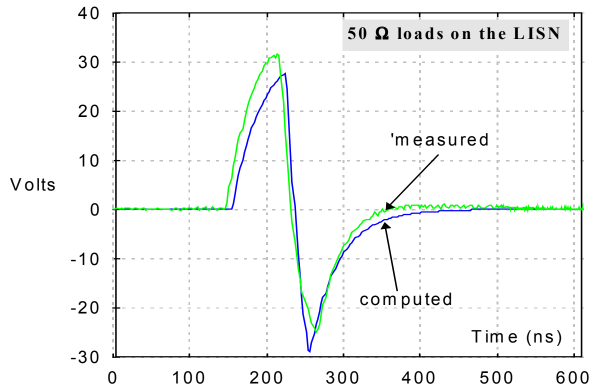


Figure 10: Derivative of waveform 1 generated by the digital/analog converter, amplified and injected with the current injector

Figure 11 represents the comparison between the computed actual response on a DUT 50 Ω load, under the hybrid plane wave and the measured result multiplied by the gain. The first two figures demonstrate the accuracy of the modified procedure for low impedance on the LISN. For high impedance on the LISN (Fig.11-c), the result is not so good. Nevertheless, one must notice that the duration of the signal and the resonance frequency are correct. Such results seem logical when analysing the ratio presented on figure 9, from 10 MHz up to 500 MHz. The discrepancy on the magnitude certainly comes from the non derivative behaviour of the inverse of the ratio below 10 MHz.



(a)



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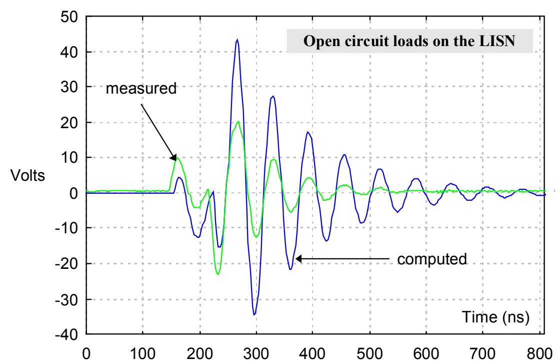


(c)

Figure 11: Voltage on a DUT 50 Ω load (WF #1)
- hybrid plane wave computation
- measured and multiplied by the gain of the amplifier

4.3 Case of Waveform #2

The same modified procedure has been carried out for the case of waveform 2.The LISN was 50 Ω loaded and the DUT loads were chosen equal to short-circuits, 50 Ω and open circuits. Figure 12 represents the time domain waveform injected on the current injector. Compared to the one injected for waveform 1, we notice that this one is not so well modelled. The difficulty of the experimental modelling comes from the high frequency contents of this signal, more difficult to reproduce with the converter.

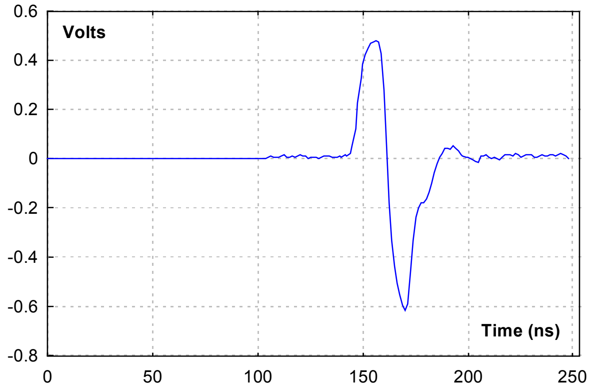
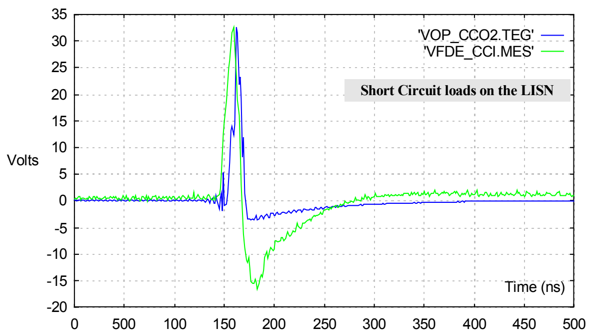


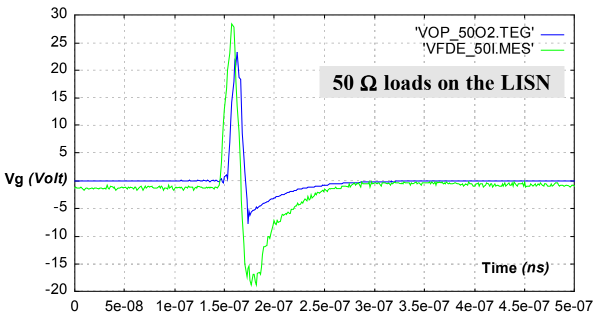
Figure 12: Derivative of waveform 2 generated with the digital/analog converter, amplified and injected with the current injector.

Figure 13 represents the three results obtained on the three respective DUT load values. On short-circuit and 50 Ω loads (13 a-b), the first positive peak is correctly modelled, whereas the magnitude of the negative one is not. This is certainly due to the shape of the injected signal which negative pulse is different from the theoretical square signal it should be.

On the contrary, the modelled response on open circuit is much more better (see figure 13-c). This can be explained if we remember that the ratio between a real plane wave injection and a localised generator (see figure 9) is perfectly derivative in the useful frequency range of waveform 2 (see figure 3). In this case we can also say that the shape of the resulting modelled signal is less sensitive to the bad definition of the injected source.



(a)



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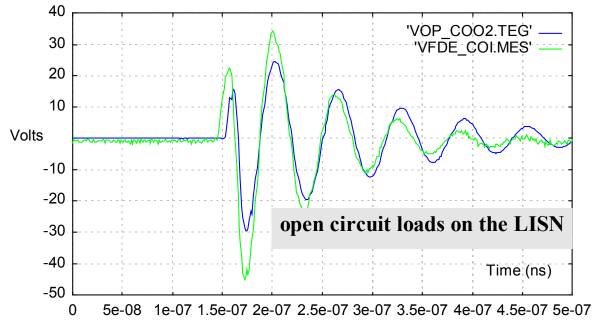

(c)

Figure 13: Voltage on a DUT 50 Ω load (WF #2)
- hybrid plane wave computation
- measured and multiplied by the gain of the amplifier

5. Conclusion

The objective of the study was to find a method based on the use of a current injector to replace tests with plane waves. Two typical E-field waveforms dealing with an ESD stress have been generated from a numerical simulation by the 3D PIC code, GEODE.

Two approaches were used. The first one is rigorous: the Thevenin generator due to the coupling of the plane wave on the cable is calculated and then, injected on the equipment. Although it is exact, this approach requires a computation of the equivalent generator depending on the wiring topology, and the synthesis of a complex signal with a digital/analog converter. The second one, is deduced from the previous one. In the frequency range of interest (10-100 MHz), the transfer function between a plane wave and the response of the wiring with different loads shows a derivative behaviour. So, the current injector is used to inject bipolar square pulses which are the derivatives of the defined triangular E-field waveforms.

Both methods have been demonstrated on a test wiring, including LISN and DUT, on which modelling and measurements could be carried out easily.

Such a test can be easily implemented and complex waveforms can be generated.

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