TRADE-OFFS BETWEEN EMC HARDENING AND GENERAL DESIGN OF LAUNCH VEHICLES

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Abstract

A launch vehicle has to face several harsh electromagnetic environments during its phases of life, from preparation/Assembly, Integration and Test [AIT] to flight: electromagnetic fields generated by lightning, High Intensity Radiated Fields [HIRF] from radars, ElectroStatic Discharges [ESD], and self-created electromagnetic environment.

The need for no malfunction during flight, and no permanent damage nor catastrophic spurious response during pre-launch, results in ElectroMagnetic Compatibility [EMC] requirements, such as protections on harnesses, equipment or vehicle structure, that may not be compatible with the overall electrical and mechanical design. Compromises must be reached between withstanding the ElectroMagnetic [EM] environment and fulfilling the mass budget and reliability/safety requirements, and the convenience of subassemblies manufacturing.

This paper presents in detail two examples of trade-offs between EM hardening requirements and overall design: primary power distribution grounding concept vs. reliability/safety, EM hardening concept vs. equipment mass budget and cost.

Given the fact that EMC design has to be tackled at the very beginning of the development, so as not to wait until the final qualification test, numerical modelling and simulation are widely used: they make it possible to assess, as soon as possible, the behaviour of the system when undergoing the EM threats, examine how to protect it, if needed, and how those protections may interfere with other design constraints; and lastly, find the better compromise between hardening and general design requirements.

1 EMC Problem Statement

1.1 EM environments and their effects on systems

Several EM environments may threaten a launch vehicle when it is on the launch pad (pre-launch phase) or in flight: EM fields from direct or nearby lightning stroke, EM fields generated by radar operation, EM fields from ESD. The launch vehicle is equipped with electrical and electronic subsystems (avionics), pyrotechnical subsystems, scattered in all parts of the launch vehicle (stages, vehicle equipment bay, nose fairing) and associated harnesses, running along the main structures, inside and outside the vehicle. By coupling of that external EM threat with the vehicle, internal and external fields and induced currents are generated. Avionics, pyrotechnical subsystems and harnesses are sensitive to those environments, the effects of which can result in permanent electronics damage or at least malfunctions. In any case, the results can be catastrophic: premature ignition of stages, premature separation, loss of vehicle control…

For the sake of argument, an unprotected (unshielded) electronic board is sensitive to a 20 V/m electrical field, corresponding to (assuming a plane wave) a magnetic field of 0.06 A/m or so. And the magnetic field induced by a 200 kA lightning stroke, occurring at 10 m, amounts to 3000 A/m.

So, both avionics and pyrotechnics subsystems have to successfully undergo all the EM environments: severe requirements, in terms of reliability, availability, safety, are imposed to those subsystems: no malfunction during flight, no permanent damage at launch pad.

In addition, the operation of each piece of avionics equipment itself generates EM fields and spurious currents, that in turn may cause malfunctions to the other pieces of equipment (internal EMC problem): the requirements are similar to the previous ones.

The payload itself may generate EM environments to the launch vehicle if operated before jettisoning, for the sake of simplification in its implementation.

Lastly, some of those EM environments may occur during preparation phases (AIT): stages preparation, final launch vehicle assembly. Of course, no permanent damage, nor malfunctions during tests, might occur.

1.2. Generals on EM hardening

As avionics, pyrotechnics and harnesses might be liable to malfunctions or damage, they have to be protected. Protections can be:

- implementation of shielded enclosures around electronics, cables…: electronics and explosive device housings, cable overshielding; the vehicle structure itself may partly play that role (cable ducts)
- implementation of electrical filters or surge suppressors at the inputs/outputs of pieces of equipment
- grounding (connection to the vehicle structure) of boxes
- and combinations thereof.

Those protections respond to the need for successfully undergoing the EM effects of lightning, radar operation, self-generated environment.

For protection to ESD, the approach is rather to prevent the external threat - discharges (electrical breakdowns) - to occur, by deposition of a specific coating onto the vehicle structure. So, avionics hardening is strongly alleviated.

1.3 Selection of hardening principles

Different trade-offs are made between some of the above-mentioned protections. For example, given that most of the EM effects onto electronics are routed by harnesses (in some cases, the effects of direct field penetration inside boxes are negligible), the hardening effort may be put either on overshielding of harnesses, or on filtering at the input/outputs of boxes; it may also be a combination thereof. Technical selection criteria are: cost, mass, easiness of implementation, natural shielding through the vehicle structure or not. The comparative ability of Prime Contractor and Subcontractors to master and justify the hardening level of the cables and boxes respectively may be taken into account as well.

Other technical trade-offs must be made since protections may not be compatible with safety requirements or manufacturing processes, or, simply, particular attention must be paid to the implementation of protections that could make the manufacturing processes more complicated.

From the very beginning of the development, EM Design Rules are written so as to clearly define what, in terms of protections, is relevant only to the Prime Contractor responsibility and what is shared between the participants in the programme, e.g. electrical grounding rules, shield efficiency of housings, etc. Those rules mostly derive from previous programmes experience and in addition have been justified (quantified) by numerical simulations and complementary experiments if needed.

Even if the EM Design Rules are written and shared at the very beginning of the programme, difficulties may be encountered along the development; additional trade-offs must be made, by paying attention to the new problems raised.

2 Example of trade-off between Reliability and EMC: grounding concept of Power Distribution

2.1 Problem statement

In space and launch vehicles, the electrical power system has to comply, in addition with the functional requirements, with several constraints such as Reliability, Availability, Maintainability, Safety [RAMS], EMC, mass and cost optimization.

It is usually based on a star distribution principle. It features a power source (solar array and/or batteries), a Power Conditioning and Distribution Unit [PCDU] which is the node or "star point" of the star distribution and a harness which feeds the user units by individual lines.

The PCDU includes the power converters and also an over-current protection device (Solid State Power Controller [SSPC], or sometimes fuses) for each user.

The harness is routed over the vehicle main structure which is designed to be a low impedance ground plane.

Concerning the grounding concept of the power network, there are several solutions and constraints to be taken into account through a trade-off analysis:

- Floating network: the power network is only referenced to the ground plane through the parasitic capacitors of the power system.
  Such a solution does not cope with the electrostatic environment encountered in the space missions from the lift-off to the on-orbit operation, because it leads to electrostatic potential enhancement (up to a few kilovolts) of the network with respect to the ground plane. The result could be dielectric breakdown featuring electromagnetic disturbances and hardware degradation by the arcing direct effects.
- Direct multi-point grounding at source and user interfaces avoiding current return wires and so saving harness cost and mass. But this results in a big drawback: the return current which has a wide frequency band spectrum flows through the structure on an uncontrolled path and could generate high level common mode noise on both power system and signal lines if the structure bonding is not reliably controlled as it can be in the composite structures.
- Single point grounding at source level with floating interfaces at user level. This concept avoids the disadvantages of the former one (uncontrolled common mode noise). It is the most used. But a question arises: what grounding impedance shall be implemented?

The forthcoming trade-off analysis will establish the best compromise.

2.2 Solutions to Power Distribution problem

The grounding impedance definition depends on two contradictory constraints:

- From the EMC point of view, the best solution is to ground the voltage reference (also called "0 V") with a link featuring impedance as low as possible (that means that both its resistance and inductance shall be minimized). Indeed, this solution induces the lowest common mode noise figures due to every possible electromagnetic coupling mode in the power system and even in the signal and control lines.
- For RAMS aspects, the best solution is to implement a resistive grounding path so as to be tolerant to an inadvertent short circuit between the "+" power line and the ground,

which could occur in a section not protected to over-currents. With the direct grounding solution, the battery would be quickly empty.

In the trade-off analysis leading to the final design, it shall be considered that the avionics has to be compliant with the system generated electromagnetic noise during the whole of the mission, when the short is a degraded mode of low probability of occurrence.

A compromise solution being more or less compliant with both aspects has been applied on some systems. It consists in implementing a parallel resistance/capacitor dipole, the resistance being of high value. In direct current and low frequency operation, the system is protected against a short, and in high frequencies the capacitor acts as a filter and minimizes the common mode voltage induced on a user interface by a common mode source from another user. But this solution is less easy to install because the reliability constraints imposes a quad series/parallel configuration for both parts.

A very simplified scheme of a single point grounded power system with a star distribution network is presented in Fig. 1. It features a power source which is a battery, a PCDU including SSPC with switching and over-current protection capability, two users and the harness. One of the users includes a common mode noise current source which induces differential and common mode noise voltage onto the other user power interface. In fact, every user has noise current sources in both differential and common modes and is submitted to the resulting noise.

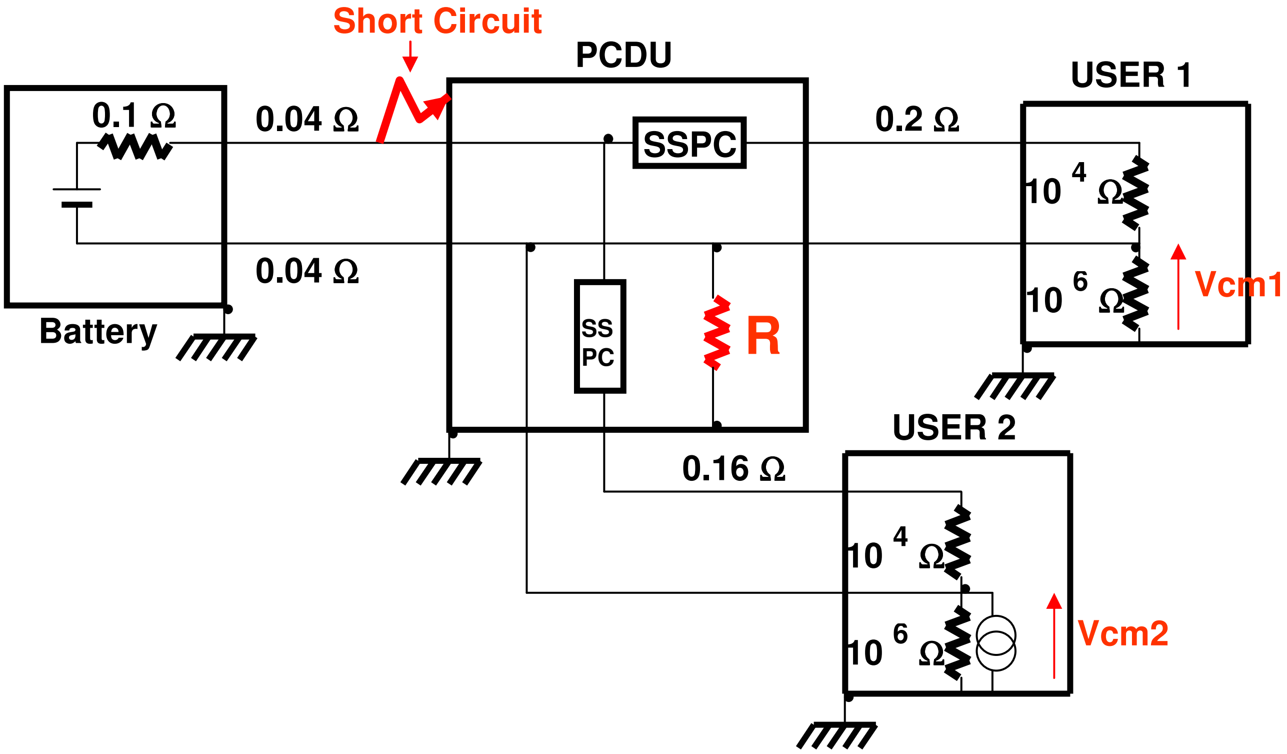

Fig. 1

Concerning the dielectric breakdown risk, it can be seen that only the section between the source and the PCDU up to the SSPC is concerned. On the other hand, the SSPC protects the user lines, then, if a short occurs, the faulty user is disconnected, but lost. This involves that a redundancy is implemented. That is the case of the ARIANE 5 design based on a full duplex redundancy of all avionic subsystem. The mission is ensured even if a power source link is lost. It has only been checked that the effect of a short in this section does not interfere with the redundant power bus. The control of the risk of a short could be reduced by reliability of the insulation improvement through double insulation implemented in the critical areas. It has been stated that the best concept for EMC efficiency is a direct grounding by a low impedance path realized by short straps in parallel, distributed between the 0 V tracks and the PCDU foot structure.

That is not possible to get with a high impedance grounding.

2.3 Figures and trade-off

The efficiency of the direct grounding concept has been demonstrated by a numerical modelling based on the former scheme, in the frame of the ARIANE 5 program. Two noise sources have been considered: intra-system common mode noise generation by the users, and radiated field illumination of the power system. The analysis has been performed in the frequency domain for three grounding dipoles: 10 mΩ, 10 kΩ and 10 kΩ//10 nF.

The results of the performed simulations have shown that the common mode voltage is for the direct grounding in both noise sources cases at least 25 dB less than the voltage get with the 10 kΩ up to 100 MHz. The hybrid grounding leads to intermediate performances: it becomes as efficient as the direct grounding only above 10 MHz.

In order to justify the results, a low frequency model is derived from the global model, according to the following figure (all values are expressed in ohms):

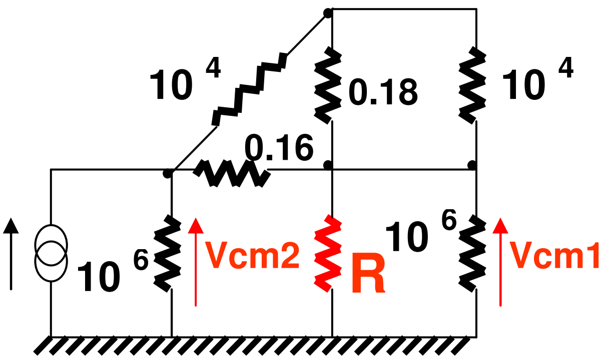

Fig. 2

The transfer function between V_{cm1} and V_{cm2} is as follows, R being the value of the grounding resistance:

$$\frac{Vcm1}{Vcm2} = \frac{R}{R + 0{,}16}$$

It is obvious that for high values of R, $V_{cm1} = V_{cm2}$.

On the other hand, for low values of R, i.e. 0.1 Ω, the transfer function is worth – 25 dB.

In conclusion, this study has shown that the choice of the best grounding concept for a system has not a unique issue, the final solution is always a compromise between contradictory technical constraints.

3 Example of trade-off between Mass and Avionics EM Hardening: concept of Avionics Hardening

3.1 Problem statement

In space vehicles, including launchers, the avionics has to comply, in addition with the functional requirements, to different environment factors. Among those factors, the electromagnetic environment represents a serious concern.

The Avionics Subsystem is composed of electronic pieces of equipment (“boxes”) interconnected by a harness. Each piece of equipment is located as far as possible inside the vehicle structures, but the harness can be partially routed outside the vehicle.

The Avionics Subsystem has to deal with the following electromagnetic threats:

- Self-generated noise, the main contributor being the power system and sometimes the fast digital signals in the conducted mode, and the high frequency transmitter in the radiated mode. Different coupling modes can act:
    - In the conducted mode
        - Inside the power system in which a lot of boxes are interconnected, each of them rejects noise due to the input converter switching. This noise is sent to all other boxes by

propagation in differential and common modes, it is not depending on the harness shielding
- From the main contributors to the sensitive signal lines by inductive or capacitive cross-coupling, or by structure common mode coupling. The harness shielding plays an important role in the coupling efficiency

- In the radiated mode
  - By “front door“ coupling between the transmitting and receiving antennas
  - By “back door” coupling between the transmitting antennas and the equipment housing or the harness, through the main structure electromagnetic apertures. The structure, harness and equipment housing shielding effectiveness takes part in the coupling efficiency

- Noise due the natural and the launch pad environment:

  - Lightning on ground or in-flight electromagnetic effects : the lightning fields and currents couple with the harness and boxes interfaces mainly by inductive coupling

  - Electro-Static Discharges due to the charging environment (atmospheric friction at low altitudes or Van Allen belts particles above the atmosphere): the coupling modes are both conducted and radiated

  - Launch pad radiated emission

  - If applicable, the electromagnetic effects of a nuclear explosion, the coupling modes of which being the same as for lightning and ESD

  - For all those threats, the structure, harness and equipment shielding effectiveness plays a major role in the coupling efficiency.

Finally, every threat induces at equipment harness interface spikes or continuous wave interferences by conducted coupling and sometimes by direct field penetration into the boxes. Then, the noise couples inside the boxes onto the sensitive devices and leads to upset or permanent damage (electronic parts break-down), according to its energy or voltage level.

From a system point of view, various susceptibility criteria are applicable, depending on the criticism for the mission of the susceptible functions, or on the life phase.

3.2 Solutions to Avionics EM Hardening

It has been pointed out here above that the coupling efficiency depends greatly of the harness shielding.

This statement about shielding introduces the general question of the protection of the avionics about the encountered electromagnetic threats. There are four levels of protection:

- The main structure of the vehicle shall act as a Faraday cage (shielded enclosure) against the external aggressions like fields due to transmitters (on-board or launch pad), lightning electromagnetic effects and ESD effects
- The harness shielding with different level of efficiency characterised by the transfer impedance of the shielding
- The equipment housing shall also act as a Faraday cage, especially against low frequency magnetic fields
- The equipment conducted ports filtering

The different levels of protection shall be balanced so as to minimize their mass and cost penalty. The forthcoming trade-off analysis will try to establish the best compromise.

3.3 Basic data

Let’s start from the following initial configuration which makes it possible to comply with the self-generated noise and medium severity ESD (excluding lightning, and high frequency radiated fields of more than 30 V/m) and defined here-above:

- The main structure provides an electromagnetic effectiveness of at least 20 dB from 1 to 18 GHz
- The power harness is not shielded
- The signal lines are shielded by a single layer braid so as to limit the coupling level with the power system
- The equipment housing is correctly designed w.r.t. low frequency magnetic fields
- The power inputs of the pieces of equipment are filtered with a single stage filter so as to limit the narrow and broadband conducted emissions and withstand the resulting noise level coming from all other units at its power interface. The signal inputs/outputs are not specifically protected
- The avionics is not protected against lightning
- The natural spike level withstanding of such a piece of equipment is about 60 V on the power inputs and 20 V on the signal interfaces.

If the system shall be protected against lightning (concerns only the launch vehicles) which is the design driver for conducted compatibility, one has to take into account the following data concerning the spike level:

- A 5 kA direct lightning stroke on a launcher like ARIANE 5 induces a spike (without margin) of about 200 V on the equipment interfaces connected to non-shielded cables. In the case of single braid shielded cables (transfer impedance of 30 mΩ/m or so), the level decreases to about 30 V and for a double layer braid (transfer impedance of about 3 mΩ/m) it leads to about 5 V
- If the stroke current is higher, the spike level at equipment interface increases approximately proportionally to the stroke level
- Those results have been established by numerical modelling of the coupling, so the equipment design shall take into account safety margin which usually are:
    - 20 dB for in-flight lightning where the system shall operate without any major perturbation
    - at least 6 dB for on-ground lightning where only non permanent degradation is required.

3.4 Figures and trade-off

Let's consider a virtual case where a launcher like ARIANE 5 has to withstand a lightning stroke of 30 kA on ground. It has to withstand the following spikes:

- (1) unshielded cables: 1200 V
- (2) single braid shielded cables: 180 V
- (3) double layer braid: 30 V

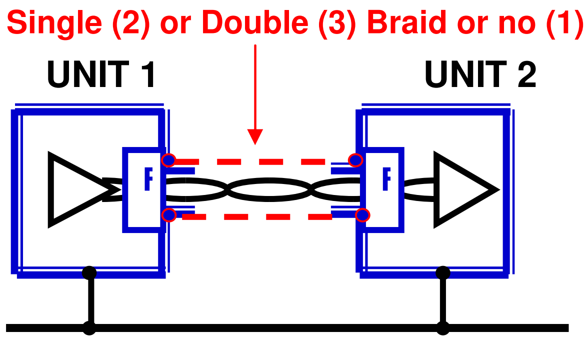

Fig. 3

The equipment qualification level becomes, taking into account the 6 dB margin:

- unshielded cables: 2400 V
- single braid shielded cables: 360 V
- double layer braid: 60 V.

The withstanding level of a space vehicle piece of equipment which is not protected to lightning is about 60 V on the power inputs and 20 V on the signal interfaces.

The following conclusions can be derived:

- the unshielded solution (1) which leads to 2400 V qualification level of the equipment is not feasible
- the single braid solution (2) needs an addi-

tional filtering of a factor of 16 dB for the power inputs and a factor of 25 dB for the signal interfaces

- the double layer braid solution (3) needs an additional filtering of a factor of 10 dB only for the signal interfaces.

So we have to choose between solutions (2) and (3).

Additional filtering on the power inputs can be achieved by redesigning the power input filter or by adjunction of surge suppressors as “transzorb”. For the signal interfaces, the same solutions apply in conjunction with the use of balanced lines or isolation by broadband transformer or opto-couplers.

The trade-off analysis between the solutions (2) and (3) will be based on mass, cost, and reliability criteria. The values given here-after are standard values and vary with the number of input/output ports.

The solution (2) needs only additional filtering which involves a mass of about 600 g for a box, and 24 kg for the whole launcher. On the other hand, there is a cost increase of the box of about 20% and the reliability decreases of about 2%.

The solution (3) needs additional filtering which involves a mass of about 150 g for a box, and 6 kg for the whole launcher. But there is also a harness mass increase of about 70 kg. The cost increase of the box is 5%, and about 30% for the harness. The reliability decreases of less than 1%.

This example shows that the trade-off is very complex because several factors have an effect on the final choice. For the cost and reliability aspects, we have only relative data, so we can only conclude on mass comparison. The solution (2) leads to 24 kg on the upper stages, and the solution (3) to 76 kg, but shared between the upper and lower stages (23 kg and 53 kg respectively). The mass penalty on the upper stage is balanced for both solutions, so the incidence on the payload mass is the same. To finalize the trade-off we need additional information about cost. But an EMC engineer should prefer the solution (3) which is technically less complex and risky than the solution (2). In some cases, the selection of the best solution will even depend on the maturity level of the box manufacturer in the field of hardening design.

4 Dealing with trade-offs between EM constraints and others

Other trade-offs have to be made during the design and development phases, such as working of payload transmitters under nose fairing vs. effects on surrounding subsystems: in order to simplify the implementation of the payload, it can be investigated if the payload transmitters may be operated before jettisoning of nose fairing; indeed, the EM fields generated in that way, together with the field confinement inside the cavity made of the equipment bay, upper stage and fairing, couple with the equipment bay Avionics and are liable to cause malfunctions. A verification of the field levels developed inside the equipment bay is necessary if such a possibility is offered to the payload.

In every case, as above discussed, it can be seen that EM requirements may not be compliant with some performances (mass…) or other operational requirements (reliability…), and at least need joint examinations. As a matter of fact, the EMC designer cannot afford to only verify, during the final qualification test, the behaviour of the launch vehicle, once designed with respect to functional and operational requirements. Given the high level of EMC requirements related to the operational stakes (on-ground or in-flight malfunction or destruction), the cost of redesign, in case of no EM compatibility, would be too high.

Then, EMC requirements have to be written and shared from the very beginning of the overall design: given a first definition of the vehicle, the EM design has to assess, as soon as possible, the behaviour of the system when undergoing the EM threats, examine how to protect it, if needed, and how those protections may interfere with other design constraints; and lastly, find the better compromise between hardening and general design requirements.

That design makes a widespread use of numerical modelling and simulation.

For that purpose, an "electromagnetic workshop" is currently used, reducing the duration of the design cycle and associated risks. Such an EM workshop consists of powerful calculation codes (™ASERIS - FD, ™ASERIS - BE, ™ASERIS – NET) and a set of elementary models of the electrical/ electromagnetic constituents of the avionic subsystem and harnesses, relevant to EM hardening process, and associated so as to build the system under EM investigation.

In that way, EM behaviour assessment can be made with full knowledge of the facts, justification files are easier to establish, and the qualification process not only relies on the final test, but the qualification results from a continuous succession of theoretical and experimental justifications, while the compromises are easier to get between the EMC designers and the Design Offices.

There is no doubt that even better results in terms of confidence and cost will be made possible by a widespread use of a digital (virtual) spacecraft approach.

5 Conclusion

Two main examples of trade-offs between EM design and general design of launch vehicles have been presented: EM hardening features several requirements not necessary easy to implement on the avionic equipment and harnesses, considering other specifications such as mass or reliability, and cost effectiveness. A continuous examination of advantages and drawbacks of hardening solutions, w.r.t to the fulfilment of other operational requirements, must be carried out along the design and development phase. For that purpose, the use of modelling and simulation is from now on necessary, in the frame of an electromagnetic workshop, which is a first step on the path to the virtual spacecraft.