EMC in Space Systems : Current Practices and Future Needs - The ESA Perspective

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Abstract

Space systems inherently belong to the category of complex systems, having specific unique traits. This paper presents an overview of the electromagnetic compatibility (EMC) activities carried out for a space mission. It addresses the impact of the EMC discipline on the spacecraft's procurement, the definition of the requirements, and the EMC program, with a number of real life examples. Finally, trends and future needs are discussed.

1. Introduction

The practical control of electromagnetic interference (EMI) generally evokes esoteric notions for the public, especially when complex systems are considered. However, extensive research and standardization activities have been carried out in the last decade, with the objective of identifying and consolidating EMI-suppression practices and test methods, and developing advanced analysis techniques for EMC. Space systems inherently belong to the category of complex systems that have specific unique traits. Examples include interaction with the harsh space environment [1], the impossibility of maintaining or refurbishing the spacecraft after launch, the unconventionally tight requirements for onboard payloads [2-6], the astonishing costs involved, and so on. In this context, EMC is the domain where engineers are exposed to the widest contrast between the complexity of technical electromagnetic issues, and the pragmatic side of system engineering. Going straight to the heart of the matter, this paper deals with the following questions:

- How important is EMC for spacecraft?
- Is it a standalone activity, or a concurrent engineering discipline?
- What is the process for establishing EMC requirements?
- What is the flow of the EMC activities in the framework of a space program?
- What are the future needs?

The relevant answers, supported by real-life examples, will hopefully give an exhaustive impression of the EMC processes, methods, and tools for the space business. These will also hopefully illustrate the rigor of a true systems approach, and the labor of knowledgeable professionals in industry, research, centers and European international organizations. Only these allow the EMC success of a space mission.

2. The Importance of EMC for Spacecraft

All spacecraft require EMC. Its verification is always the subject of a dedicated test campaign for acceptance by the procuring body. This fact establishes the implicit contractual importance of the discipline.

EMC engineering ensures that space vehicles and their parts do not produce or suffer from EMI throughout the program's life cycle. This must be attained through built-in-design compatibility – instead of after-the-fact remedial measures – which is the real indicator of success.

The rapid development of technology has increased not only the number of onboard pieces of electrical equipment, but also their complexity. The effectiveness of performing any single basic function is hence presently dependent on the efficient performance of many other functions. Faster and more sensitive electronic technologies for space applications, and the use of wider bandwidths in the design of equipment, drive new and challenging requirements for the flight hardware, with increasing pressure to accommodate the hardware in ever-smaller and more-crowded spaces. As a result, this unfortunately increases the

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probability of performance degradation by undesired electromagnetic interaction.

Depending on the nature of the mission, EMI can upset spacecraft in a variety of ways. These range from direct-current (dc) effects, such as electrostatic charging [7-11] and magnetization [12, 13], to alternating-current (ac) and transient effects. The latter include both conducted and radiated effects [14-16], which include interference hazards at the intra-system level (i.e., within the spacecraft's avionics and payload elements), and the inter-system level (between the launch vehicle and spacecraft, or in the framework of the space systems' docking [17]). The interaction with the natural space environment (e.g., radiation, plasma, cosmic rays, occurrence of geomagnetic sub-storms), which may cause potentially disruptive effects (e.g., electrostatic discharges), is another issue that needs to be taken into account [18-20].

The consequences of EMC-related disturbances on spacecraft can include nuisances, which jeopardize the correct performance of the mission and reduce the efficiency of some functions. The consequences can also be catastrophic. These can lead to irreversible loss of some operational capabilities, with relevant impact in terms of scientific and programmatic yields, cost overruns, and schedule impacts. The effects of these disturbances can be temporary telemetry interruption, noisy science data, and permanent damage of power supplies, accidental tripping of the protection devices, false commanding, and instability of the power distribution subsystem, to mention just a few [21].

It is apparent that EMC involves risk management, and implies a working knowledge of the spacecraft's subsystems. The EMC process requires cost-effective considerations throughout every phase in the system's life cycle. In fact, EMC control decisions are particularly susceptible to the influence of cost-effective tradeoffs. Analysis, testing, and correction involve considerable program expenses. Every effort should be made to apply a commensurate level of EMC work and provisions to achieve the mission's objectives, while safeguarding reliability. Therefore, EMC engineering also encompasses programmatic responsibilities.

The aspects outlined here show the technical and programmatic importance of EMC for the space business as a critical activity for meeting cost, schedule, and performance goals.

3. A Concurrent Engineering Discipline

From the above short overview, it emerges that EMC for space systems interfaces with several disciplines. However, it is per se a subject for specialists. The control of noise and interference on spacecraft involves generic applications, covering many engineering domains, knowledge of which is a key issue for successful implementation. In general, EMC is an integral part of the overall spacecraft-system engineering process. Understanding of electromagnetic theory and modeling techniques, as well as being familiar with sophisticated practices for both manufacturing and testing, are hence necessary but not always sufficient conditions for implementing a successful EMC program for spacecraft.

The following list of functions gives a non-exhaustive idea of the mutual interactions that influence and are influenced by the EMC discipline:

- Program and mission management
- System engineering
- Electrical design engineering
- Mechanical engineering
- Quality, safety, reliability, and product assurance
- Configuration management
- Environmental design
- Ground support equipment engineering
- Manufacturing, assembly, integration and test engineering
- Parts, materials, and processes
- Payload Engineering

Adequate definition and management of the interface specifications is also essential, in order to enforce correct EMC engineering solutions with little impact on the other disciplines. In principle, EMC is thus a cross-disciplinary activity that requires full system visibility. As such, EMC engineers are part of the system team.

The above concepts are applicable to all ESA (European Space Agency) programs that rely on system specifications. The underlying principle is to establish system-performance requirements, which in turn drive a design that directly controls the interactions between individual pieces of equipment or subsystems. In other words, the objectives of the mission and the payloads drive the requirements and the design of the spacecraft. However, for specific cases, the converse is viable. In fact, some complex space systems – such as the International Space Station and the former soviet orbital station, MIR (from the Russian word "[illegible]," which can mean both *peace* and *world*) – have a configuration that evolves in time. These include orbit replaceable units (ORP), which are generic payloads of arbitrary nature. These orbital infrastructures are platforms for micro-gravity and manned-space-related studies, where the driving requirement is essentially human safety. Payloads have to comply with severe safety rules and have to meet equipment-level limits, which should effectively control both the equipments' contribution and tolerance to the environmental levels with abundant margins. It is thus the payload that shall fit the platform requirements, rather than vice versa. If a payload fails for any reason, it must fail safely. Consequently, in this particular context, the EMC discipline has less-frequent system interaction than in the previous cases, and more-pronounced relations with the safety process.

4. The Process of Establishing EMC Requirements

4.1 System-Level Requirements

The system specification approach, which is the most common in ESA spacecraft, is outlined hereinafter. At the beginning of a space program, the System Requirement Document (SRD) is issued, which is a fundamental part of the Invitation to Tender (ITT), i.e., the first step of the procuring activity. The System Requirement Document specifies the mission's scientific objectives, and, as a consequence, the first level of the technical performance that the spacecraft shall fulfill, in a broad sense. The EMC system-level requirements of the spacecraft can be either explicitly addressed in the System Requirement Document, or can be derived from the mission's goals.

The development of this process is now illustrated with two complementary real-life examples, addressing the same topic: magnetic cleanliness control. Magnetic cleanliness control constitutes the set of design and manufacturing rules, and assembly, integration, and verification (AIV) activities at large, which are necessary to ensure that the magnetic characteristics of spacecraft do not interfere with the quality of the scientific data [22-25].

4.1.1 CLUSTER

CLUSTER is an ensemble of four spacecraft. These are presently operational, carrying highly sensitive magnetometer experiments for measuring the magnetic field in the magnetosphere. The magnetic fields of interest are within the range of few nanotesla [26, 27]. In order to avoid interference with the science data, the spacecraft-generated magnetic disturbance can not exceed 250 pT at the magnetometer's location, with a stability of ± 100 pT per 100 s. The EMC system-level requirement was therefore straightforward, in this case. Not only did the requirement implicitly put constraints on the magnetic cleanliness of the spacecraft, but also it had implications for the mounting position of the sensor and, consequently, on the mechanical complexity of the telescopic boom supporting the magnetometer.

A deep analysis was made to trade the boom length off against the estimated spacecraft-generated magnetic field. The starting point was the experience acquired with previous spacecraft, such as Helios 1-2, GEOS, Giotto, Ulysses, and Cassini-Huygens. These conducted extensive and successful magnetic-cleanliness programs to ensure the success of the mission. Each unit of the spacecraft was represented by a magnetic dipole, the magnitude of which was derived from data available from previous missions that embarked with similar units. Each dipole was assumed to be at the center of the corresponding unit in the spacecraft's system of reference. These were the inputs for running a Monte Carlo analysis that computed the probability density distribution of the magnetic field around the spacecraft. This was done in order to optimize the boom length to meet the magnetic requirement, within a given margin of confidence.

Simultaneously, considerations of magnetic cleanliness had a high priority during the design phase. This imposed severe screening of materials, parts, and process for magnetic properties; degaussing of the unavoidable soft magnetic parts; and, eventually, dc field compensation [28]. Magnetic shielding was not permitted, since the shielding material could be easily magnetized during handling, vibration, launch, etc., and would produce an unknown variable field that could not be controlled during flight. It was therefore preferable to accept a known (but still small) permanent field background, which was stable, instead of having a lower but variable field produced by the soft magnetic material. Many other provisions and precautions have been implemented throughout the

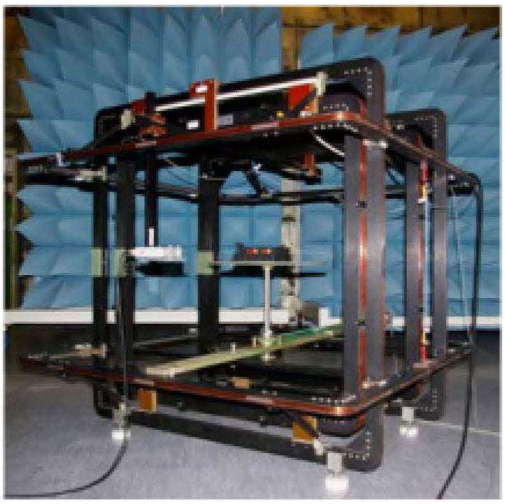

Figure 1. The magnetic-coil facility (MCF) at ESTEC. The magnetic-coil facility is used to determine (i) the permanent magnetic momentum of a test object by taking several readings of the magnetic field produced in a zero magnetic background, and (ii) the induced field momentum by illuminating the test object with a sequence of magnetic-field vectors.

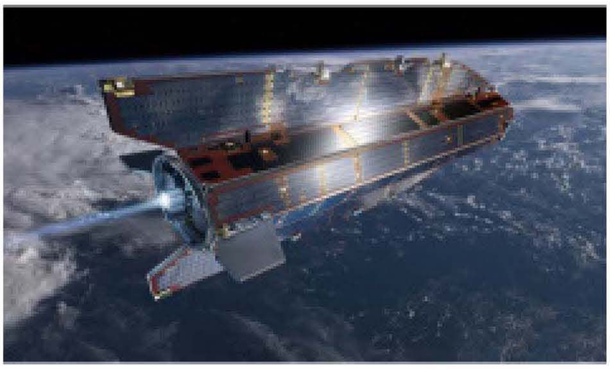

Figure 2. An artist's impression of the GOCE satellite.

CLUSTER life cycle under the program-integrator's responsibility. These have ranged from handling procedures to magnetic-compensation techniques (e.g., back-wiring of solar arrays) and design (i.e., balanced-differential interfaces, synchronization of dc-dc converters, etc.).

The 250 pT requirement was finally verified by tests and analyses. A spacecraft magnetic model was built by representing each unit by a multi-dipole equivalent source, extracted from equipment-level measurements (Figure 1) using a least-square technique [29, 30]. This model also allowed the identification of the critical units that required compensation techniques, e.g., gluing additional magnets in such a way that the main moment of the unit was decreased. The magnetic-field values predicted with the spacecraft model were then compared to the results of the system test with the magnetometer boom deployed [13, 31].

4.1.2 GOCE

GOCE [32, 33] is a spacecraft designed to determine the stationary Earth's gravity field – the geodic height and gravity anomalies – with high accuracy (1 cm and $10^{-6} g$, respectively) and spatial resolution (100 km), after ground data processing (see Figure 2 for an artist's impression). An electrostatic gravity gradiometer, composed of six tri-axial accelerometers, will measure the gravity-gradient tensor along the GOCE orbit (250 km circular, inclination 96.5°). The principle of operation of the gradiometer relies on measuring the forces that maintain a "proof mass" at the center of a specially engineered "cage." In each accelerometer, a platinum-rhodium proof mass (4 cm × 4 cm × 1 cm, 320 g) is suspended by electrostatic forces, and actively controlled in six degrees of freedom at the center of a cage via sixteen electrodes machined on the internal walls. A voltage is applied to the proof mass through a gold wire of 5 mm diameter, which also drains the excess charged particles from the proof mass. The control voltages are representative of the accelerations of the proof mass relative to the cage.

The gradiometer's specifications require that the total measurement-error spectral density of the gravity-gradient tensor's diagonal components can not exceed 4 $\mathrm{mE/Hz^{1/2}}$ in the measurement bandwidth of 0.005 Hz to 0.1 Hz [33] ($1\ \mathrm{E} = 10^{-9}\ \mathrm{s^{-2}}$ is a unit of gravity gradient called the Eotvos).

These requirements do not appear very pertinent to EMC. However, they do influence the magnetic design of the spacecraft. In fact, although weakly paramagnetic, the accelerometer mass couples with any external magnetic induction field of strength **B** by virtue of its magnetic susceptibility. The magnetic-induced force disturbs the measurement of the acceleration, according to the following approximate formula:

$$\mathbf{a}_m = \frac{1}{2}\frac{\chi_m}{\mu_0}\frac{V}{m}\alpha\nabla(\mathbf{B}\bullet\mathbf{B}),$$

where $\mathbf{a}_m$ is the acceleration induced by the magnetic disturbances; V and m are the volume and the mass of the proof mass, respectively; μ_0 is the vacuum magnetic permeability; χ_m is the magnetic susceptibility of the material (3×10^{-4} for the specific alloy used in GOCE); α is the magnetic shielding of the accelerometer housing; and $\mathbf{B} = \mathbf{B}(\mathbf{r}, t)$ is the external magnetic induction field.

The magnetic induction field, $\mathbf{B}(\mathbf{r}, t)$, follows a stochastic process, including both the natural space environment and the spacecraft-induced disturbances. As such, it is more conveniently characterized in terms of its power spectral density (PSD), in line with the initial definition of the gravity gradient spectral density error.

The high sensitivity of the scientific requirement did not allow the spacecraft integrator to neglect this contribution, which had to be necessarily accounted for in the overall satellite error budget. A portion of the specified error for gradient fluctuation was hence allocated to magnetic disturbances following system-level considerations. The system-level requirement was then apportioned at the equipment level as a function of the preliminary satellite layout with various techniques (e.g., Monte Carlo), under the assumption that any equipment could be modeled by magnetic dipoles. The calculation of the apportioning exercise brought values of magnetic field fluctuations of a few $\mathrm{nT/Hz^{1/2}}$, measured at a distance of 1 m from the equipment. Apart from the technical consideration of this requirement – which is apparently stringent – it could have potentially brought severe programmatic drawbacks, impacting both the cost and the schedule of the program. In fact, any equipment would have required a long testing time, uncommon facilities, data processing, and difficult retrofit in case an out-of-specification situation was detected. The program integrator performed a tradeoff, the results of which showed that sufficient magnetic shielding on the accelerometer heads was the more cost-effective solution in order to reduce excessive use of program resources.

These two examples addressed the same topic (magnetic requirements), and were handled with different but equally effective approaches. They allow insight into the complexity and the programmatic responsibilities involving EMC.

There are numerous cases where EMC directly influences spacecraft system design. They are so mission-specific that it is impractical to give a universal paradigm, covering all the possible cases, here. For system-level requirements, it is hence convenient to proceed with examples. This time, let us briefly consider the different implementation of a fundamental EMC concept: the spacecraft's power-bus grounding.

A well-posed electrical grounding architecture is the primary ingredient for achieving EMC at the spacecraft level in a cost-effective way. Grounding provides a common voltage reference for spacecraft electronic equipment and subsystems, while minimizing EMI and unintentional interactions between them. Different grounding concepts have pros and cons, including reliability considerations that are the subject of deep tradeoff studies since the conceptual phase of the spacecraft's definition [34]. A conclusion must be reached before the equipment's EMC design takes place.

A widely used architecture in spacecraft, adopted by a number of ESA projects (e.g., ENVISAT, Herschel and Planck, SMART-1, ROSETTA, MARS Express, and BEPICOLOMBO, to mention a few) is distributed single-point grounding (DSPG). The basic principle is to isolate power networks in the system through dc/dc converters, to minimize the mutual interactions. Generally, the negative terminal of the battery is connected to ground.

On the contrary, Russian spacecraft have the main power distribution isolated with respect to the chassis. More precisely, the return power line is connected to the chassis through a bleed resistor, shunted by a capacitor (typically a few kΩ and a few hundred nF, respectively) close to the power source. The resistor ties the power bus to the chassis potential, and simultaneously limits the current flowing onto the structure in case of an isolation fault of the main power bus. The Russian system has an intrinsic single-failure tolerance against short circuits of the primary bus that could cause a loss of mission. The disadvantage is increased common-mode noise at the user interfaces, and, consequently, an increased radiated emission from the power harness [35]. The bus users hence have to make provisions for common-mode immunity. This can be tolerable if performance is traded against the mission loss.

Figure 3 reports a typical example of the common-mode noise (i.e., the voltage between the positive line and the chassis, the return line and the chassis) taken from the Automated Transfer Vehicle (ATV) [36]. The ATV is an automatic, unmanned space-transport vehicle developed by the European Space Agency. It carries cargo and supplies from Earth to the International Space Station (ISS). The ATV docks to the Russian segment of the ISS, which provides the necessary power with a 28 V regulated power bus that presents the configuration described above.

Reliability considerations have suggested using this grounding architecture for critical interplanetary missions, especially those using radioisotope thermoelectric generators (e.g., Huygens-Cassini, Voyager, and Galileo, to mention a few examples). In fact, nuclear radiation in the long term may alter the properties of the insulation materials inside the generator container, leading to current leakage or short circuits. Launch vehicles (e.g., ARIANE 4) also have such a grounding architecture. Of course, systems using the primary power bus must be designed in order not to violate the isolated-grounding concept. The success of many space missions demonstrates the validity and sometimes the necessity of this approach.

Pyrotechnic initiator units [37] widely use the isolated grounding architecture, even when the rest of the spacecraft follows a different grounding architecture at the system level. The reason is always the same: reliability. When an electro-explosive device (EED) blows, the conductive hot plasma generated by the powder charge may close the loop from the positive power line to the chassis, causing a persistent short circuit. In this case, currents of the order of 10 A can flow onto the chassis, giving rise to magnetic

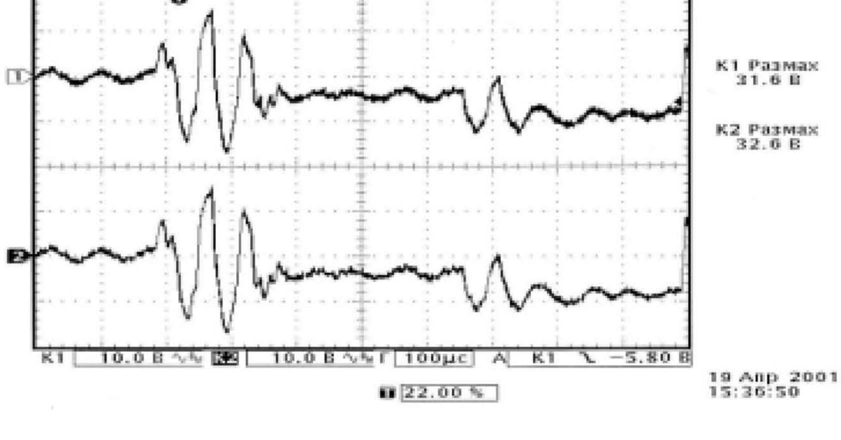

Figure 3. A typical common mode voltage (~30 volts) on floating power buses. This is a transient measured at the interface between the Automated Transfer Vehicle and the Russian Service Module in March 2001 (the test was carried out with a representative interface).

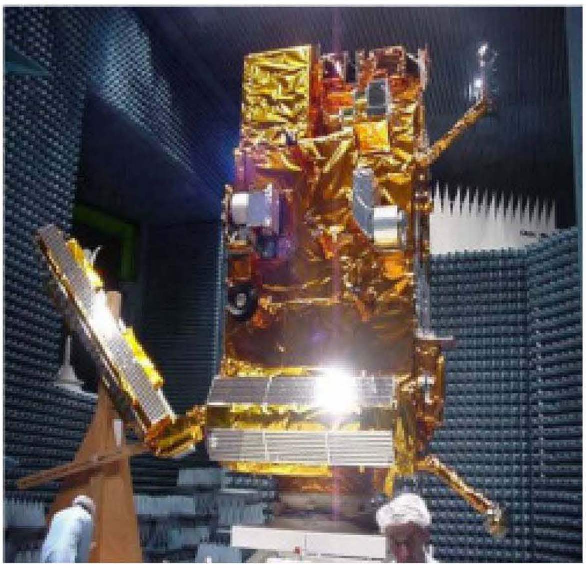

Figure 4. EMC testing of the METOP EQM spacecraft.

coupling into nearby circuits, until possibly exhaustion of the available power. An isolated power bus with an appropriate bleed resistor can be a simple remedy that will limit the consequences of this phenomenon.

4.2 Equipment-Level Requirement

While the definitions of the system-level requirements are directly or indirectly derived from the mission-specific demands, not all the equipment-level requirements can follow the same process. An apportioning from system to equipment level is possible only for certain unconventional requirements. Otherwise, EMC engineers have recourse to tailored standards (e.g., ECSS [15-16]), or to the mature experience of previous projects.

Typical unit-level requirements are the radiated emissions and susceptibility notches:

- To cover the bands used for telemetry and tele-command (TT&C) signals (e.g., unit-level emissions are limited to 10 dBμV/m in the tele-command band around 7.2 GHz for Herschel-Planck, and even-more-stringent requirements are applied to deep-space missions)
- For launcher compatibility ([38] provides the essential data on the Ariane 5 launch system, which together with Soyuz and Vega constitutes the European Space Transportation union), and
- To protect relay communication (e.g., the UHF link between the orbiter and the rover of the EXOMARS mission).

When very sensitive payloads are embarked, specific requirements and design measures are implemented to assure adequate EMC performance of the satellite. In [39], experience was presented from the METOP satellite (Figure 4), a meteorological satellite program jointly established by ESA and EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites). METOP features very sensitive receivers in the frequency range of 120-406 MHz for the search and rescue instrument (S&R). In order to ensure the compatibility with the METOP search and rescue receivers, the radiated emissions from the whole satellite have to be as low as –28 dBμV/m [39].

5. The Flow of the EMC Activities in the Framework of a Space Program

The final objective of the EMC activities performed throughout the development of any space system is to ensure that during the spacecraft's lifetime – from equipment integration over launch until spacecraft decommissioning – the system is self compatible, and neither causes disturbances to other systems nor suffers loss of performance due to other systems or any external environment. This goal is pursued by a balanced combination of standards, guidelines, the heritage of previous projects, and modeling and testing spanning from the earliest stage of the program to the final integration of the space system. In the following, the skeleton of the procedure and the relevant documentation aimed at ensuring the attainment of system-level EMC are presented.

The main documents tailored towards the system requirements are:

- EMC Specification: contains the requirements at the system, subsystem, and unit level.
- EMC Control Plan: describes methods, means, and rules that will be followed throughout the project to guarantee compliance with the requirements as defined in the EMC Specification.
- EMC Test/Verification Plan and Procedure: presents the test setup and procedures to verify the specifications.
- EMC Test/Verification Report: reports the test results and the relevant non-conformance.
- EMC Analyses: contains all the ancillary analyses carried out in support of design and testing activities, e.g., predictions of intra-system EMI/EMC based on equipment EMI characteristics to assess design solutions such as filtering, grounding, and shielding.

The above documents are managed by the EMC engineers, and are periodically updated throughout the development phases of the system. Several milestones trace the life of the spacecraft. Failure to complete any of them precludes the possibility for stepping to the subsequent milestone.

A non-exhaustive list of data/deliverables that must be completed for each milestone is presented hereinafter [40].

5.1 Request for Proposal (RFP) or Response to Invitation to Tender (ITT)

In the preparation of the response to the Invitation to Tender, the EMC engineers study and define the known operational environments. They identify the functional criticality for all the equipment and subsystems that are classified in adequate categories of risk. At this stage of the program, a safety margin is defined for critical functions and electro-explosive devices (EEDs), to account for lifetime degradation of circuits and circuit protection. Typically, 20 dB are allocated for electro-explosive devices, and 6 dB for signal, power, and control lines [15, 16]. Finally, general guidelines (e.g., separating signals and primary power bus, selecting the frequencies of dc/dc converters outside signal bands, twisting and shielding the harness with the appropriate twist rate, etc.) are defined and made applicable to the procurement of units and subsystems, as well as to the integration of the system.

5.2 System Readiness Review (SRR) or Requirement Definition Review (RDR)

At the system readiness review, the EMC specification must be consolidated with requirements at the system, subsystem, and unit levels. Typical requirements are grounding, bonding, in-rush current, conducted (continuous-wave and transient) and radiated emissions, as well as susceptibility, electrostatic discharge, and magnetic cleanliness control [15, 16]. The EMC engineer is also responsible of the definition of the margin-verification methods at the system level in the EMC Control Plan. The verification of the compatibility of the system is de facto achieved by imposing and demonstrating a safety margin between the susceptibility threshold of the units and the actual noise at the system level under worst-case conditions [15, 16].

The EMC guidelines are final consolidated, with special precautions for the critical cases. As seen in the previous sections, for magnetically sensitive spacecraft (e.g., CLUSTER, GOCE) several preventive measures have matured along the years. Nowadays, very good reliable engineering practices are known and implemented [23-26].

5.3 Preliminary Design Review (PDR)

At the preliminary design review, the most critical EMI aspects must be identified (in EMC Analyses), and appropriate countermeasures consolidated (in the EMC Control Plan). The impact of the components-off-the-shelf (COTS) on the system and their EMI/EMC performance are assessed (in EMC Analyses). An accurate grounding diagram of primary/secondary power, units, shields, and principal interfaces (EMC Control Plan) is built. The EMC engineer finally consolidates the model philosophy and the relevant verification methods (in the EMC Control Plan) that will be followed throughout the course of the program.

The principal spacecraft models are the avionic model (AVM), the engineering/electrical qualification model (EM/EQM), the proto flight model (PFM), and the flight model (FM).

The applicable verification methods can be (i) analysis; (ii) review of design (e.g., correct use of shielded twisted wires, shield grounding, power isolation by review of drawings); (iii) inspection to verify the conformance of drawings, the use of proper parts and materials, e.g., harness separation, correct routing, etc.; (iv) testing to demonstrate the compliance with the requirements during different stages of the project (i.e., development, qualification, and acceptance); and (v) similarity applied to equipment/subsystems that have been previously qualified to the same or more severe environments.

5.4 Critical Design Review (CDR)

Between the preliminary design review and the critical design review, all the units and subsystems are designed, assembled, and qualified. The System EMC Control Plan is updated with the unit/subsystem results (the EMC Test Report), and any potential criticality is identified and the relevant countermeasures are decided. The EMC managers evaluate all requests for waiver (RFW) and non-conformance reports (NCR), and dispose of the relevant actions to be completed prior to the final system-level test. The system level test, to be performed before the flight acceptance review, is fully defined in light of the results at the unit and subsystem levels.

5.5 Flight Acceptance Review (FAR)

In the preparation for the flight acceptance review, limited system-level testing is performed, in order to collect the ultimate results necessary to complete the system-level analyses. The emissions and susceptibility tests conducted are typically confined to those areas that have shown a

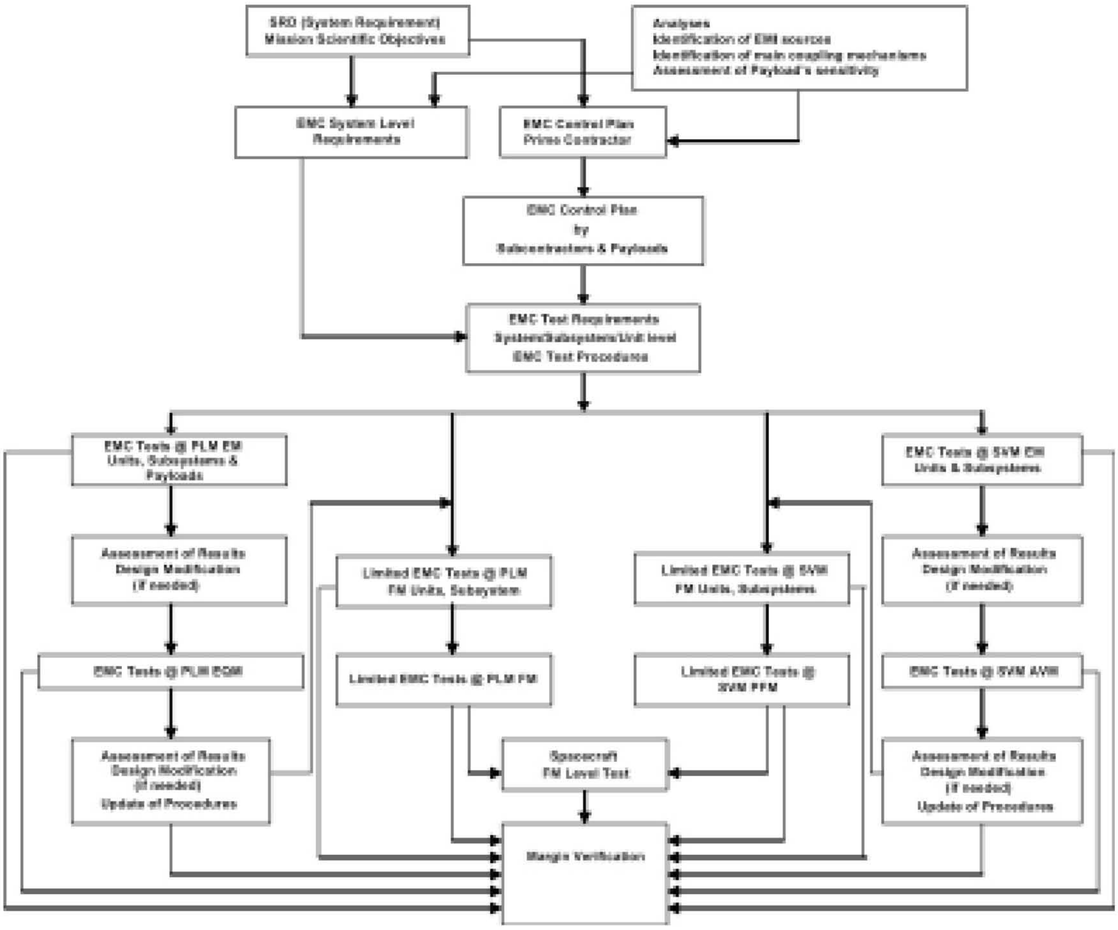

Figure 5. A flowchart of EMC program activities.

certain degree of marginality at the sublevel, or that constitute the core power-distribution points of the spacecraft. Radiated emission and susceptibility tests are carried out to prove the system's margin (6 dB). Particular attention is devoted to the measurements of specific notches (e.g., tele-command, launcher, sensitive payloads). The final issues of the EMC analyses and of the EMC Test/Verification Report are prepared, in order to demonstrate the electromagnetic compliance of the system with an adequate margin of safety.

The activities described in the sections above are summarized in the flowchart presented in Figure 5. This constitutes an overview of the various stages of the EMC program adopted by many spacecraft. For the sake of generality, the flowchart presents an approach based on analyses and tests at the service-module level (SVM: the part of the satellite that ensures power supply, attitude control, and RF communication with the ground station); the payload-module level (PLM: the part of the satellite that carries out the scientific mission); and the system level. However, the reader should be aware that for the sake of cost reduction, some spacecraft follow a reduced program, possibly with testing only of the fully integrated satellite.

6. Conclusions, Trends, and Future Needs

The limited budget for space-related industry, and the simultaneous introduction of innovative electronic technology and services, require a rationalization of the EMC discipline. The increasing complexity of spacecraft systems, i.e., buses, payloads, and their mutual interaction, calls for EMC design and verification based on a systematic analytic methodology. The insufficient a priori knowledge of large electromagnetic systems – including the details of their elements and the mutual-interaction paths – plays a significant role in consolidating the EMC discipline as prominently empirical.

EMC deals intrinsically with electromagnetic noise, which is rigorously described by the methods of stochastic process theory. In many instances, very sensitive scientific payloads (e.g., LISA, Herschel and Planck, LISA Pathfinder, etc.) specify their tight science requirements in terms of power spectral density, rather than in those units conventionally adopted by the EMC community. The verification of such requirements and their implication for the spacecraft's specification and design deserves a great deal of analysis that still needs to be finalized. Although classical EMC requirements are in place to impose canonical design criteria at the equipment level, to limit the generated disturbances and to ensure that sufficient immunity is built in, a rigorous treatment of the science requirements and their implications for the equipment level is still to come.

EMC engineering has several issues in common with reliability related disciplines. These regularly rely on statistical approaches [41], especially when we consider the margin evaluation and the overall functional assessment at the system level.

The above considerations point the next generation of electromagnetic tools for intra-system compatibility toward a probabilistic approach, i.e., where the probability of having interference exceeding a given threshold at a predetermined point is the output. The feasibility of achieving estimated solutions with moderately high statistical accuracy depends critically on how effectively available information is exploited [41].

New communication and information devices and services in space, together with the trends toward further miniaturization of electronic components, pose new EMC problems. Ultra-fast digital electronics, clock frequencies beyond 1 GHz and power-supply switching frequencies above 1 MHz, coexisting in densely packed printed circuit boards (PCB), require further research to achieve reliable design and analysis. The frequency range of interest will easily exceed the upper limit of today's EMC methods, especially for conducted disturbances. Not only does this put into discussion the validity of the usual EMC requirements, but also it asks for EMC modeling and instrumentation readiness to deal with this emerging technology for space applications.

Innovative testing concepts, supported by new-generation sensors and devices, constitute the essential supplement to face the present and future technological developments. Relying on existing test instruments (i.e., oscilloscopes and spectrum analyzers) and on the physics of the EMC phenomena, the new testing approaches focus on both the reduction of cost and time, while bringing added value to system verification. A valid alternative could consist of using time-domain techniques to the maximum extent for system verification [42, 43]. Of paramount importance is further investigation of alternative methods to radiated tests, which are expensive in terms of facilities and test time. This imposes a cost burden on EMC development and testing, especially for small and medium enterprises. Despite these costs, such tests are afflicted by inherently large uncertainties in the results. Bulk-current injection (BCI) [44-46] and stirred-mode or reverberation chambers [47] could be both more efficient and less expensive.

Numerical three-dimensional solvers also constitute valid support for EMC engineers for the selection of appropriate solutions during the design phase, and the detection of possible anomalies and troubleshooting analyses. They can therefore lead to cost and time savings. In the last decade, electromagnetic numerical simulations of large-scale systems have shown significant progress, profiting from the growth of computational electromagnetics and computer performance. A good overview of the current numerical-simulation capabilities for modeling complex systems, including structure, cabling, and electronic equipment, was provided in [48].

The European know-how for the space EMC discipline has the potential to both keep pace with the technology evolution, and to foster industrial competitiveness in the market at large. Institutional R&D funding with space agencies, in order to harmonize EMC practices, methods, and standardization for this specific market, appears the only viable strategy for success.

This concept constitutes the core of the desired roadmap to future developments, which can be summarized as follows:

- Provide the tools to evaluate and control electromagnetic interference effects that clearly have an impact on economics and competitiveness;
- Cut the test costs and improve analysis capability;
- Improve technology readiness for future missions and needs by developing low-cost EMC instrumentation with optimized performance; and
- Produce and maintain the technical standards necessary for the European market in space EMC and related areas, accounting for cost/benefit analysis and the inherent business-impact assessment.

EMC is the result of the efforts of the project team technically concurring to achieve the objectives of a space mission. There are still many issues to clarify and many challenges to face, but the variety of options and the continual technical challenges nourish the charming nature of this discipline.

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