



BSI Standards Publication

Space engineering — Electromagnetic compatibility handbook

National foreword

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Space engineering - Electromagnetic compatibility handbook

Ingénierie spatiale - Manuel pour la compatibilité
électromagnétique

Raumfahrttechnik - Handbuch zur
elektromagnetischen Kompatibilität

This Technical Report was approved by CEN on 29 November 2021. It has been drawn up by the Technical Committee CEN/CLC/JTC 5.

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European Foreword

This document (CEN/TR 17603-20-07:2022) has been prepared by Technical Committee CEN/CLC/JTC 5 "Space", the secretariat of which is held by DIN.

It is highlighted that this technical report does not contain any requirement but only collection of data or descriptions and guidelines about how to organize and perform the work in support of EN 16603-20.

This Technical report (CEN/TR 17603-20-07:2022) originates from ECSS-E-HB-20-07A.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN shall not be held responsible for identifying any or all such patent rights.

This document has been prepared under a mandate given to CEN by the European Commission and the European Free Trade Association.

This document has been developed to cover specifically space systems and has therefore precedence over any TR covering the same scope but with a wider domain of applicability (e.g.: aerospace).

Introduction

The purpose of the present handbook is to support the use of ECSS-E-ST-20-07C. It aims at providing practical and helpful information for electromagnetic compatibility (EMC) in the development of space equipment and systems.

It gathers EMC experience, know-how and lessons-learnt from the European Space Community with the intention to assist project groups and individual implementers.

1

Scope

The objective of this EMC Handbook is to point out all the issues relevant to space systems EMC, to provide a general technical treatment and to address the interested reader to more thorough and in-depth publications.

NOTE It is possible to find fundamental and advanced treatment of many aspects related to EMC: many universities offer courses on EMC and a large number of textbooks, papers and technical documents are available. Therefore replicating in this Handbook the available knowledge is impractical and meaningless.

Emphasis is given to space systems EMC design, development and verification, and specifically to the practical aspects related to these issues.

NOTE This has been possible thanks to the collaboration of space industry, especially on items which are not textbook issues and whose solution needs the widespread experience gained in large number of projects.

2 References

EN Reference	Reference in text	Title
EN 16601-00-01	ECSS-S-ST-00-01	ECSS System: - Glossary of terms
EN 17603-20	ECSS-E-ST-20	Space engineering - Electric and electronic
EN 17603-20-07	ECSS-E-ST-20-07	Space engineering - Electromagnetic compatibility
EN 17603-33-11	ECSS-E-ST-33-11	Space engineering - Explosive systems and devices
EN 17603-10-03	ECSS-E-ST-10-03	Space engineering – Testing
EN 17602-70-71	ECSS-Q-ST-70-71	Space product assurance - Materials, processes and their data selection

Terms, definitions and abbreviated terms

3.1 Terms from other documents

For the purpose of this document, the terms and definitions from ECSS-S-ST-00-01 apply

For the purpose of this document, the following terms and definitions from ECSS-E-ST-20C apply:

electrical bonding
electromagnetic compatibility (EMC)
electromagnetic interference (EMI)
electromagnetic interference safety margin (EMISM)
grounding
susceptibility

For the purpose of this document, the following terms and definitions from ECSS-E-ST-20-07C apply:

line impedance stabilization network (LISN)
overshield

3.2 Terms specific to the present document

3.2.1 balun

type of transformer converting balanced electrical signals to unbalanced electrical signals and vice versa

NOTE The term balun comes from BALanced/UNbalanced.

3.2.2 shield transfer impedance

ratio of the current on one surface of a shield to the voltage drop generated by this current on the opposite surface of this shield

NOTE Shields with lower transfer impedance are more effective than shields with higher transfer impedance.

3.2.3 probe transfer impedance

ratio of voltage at the output port of the probe with respect to the causing current on the electrical line or cable bundle under test

NOTE This ratio can be influenced by the setup.

3.3 Abbreviated terms

For the purpose of this document, the abbreviated terms from ECSS-S-ST-00-01 and the following apply:

Abbreviation	Meaning
A5	ARIANE 5
AC	alternating current
ACF	antenna calibration factor (reverberation chambers)
ACS	attitude control system
A/D	analogue/digital
ADC	analogue-to-digital converter
AF	antenna factor
AGND	analogue ground
AIT	assembly integration and test
AIV	assembly integration and verification
AM	amplitude modulation
AMUX	analogue multiplexer
ASD	amplitude spectrum density
AWG	American Wire Gauge
BCI	bulk current injection
BIPM	Bureau International des Poids et Mesures
BW	bandwidth
CAD	computer-aided design
CCF	chamber calibration factor (reverberation chambers)
CCS	coupling cross section
CE	conducted emission
CEI	Commission Electrotechnique Internationale
CFRP	carbon fibre reinforced plastic
C/I	carrier to interference (ratio)
CISPR	Comité International Spécial des Perturbations Radioélectriques
CLF	chamber loading factor (reverberation chambers)
CM	common mode or communication module
CMI	common mode impedance
CMV	common mode voltage
CMVR	common mode voltage rejection
CMVRR	common mode voltage rejection ratio
CNES	Centre National d'Etudes Spatiales
CS	conducted susceptibility
CSG	Centre Spatial Guyanais
CW	continuous wave

Abbreviation	Meaning
DAQ	data acquisition
DBCI	double bulk current injection
DC	direct current
DGND	digital ground
DM	differential mode
DUT	device under test
EED	electro-explosive device
EFIE	electric field integral equation
e.g.	exempli gratia (for example)
EGSE	electrical ground support equipment
EHF	extremely high frequency (30 GHz – 300 GHz)
EICD	electrical interface control document
EIRP	equivalent isotropic radiated power
EM	electro-magnetic or engineering model
EMC	electro-magnetic compatibility
EMCAB	electro-magnetic compatibility advisory board
EMCCP	electro-magnetic compatibility control plan
EMEVP	electro-magnetic effects verification plan
EMEVR	electro-magnetic effects verification report
EMF	electromotive force
EMI	electro-magnetic interference
EMISM	electro-magnetic interference safety margin
EMP	electromagnetic pulse
EPS	electrical power subsystem
ESCC	European Space Components Coordination https://escies.org/escsc/
ESCIES	European Space Component Information Exchange System https://escies.org/
ESD	electro-static discharge
ESI	ESA standard initiator
ESTEC	European Space Research and Technology Centre
EUT	equipment under test
FAR	fully anechoic room
FDFD	finite difference frequency domain
FDTD	finite difference time domain
FEM	finite element method
FET	field effect transistor
FFT	fast Fourier transform

Abbreviation	Meaning
GND	ground
GPS	global positioning system
GTO	geostationary transfer orbit
HBM	human body model
HV	high voltage
IABG	Industrieanlagen-Betriebsgesellschaft
ICD	interface control document
i.e.	id est (that is)
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
L band (IEEE)	1 to 2 GHz
LCL	latching current limiter
LEMP	lightning electromagnetic pulse
LEO	low earth orbit
LISN	line impedance stabilisation network
LIDAR	light detection and ranging
LSB	least significant bit
LUF	lowest usable frequency (reverberation chambers)
MDM	multiple dipole modelling
MFIE	magnetic field integral equation
MFSA	magnetfeld-simulationsanlage
MIL-STD	United States Defence Standard
MLI	multi-layer insulator
MoM	method of moments (computational electromagnetics technique)
MSC	mode-stirred chamber
MTB	magneto-torquer bar
MTC	mode-tuned chamber
NCR	nonconformance report
NSI	NASA standard initiator
OBC	on-board computer
OCT	oversized cavity theory
PCB	printed circuit board
PCDU	power conditioning and distribution unit
PCU	power conditioning unit
pdf	probability density function
PDR	preliminary design review
PDU	power distribution unit
PFD	power flux density

Abbreviation	Meaning
PSD	power spectrum density
RADAR	radio detection and ranging
RC	reverberation chamber
RE	radiated emission
RF	radio frequency
RFC	radio frequency compatibility
RFD	request for deviation
RFW	request for waiver
RMS	root mean square
RS	radiated susceptibility
RTCA	Radio Technical Commission for Aeronautics
RX, Rx	receive (frequency, band, antenna...) or receiver
S band	2 to 4 GHz
SAR	semi-anechoic room, or search and rescue
S/C	spacecraft
SH	spherical harmonics
SHA	spherical harmonics analysis
SHF	super-high frequency (3 GHz – 30 GHz)
SMD	surface-mounted device
SMT	surface-mount technology
S/N	signal to noise ratio
SoW	statement of work
SRD	system requirements document
SRR	system requirements review
SSE	space segment element
SSPC	solid state protection circuit
STP	shielded twisted pair
SVM	service module
TC	telecommand
TDMA	time domain multiple access
TL	transmission line
TLM	transmission line matrix method (computational electromagnetics technique)
TX, Tx	transmit (frequency, band, antenna...) or transmitter
TWTA	travelling-wave tube amplifier
UHF	ultra-high frequency (300 MHz – 3 GHz)
USAF	United States Air Force
US DoD	United States Department of Defence
VHF	very high frequency (30 MHz – 300 MHz)

Abbreviation	Meaning
Via	vertical interconnect access (vertical connection in PCB)
VNA	vector network analyzer
WGBCO	waveguide below cut-off

3.4 Nomenclature

By default and unless otherwise specified, the following notations apply in the rest of the document.

f	frequency
ω	$= 2\pi f$, cycle frequency
i or j	imaginary unit
λ	wavelength
c	$= 299792458 \text{ m/s} \approx 3 \cdot 10^8 \text{ m/s}$, speed of light in vacuum
μ_0	$= 4\pi \times 10^{-7} \text{ H/m} \approx 1,257 \dots \mu\text{H/m}$, vacuum permeability or magnetic constant
ϵ_0	$= 1/(\mu_0 c^2) \approx 8,854 \dots \text{pF/m}$, vacuum permittivity or electric constant
μ	permeability
σ	electrical conductivity
p or s	Laplace's variable

Unless otherwise stated, the International System of Units (Système international d'unités, SI) is used.

Rationale for ECSS-E-ST-20-07C unit level test requirements

4.1 General rationale for standard EMC test requirements

The objective of EMC is to ensure that any equipment belonging to a system can function and perform nominally within the system. The approach ensuring this result involves three steps. First, each equipment of the system is characterised as a source of EMI and as sensitive equipment. It is important to note that the EMC of a system is primarily based on unit level performances in terms of emission or susceptibility. The second step is the assessment of transfer functions in conducted and radiated modes between each possible source of EMI to each circuit potentially sensitive. They closely depend on the mechanical and electrical architecture resulting from the trade-offs between all technical domains relevant to the project. The last step is the assessment of the EMISM at the critical points by a combination of tests and calculations comparing the effective level of EMI to the susceptibility threshold.

Because it is an essential aspect of EMC control, the ECSS-E-ST-20-07C specifies a number of EMC test methods for EMC qualification at unit level.

The objectives are several:

- Standardising the use of correct and useful test set-ups;
- Discouraging wrong or obsolete practices;
- Limiting the need for delta-qualification of recurrent equipment.

It is important to note that most test limits in the ECSS-E-ST-20-07C are informative. They are provided as a starting point for the definition of EMC requirements.

4.2 Test set-up requirements

4.2.1 Line impedance stabilization network

The LISN definition in the ECSS-E-ST-20-07C is similar to most LISNs used on space projects.

The LISN, shown in Figure 4-1, has the following functions in order of importance:

- Decoupling the equipment CE and CS signals from the facility/EGSE power supply: in other words, the CE measured on the EUT power lines, both in differential and common mode should originate from the EUT only; and the injected CS power should only contribute to test the EUT, without disturbing the facility/EGSE power supply;
- Making the impedance seen by the EUT independent of the facility/EGSE power supply impedance;

- Reproducing roughly the power line impedance of the actual installation;
- Maintaining a standard test set-up making analysis and diagnostic easier; the same LISN should then be used within a project and preferably between projects as well.

The series inductances (air coils) represent the inductance of the wiring; the series resistances represent the resistance of the wiring and of the central protections; the $50\ \Omega$ resistors result in $100\ \Omega$ at high frequency, similar to the characteristic impedance of the line (widely used LISN design); the feed-through capacitors provide a short-circuit at high frequency. The large capacitance of 1 mF to 10 mF is a reserve of charge, needed for inrush current measurements. It provides low impedance at low frequency and participates in decoupling the EUT from the facility/EGSE power supply.

In most cases, the LISN is used with the return grounded at the input.

In such cases, in order to control better the common mode impedance and to improve the decoupling from the facility/EGSE power supply, it is advisable to make a LISN with internal grounding of the return lead at the input, as shown in Figure 4-2.

The LISN metallic enclosure should be in tight contact with the facility ground plane. Bonding it to the facility ground plane only through its bonding stud and a bonding strap is not deemed sufficient, cf. 5.2.3.8.

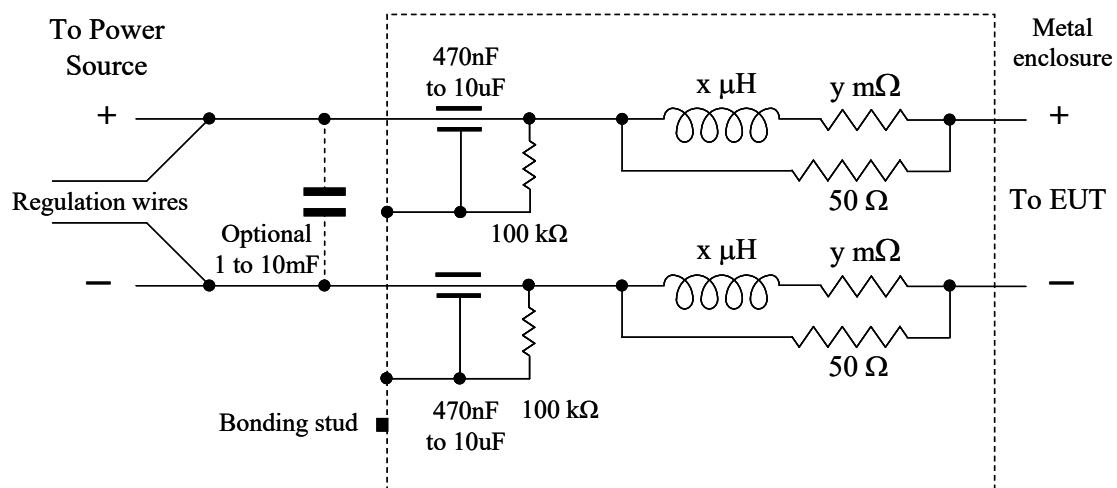


Figure 4-1: Line impedance stabilization network schematic

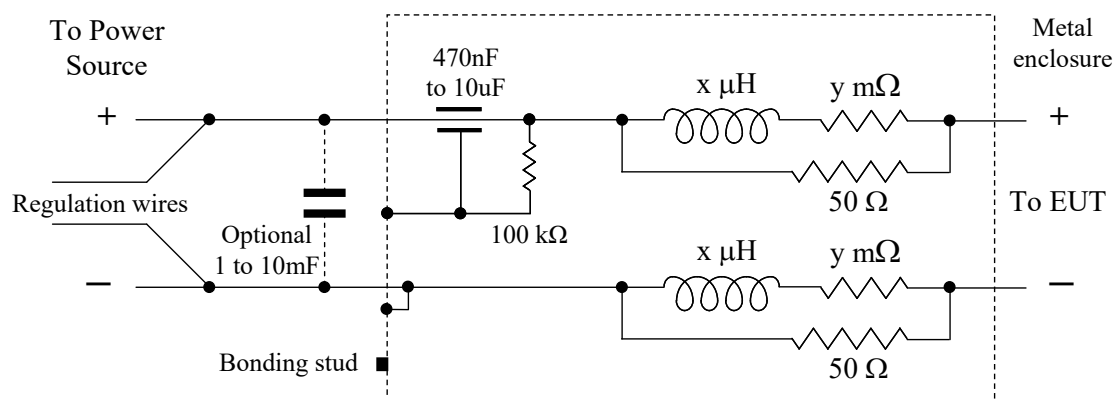


Figure 4-2: LISN with return internally grounded at input

All internal connections should be short in order to limit parasitic inductances and capacitances.

4.2.2 Mains isolation transformers

None of the test methods in the ECSS-E-ST-20-07C necessitate an isolation transformer.

Mains isolation transformers may only be useful for low frequency measurements (below 100 kHz) of very low level signals.

At high frequencies, the capacitive coupling between windings becomes preponderant, even with electrostatic screens because of inductive screen grounding bonds.

If the idea of the isolation transformer is to reject common mode in measurement, then using active differential probes for voltage measurements ensures good results without any impact on safety.

4.2.3 Anechoic chambers

An anechoic chamber as specified in ECSS-E-ST-20-07C, clause 5.3.2.2. is a shielded chamber behaving as a Faraday cage and equipped with electromagnetic absorbers (usually in the shape of pyramids) in order to limit the effects of standing waves that can occur when the wavelength has the same order of magnitude as the cages dimensions. Ferrite tiles can also be used to provide absorption at lower frequencies, or hybrid absorbers consisting of pyramids and ferrite tiles.

With respect to an open test site, an anechoic chamber offers the following advantages:

- Availability independent on climatic conditions;
- Shielding from external perturbations;
- Possibility to perform immunity tests without polluting the external environment.

It is however limited at low frequencies because of the characteristics of the foam absorbers that are seldom efficient below 100 MHz.

In order to decrease the low frequency limit of anechoic chambers to a few tens of MHz (where the size of absorbers are prohibitive) ferrite tiles featuring magnetic effect absorption can be used.

Typically recommended E-field shielding effectiveness values are between 60 dB at 10 kHz and 100 dB at 1 GHz.

In order to be functional, a chamber is also equipped with power line filters, feed-through pipes / cable ducts and penetration panels equipped with feed-through connectors.

If high power levels and flammable absorbers are used, a fire detection and extinguisher system is necessary.

The sizes of anechoic chambers depend on the type of applications; small chambers are sufficient for the tests at unit/subsystem level specified in the ECSS-E-ST-20-07C, but much larger ones are obviously needed for tests at spacecraft module or integrated spacecraft levels.

As an example, the Maxwell facility at ESTEC has the following dimensions:

- Length x width: 14,6 m x 10,8 m between absorber tips
- Height: 11 m between floor and absorber tips

(<http://www.european-test-services.net/services-emc-maxwell.html>)

4.3 EMC test requirements

4.3.1 Overview

This section 4.3 provides a rationale for the requirements in clause 5.4 of ECSS-E-ST-20-07C (Equipment and subsystem level test procedures). For an easy reference, the sub-sections of this section 4.3 can be directly mapped to the sub-clauses of clause 5.4 of ECSS-E-ST-20-07C.

Additional rationale is provided in section 4.3.6 for the absence in ECSS-E-ST-20-07C of a requirement and test method to measure the RE magnetic field between 30 Hz to 50 kHz.

4.3.2 CE, power leads, differential mode, 30 Hz to 100 kHz

The conducted emission is measured as interference current because the power source impedance in the test set-up is difficult to control at low frequencies. In addition, as in a number of situations the emission source impedance (within the EUT) can be assumed to dominate the power source impedance (*i.e.* the LISN impedance), conducted emission current levels can to some extent be independent of the power source impedance.

Low frequency conducted emission requirements are mainly intended to ensure that the EUT does not corrupt the power bus quality (in terms of voltage ripple).

4.3.3 CE, power and signal leads, 100 kHz to 100 MHz

Although in other standards, such as the US DoD MIL-STD-461F [1], CE measurements on the power lines are specified in terms of voltage for the upper frequency part (above 10 kHz for the MIL-STD-461F), the test specified in the ECSS-E-ST-20-07C is CE as interference current. Actually, specifying CE in terms of voltage involves using a rather high impedance LISN (50 μ H in the MIL-STD-461F) so that measurements can be reproducible. This is considered not representative of realistic power bus impedance values on-board spacecraft. We note that the AIAA S-121-2009 [2] takes the approach of using a 5 μ H LISN, which is more representative of the power harness length on a small platform. They still use the CE voltage measurement method of the MIL-STD-461F (CE102), but only above 150 kHz, where the impedance of their LISN is 5 Ω .

The ECSS requirement of interest is specified for both power and signal lines.

For power lines, the CE is specified to be measured separately on the hot and return power leads, and also in common mode (*i.e.* with both leads inside the probe). We are aware that measuring the CE on each lead separately is not truly measuring the differential mode CE, but we acknowledge that it is a common misuse of the word “differential” (cf. 7.4.2 for guidance on how to measure differential CE).

For both power and signal lines, specifying a limit to the common mode CE between 100 kHz and 100 MHz also aims at controlling the radiated emission from the harness, and the risk of crosstalk between bundles. This is preferred to traditional military and aerospace standards (*e.g.* MIL-STD-461F) measuring emission below 30 MHz with a rod antenna, essentially characterising extreme near electric field emission. Such measurement can only be useful to:

- Protect a victim inherently sensitive to purely electric field;
- Prevent capacitive crosstalk between cables.

The first case is mission specific. The second one is unlikely because of the widespread use of shielded cables that are enough to prevent capacitive cross-talk, even with poor grounding. As a consequence, in the frequency range of interest, inductive crosstalk between cables or cable bundles is the main

crosstalk scenario of interest, and is better controlled by putting a limit on the common mode conducted emission.

The limit specified in the Annex A of the ECSS-E-ST-20-07C has a -20 dB per decade slope up to 10 MHz and then is flat up to 100 MHz. This can be interpreted as a way of limiting inductive crosstalk to a constant level according to the frequency, as inductive crosstalk is proportional to the frequency over the frequency range, where the cable common run is electrically short (so +20 dB per decade) and maintain a constant level starting from the frequency where the cable common run is electrically long.

The corner frequency in the Annex A of the ECSS-E-ST-20-07C is 10 MHz, which corresponds to one half wavelength of 15 m. Considering that cables are in practice much shorter than this, a possible tailoring of the limit is to propagate the -20 dB per decade slope up to 30 MHz.

It is important to note that although the limit is specified in the frequency domain for practical reasons, crosstalk is rather a broadband or time domain problem. As a consequence, the use of a current probe with flat transfer impedance should be considered, allowing switching to time domain by connecting it to an oscilloscope in order to get the information of the waveform, slope and peak amplitude.

4.3.4 CE, power leads, inrush current

At units switch on, current transients happen on their power leads before the steady state is reached. It is necessary to limit this inrush current in order to:

- Ensure the compatibility with the central protections in the distribution unit (PDU or PCDU) that may be SSPC or fuses;
- Limit the resulting voltage transient on the power bus.

The ECSS-E-ST-20-07C considers various types of inrush current tests:

- Switch on of the EUT via an external fast bounce-free power switch;
- Switch on of the EUT by its own internal switch (in case the EUT features built-in switching capability);
- Switch on via a SSPC (e.g. a LCL) representing central protections in the distribution unit (PDU or PCDU).

The typical inrush current shape shows a peak corresponding to the charging of the EUT power input filter capacitors, followed by the start-up of the electronics (DC/DC converter) and finishing with the steady state current. Its rise time, shape, amplitude and duration depend on the design of the input filter, on the SSPC characteristics (if included in the test set-up) and on possible active circuits in the EUT (soft start or current limiter).

Several oscilloscopes time bases are needed in order to capture the full event, while showing in sufficient detail the rise time of the initial peak and its duration.

4.3.5 DC Magnetic field emission, magnetic moment

The measurement of the magnetic moment at unit level may be needed for two main purposes:

- Ensuring that the resulting magnetic field at the ACS magnetometers location is under control and doesn't affect the angular error beyond acceptable limits (cf. ECSS-E-ST-20-07C, clause 4.2.5.2);
- Limit the field at the location of susceptible payloads.

Examples of susceptible payloads are scientific magnetometers, inertial sensors involving floating proof masses, ultra-stable oscillators, atomic clocks.

In any case, the limits imposed at unit level should be specified considering the following criteria:

- Possible presence of magnetic materials unavoidable in the equipment design;
- Current consumption of the equipment;
- Distance of the equipment from the sensitive element.

Magnetic moment requirements should not in general be specified to solar arrays; their contribution to the spurious field at the sensitive device location should be specified directly in terms of magnetic field and can be calculated from the Biot-Savart law.

In the ECSS-E-ST-20-07C, no advanced magnetic moment test method is specified as this requires special hardware and software not commonly available. More accurate methods involving multiple dipole modelling or spherical harmonics are described in 7.1.1 and 7.1.2 respectively.

NOTE The sources of DC magnetic field and the ways to limit them by design are addressed in 5.2.7 and 6.2.

4.3.6 Absence of RE magnetic field requirement, 30 Hz to 50 kHz, in the standard

Contrary to what was often specified in EMC requirement specifications of European space projects, there is no requirement in the ECSS-E-ST-20-07C to measure the RE magnetic field between 30 Hz to 50 kHz, and even no test method is specified.

NOTE In the same way, in clause 8.19 of the AIAA S-121-2009 [2], it is stated that “this requirement (*i.e.* MIL-STD-461F [1] method RE101) is not applicable unless otherwise specified by the procuring activity”.

Actually, such requirement should only be specified (together with an ad-hoc verification test method) for spacecraft that embark equipment sensitive to low frequency magnetic field.

Examples are scientific AC magnetometers and inertial sensors involving floating proof masses, as eddy currents induced by the low frequency magnetic field can cause DC forces and force noise. Highly sensitive detection chains can also be susceptible to AC magnetic field.

In general such measurements are significantly affected by the presence of radiated emission from the mains at the main frequency (50 Hz) and harmonics, at least if they are performed according to the MIL-STD-461F [1] method RE101.

On-board a space vehicle, a possible source of low frequency magnetic field is the solar array, which in general needs to be addressed by analysis as it would be difficult to test in realistic conditions. The PCU regulation technique plays a major role in the amplitude and spectral content of the magnetic field emission from the solar array. Other possible sources are cryocoolers involving compressors, and reaction wheels.

4.3.7 RE, electric field, 30 MHz to 18 GHz

This requirement should be mainly used to protect antenna-connected receivers from interference coupled through their antennas (including wireless receivers if applicable).

In the past, because RE requirements were based on the US DoD MIL-STD-461 [1][3], it was common to find RE requirements starting at 14 kHz or 10 kHz. This should in general be discouraged, except for spacecraft where equipment is present that is sensitive by design to low frequency electric field.

It should be noted that low frequency electric field measurements, performed in general with a rod antenna, are not easily reproducible unless a number of precautions are taken in the test set-up (cf. 7.3.1.1).

Depending on the spacecraft (for single-use equipment) or on the category of spacecraft a given unit is designed for, the requirement may be specified over the whole 30 MHz – 18 GHz frequency range or only in the relevant receive bands.

It is important to note that the antenna-connected receivers of interest may belong to the same segment or to a different one. As a typical example, RE requirements are specified to satellite equipment that is on at launch to avoid interference in launcher protected bands, cf. 5.1.3.2.1b.

In addition to the need to protect RF receivers, RE requirements are also specified to limit the RF leakage from RF units at their transmit frequency and more generally to limit the RE from digital electronics, thus forcing a good internal grounding, cf. 6.1.2.

4.3.8 CS, power leads, 30 Hz to 100 kHz

This requirement is used to ensure that equipment performance is not degraded from ripple present on the power bus. Corresponding power quality requirements are defined in the ECSS-E-ST-20C, Chapter 5. Verification methods are also mentioned.

The resistor specified in parallel with the primary winding is needed to prevent the DC/DC converter of the EUT from entering an instable working regime (oscillations) as a consequence of inadvertent amplifier switch-off or disconnection [4], leading to damage to it.

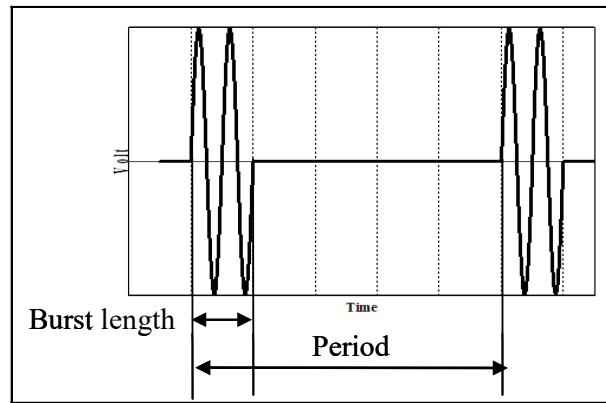
With the primary winding in open circuit, typical injection transformers have an inductance of 1 mH in series on the power line.

It is important to note that no differential mode CS is specified in the ECSS-E-ST-20-07C above 100 kHz. In this respect, it is not different from other standards such as the AIAA S-121-2009 [2]. Differential mode CS above 100 kHz can be introduced as part of tailoring. A test set-up is proposed in Figure 7-36.

4.3.9 CS, bulk cable injection, 50 kHz to 100 MHz

4.3.9.1 General

This test resembles the MIL-STD-461F/CS114-5-6 BCI methods, but the signal shapes (cf. Figure 4-3 through Figure 4-6) and the objectives are different.



Recommended signal level: 3Vpp calibrated on the BCI jig loaded with 50 Ω .

Frequency range	Pulse repetition frequency	Duty cycle
50 kHz-1 MHz	1kHz	50% (square wave)
1 MHz-10 MHz	100 kHz	20%
10 MHz-100 MHz	100 kHz	5%

Figure 4-3: ECSS-E-ST-20-07C BCI signal test characteristics

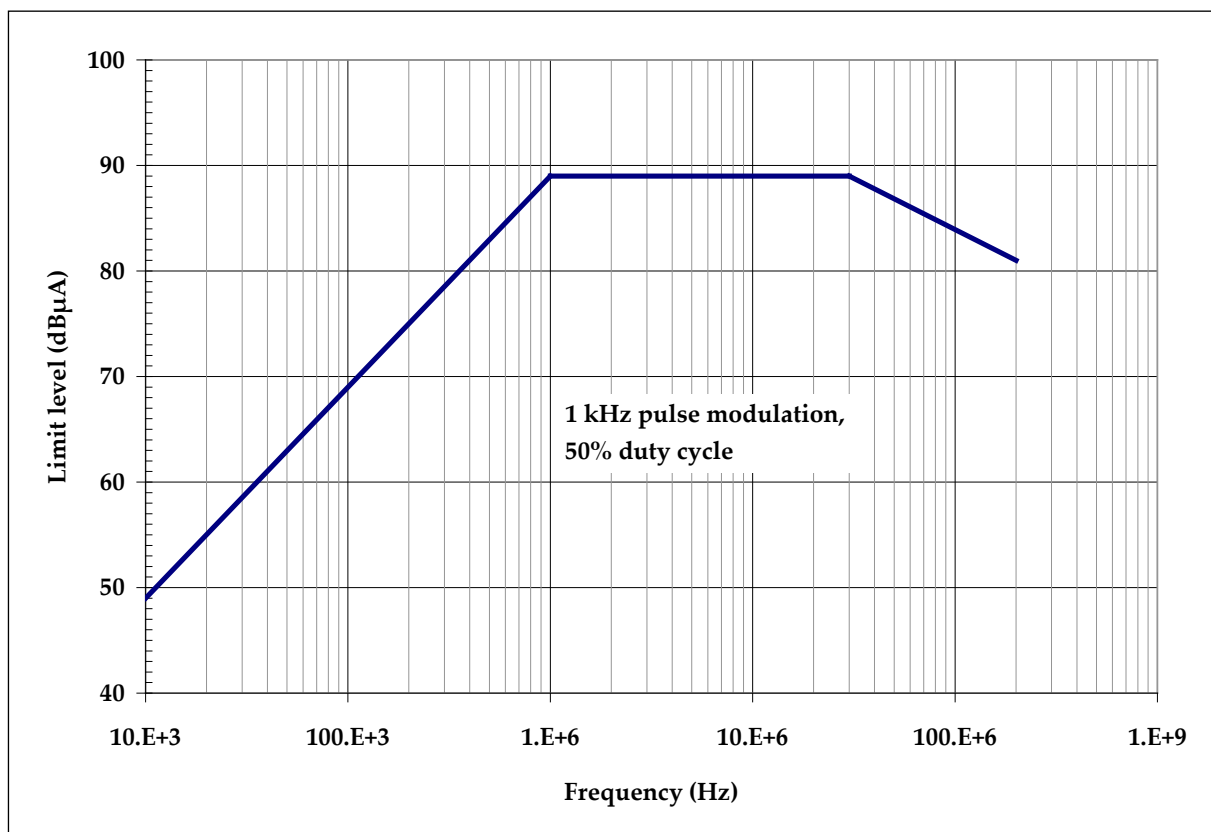


Figure 4-4: MIL-STD-461F/CS114 signal characteristics

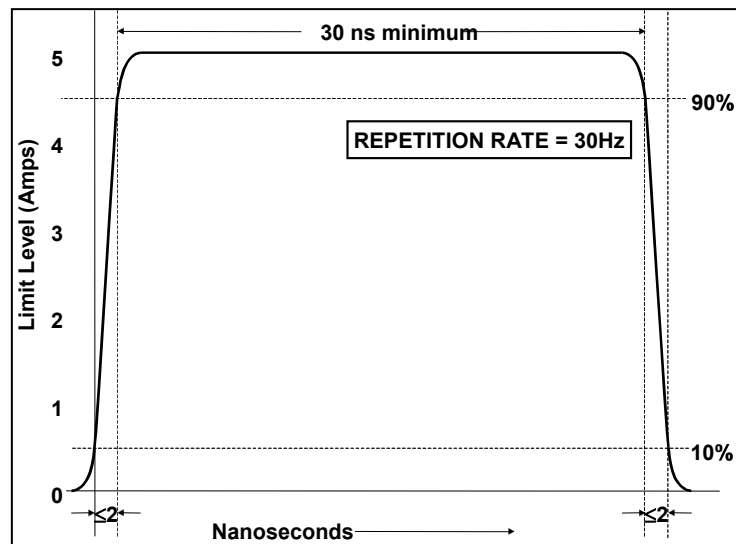
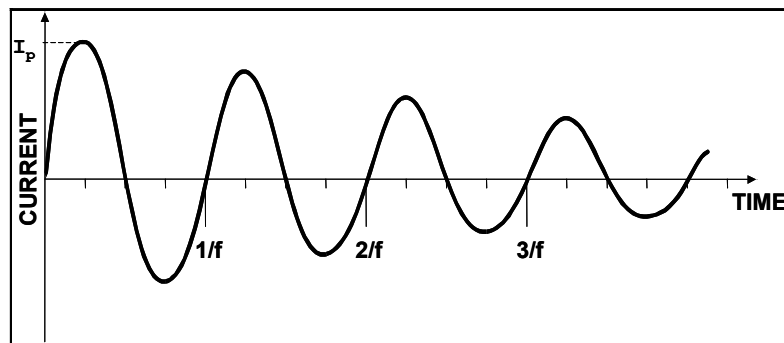


Figure 4-5: MIL-STD-461F/CS115 signal characteristics



Normalised waveform: $\exp\left(-\frac{\pi f t}{Q}\right) \sin(2\pi f t)$ with $Q = \frac{\pi(N-1)}{\ln(I_p/I_N)} = 15 \pm 5$
 and I_N = Peak current at cycle closest to 50% decay.

Figure 4-6: MIL-STD-461F/CS116 signal characteristics

According to the MIL-STD-461F:

- CS114 is used to verify the ability of the EUT to withstand RF signals coupled onto EUT associated cabling; the basic concept is to simulate currents that are developed on platform cabling from electromagnetic fields generated by antenna transmissions both on and off the platform;
- CS115 is used to verify the ability of the EUT to withstand impulse signals coupled onto EUT associated cabling; the basic concern is to protect equipment from fast rise and fall time transients that may be present due to platform switching operations and external transient environments such as lightning and electromagnetic pulse; the 5 A amplitude result in 500 V across 100 Ω loop impedance calibration fixture!
- CS116 is used to verify the ability of the EUT to withstand damped sinusoidal transients coupled onto EUT associated cables and power leads; the basic concept is to simulate electrical current and voltage waveforms occurring in platforms from excitation of natural resonances; in contrast to CS115 that excites natural resonances, the intent of this requirement is to control the

waveform as a damped sine; again the maximum value (from 1 MHz to 30 MHz) is 5A for USAF.

4.3.9.2 Discussion

The MIL-STD-461F recommends CS114 to overcome the difficulties to properly illuminate the harness in the low frequency range (below 30 MHz) with the classical RS. In addition, CS114 is supposed to cover a comprehensive range of antenna transmission frequencies, whereas on a spacecraft the transmit frequencies are only a few, well identified and almost always above 1 GHz. So, although it has been sometimes used on European Space projects, it was obviously with a different purpose, that was testing the immunity of the EUT against signal coupled on its bundles, or its immunity against common mode originated internally to the spacecraft (crosstalk, common impedance coupling, common mode emission from the interface units.).

The BCI method specified in the ECSS-E-ST-20-07C is supposed to fit better the EMC verification needs of typical spacecraft that is to say maximising the chances to discover susceptibilities pointing to design shortcomings, while keeping low the amount of “false alarms” resulting in unnecessary NCR and RFW/RFD to be processed.

CS115 and CS116 methods cover the effects of external transient environments, such as lightning strike, EMP, and maybe ESD as far as the CS115 is concerned. No equivalent test is specified in the ECSS-E-ST-20-07C but there is a dedicated ESD test with coupling to bundles (cf. ECSS-E-ST-20-07C, clause 5.5.12 “Susceptibility to electrostatic discharges”).

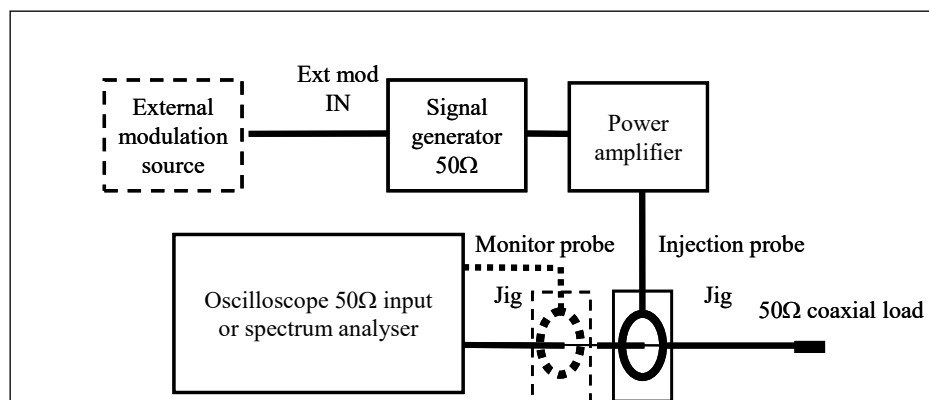


Figure 4-7: ECSS-E-ST-20-07C BCI calibration setup

It is important to note that during calibration of BCI injections, the two 50 Ω loads are in series, resulting in a total of 100 Ω in series (cf. Figure 4-7). As a consequence, the total drive voltage is actually two times that being measured during the calibration, so 6 Vpp for the level 3 Vpp recommended calibration level of the ECSS-E-ST-20-07C.

A common difficulty in BCI tests, although they are very practical, is that simulated loads or diagnostic equipment connected at the other end of the bundle under test are also being submitted to some injection. If susceptibility is noted, it is necessary to be able to determine whether the EUT or the simulated load was upset / susceptible.

4.3.10 CS, power leads, transients

The short spikes on the input power lines of the EUT specified in this requirement are meant to cover with a margin the voltage transients that can happen as a consequence of other power bus users switching on or off, or as a consequence of a short circuit happening somewhere else on the power bus, before the central protections can react.

This is sometimes known as “source common impedance coupling”.

This test method was known as CS06 in the old MIL-STD-461C [3]. It has disappeared in the following issues (D, E) and a similar test has reappeared (for US Navy ships only) in the new MIL-STD-461F [1], known as CS106. In the ECSS, the purpose is however different and the test levels, shown in Figure 4-8, are much lower.

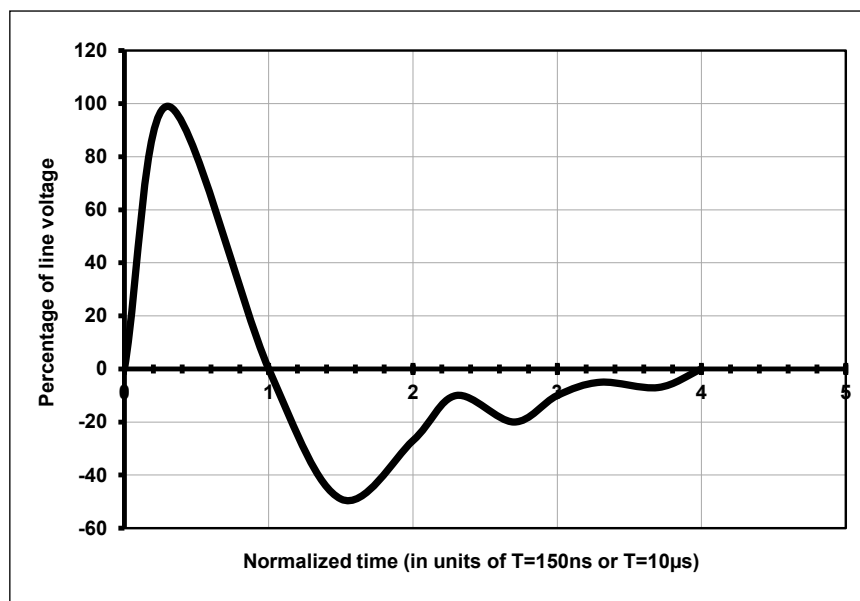


Figure 4-8: CS transient, as a percentage of power line voltage, as recommended in ECSS-E-ST-20-07C Annex.

In both cases, the injection is specified to be calibrated on a 5 Ω resistor, and used with the same settings for the injection, even if the resulting voltage transient on the power lines of the EUT is lower or much lower than what was measured on 5 Ω . This may be the case in particular if the EUT features active protection circuits. In the past, requirements specified a voltage transient level (usually 100% of the line voltage level), together with a current limitation. The pre-calibration method is preferred as it leaves the EUT reacting naturally and prevents over testing.

Alternative set-ups to the ones specified in the ECSS-E-ST-20-07C are possible and discussed in 7.5.1.

4.3.11 RS, magnetic field, 30 Hz to 100 kHz

This requirement is primarily intended to ensure that performance of equipment is not degraded when submitted to low frequency magnetic fields. In general, it should only be specified to equipment potentially sensitive to low frequency magnetic fields, installed in the vicinity of an identified source.

Because of the size of the loops used, the method described in ECSS-E-ST-20-07C is not suitable for an immunity test involving the coupling of low frequency magnetic field to harness. Such a situation can happen for example if a sensitive detection chain harness is submitted to the magnetic field from the

solar array (originating from regulation noise in the PCU/PCDU). For any such situation where immunity by test needs to be verified, specialised tests are created.

When the magnetic field environment originates from high current pulses, the impact of the resulting broadband magnetic field excitation cannot be extrapolated from a traditional CW test as per ECSS-E-ST-20-07C nor from a CW analysis. In such a case as well, specialised tests are created

In general, it should be up to the EMCAB to:

- assess the need for a RS magnetic field test;
- specify the extent of its applicability;
- specify the test method, setup and levels.

The RS magnetic field requirement of the ECSS-E-ST-20-07C doesn't cover the low frequency magnetic field due to the functioning of the magnetotorquers, which is rather in the [1 Hz – 10 Hz] frequency range. Specifying dedicated requirements can be considered as part of tailoring.

4.3.12 RS, electric field, 30 MHz to 18 GHz

This requirement should be mainly used to ensure that equipment can operate without degradation when submitted to electromagnetic fields generated by antenna transmissions either from the platform or from an external source, *e.g.* spacecraft, launcher, launch pad. This may include the field generated by wireless transmitters if applicable.

Using circularly polarized antennas is not allowed because, at some frequencies, the antenna pattern of the conical log spiral antenna is not centred on the antenna axis.

In the past, because RS requirements were based on the US DoD MIL-STD-461C, it was common to find RS requirements starting at 14 kHz. This should in general be discouraged, as this frequency range can be covered by conducted susceptibility tests on cable bundles.

4.3.13 Susceptibility to electrostatic discharges

In the 70's and 80's, tests on MARECS-A, TC1-A, METEOSAT and others were performed using the MIL-STD-1541A procedure, using commercial ESD generator set in contact or air discharge mode.

All satellites "qualified" with this procedure experienced in orbit anomalies due to ESD. The ESD test setup proposed in the ECSS-E-ST-20-07C was developed with the objective to reproduce on ground the in-orbit anomalies.

The test setup is proposed in the ISO 14302 and is in use in several companies.

The bundle under test is actually resonating for several hundreds of ns, but the injection circuit itself is not, because it is short.

The open circuit common mode voltage reached on the victim bundle is in the order of 100 V, which is in line with levels measured in flight. The resulting energy is actually low (0,9 mJ) but experience has shown that the most important parameter is the extension of the frequency band of the ESD source and not its energy.

Proper spark gaps for this test can be difficult to procure; investigations have shown that a commercial ESD generator, set in contact discharge mode and equipped with an *ad hoc* pulse forming network (R-C) can be an acceptable alternative [5].

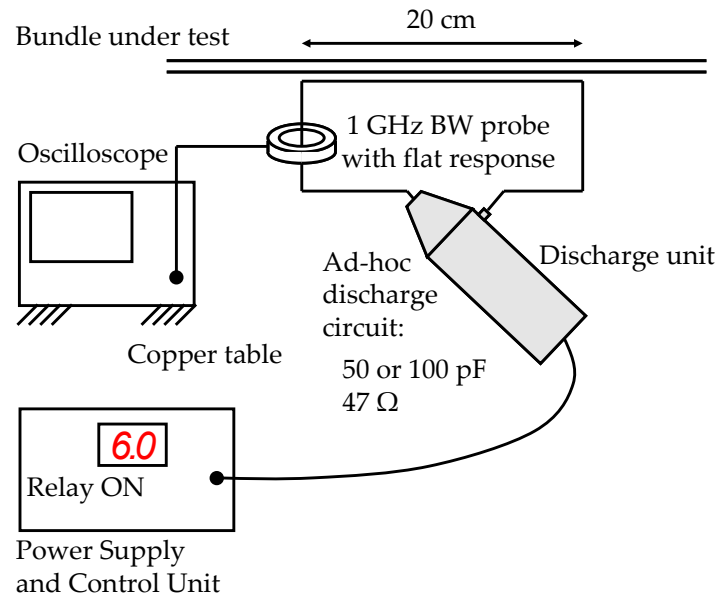


Figure 4-9: ESD test performed with a commercial ESD generator

System level activities

5.1 EMC Programme

5.1.1 Introduction

ECSS-E-ST-20C, clause 6.2.1 specifies that the prime supplier of a spacecraft (or space system) is obliged to carry out an EMC programme in order to ensure that the spacecraft is designed to achieve:

- EMC between all equipment and subsystems within the spacecraft (or space system);
- EMC with the external electromagnetic environment.

5.1.2 EMC Programme philosophy

5.1.2.1 The concept of EMC margin

The concept of electromagnetic compatibility is always introduced as a quantitative comparison between some unintentional electromagnetic disturbance, called “emission”, and the corresponding “susceptibility” of some circuit this disturbance is coupling to. The compatibility is ensured if the susceptibility threshold of the “victim” is higher than the emission level coupled to it. The EMC margin is the ratio between the two, or the number of dB separating the two. Obviously, the margin is represented by a positive number of dB if the susceptibility threshold is higher than the emission level and by a negative number otherwise. The EMC margin can then be considered as a safety gap allowing the covering of uncertainties, e.g. ageing.

The definition of the electromagnetic interference safety margin (EMISM), introduced in the ECSS-E-ST-20C, is expressed as follows:

ratio between the susceptibility threshold and the interference present on a critical test point

The purpose of that “test point” is to make the comparison possible. One common example of “test point” is the power input leads of an electronic unit. The susceptibility (or immunity) threshold of that unit to voltage ripple can be compared to the voltage ripple actually present at that interface (from other electronic units connected to the same power bus), in order to derive the system margin at the “test point” of interest.

In the ECSS-E-ST-20C, depending on the criticality of circuits, the margin at the relevant test points, now called “critical points” is specified to be 20 dB for safety critical circuits and 6 dB for mission critical circuits.

This calls for a number of remarks to avoid common misconceptions:

- The definition does not specify if the comparison is done in the frequency or time domain;
- The definition does not specify if voltage, current, power or energy levels are compared;

- The margin requirements do not imply that margins exceeding 6 dB indicate overdesign;
- The margin requirements do not imply that the margins need to be known with any accuracy, as long as it is demonstrated that they are sufficient.

5.1.2.2 Requirements philosophy

From section 5.1.2.1 it follows that a strategy aiming at achieving the minimum specified margin at most test points is not optimal. Small margins are difficult to verify and, often, more comfortable margins can be achieved with limited extra efforts.

As a consequence, there are two categories of EMC requirements:

- Requirements meant to verify design standards;
- Requirements driven by specific needs, *i.e.* based on the intrinsic susceptibility or emission of such or such equipment or payload (cf. 5.1.3.1), known from the preliminary design.

For example, conducted emission limits specified to power bus users have multiple objectives:

- Ensuring CE/CS compatibility between power bus users;
- In some cases, limiting the radiated emission from the power harness and the risks of crosstalk between cables;
- Leading unit suppliers to properly filter their DC/DC converters in both DM and CM and to properly damp the filters;
- Limiting the need for redesign and delta-qualification of recurrent equipment.

In addition to emission and susceptibility requirements, design requirements are also specified, like for instance grounding requirements. Requirements should be restricted to interfaces between units, which are managed by the prime contractor (customer, in this case) through requirements applicable to all his contractors (suppliers).

Requirements driven by specific needs should be derived and settled in the first half of phase B, as part of the early EMC activities (cf. 5.1.3.1).

5.1.2.3 Verification philosophy

EMC requirements should be always accompanied by the appropriate verification method. The overall logic is outlined in the EMC Control Plan (cf. 5.1.4).

Testing is deemed the preferred verification method. However, when testing in representative environment conditions is not possible, an adequate combination of tests and analyses is the preferred solution.

The definition of the model for EMC qualification entails a trade-off between early verification, to allow for design retrofits (when necessary), and the need of testing in representative conditions. Delta-qualification on more representative models often follows early tests.

Another important decision to make is about the EMC tests to be performed at the various integration levels. For example, testing the biasing and amplifying electronics of a detection chain separately from the detectors can have some merit but usually strongly impacts representativeness, so EMC tests at integrated detection chain or Instrument are needed.

For Instruments involving detectors working at cold temperature, it is often the case that performance-related susceptibility criteria can only be verified at cold temperature. It is then advisable to perform the conducted susceptibility tests as part of the thermal vacuum test campaign, cf. 5.3.2.2.2. Radiated susceptibility tests can also be considered as part of the thermal vacuum, provided that the thermal chamber can be used as a reverberation chamber, and frequency stirring is implemented.

5.1.3 Early EMC activities

5.1.3.1 Early identification of critical EMC areas

In order to limit the impact of EMC issues on programme cost and schedule, it is recommended to:

- Identify possible compatibility issues as early as the first half of phase B (cf. ECSS-M-ST-10C);
- Derive ad hoc design requirements;
- Derive ad hoc emission or susceptibility requirements;
- Specify ad hoc verifications activities (analyses and tests) to tackle EMC aspects anticipated as critical.

Examples of compatibility issues are listed hereafter:

- Radiated compatibility between digital electronics and a L-band radiometer;
- Radiated compatibility between digital electronics and sensitive VHF or UHF receivers;
- Radiated compatibility between electric propulsion and on-board RF receivers;
- RFI caused by RF communication link coupling with the plasma plume of electric thrusters [6];
- Conducted compatibility between a pulsed power user (e.g. RADAR, LIDAR), the Electrical Power Subsystem and the other power users;
- Autocompatibility of telecommunication payloads at transmit frequencies;
- AC magnetic field compatibility between a body mounted Solar Array and a detection chain harness [7];
- Compatibility between the DC and AC low frequency magnetic field emitted by spacecraft equipment and scientific magnetometer payloads (e.g. fluxgate, search coil);
- Compatibility between externally mounted equipment and instruments measuring the low frequency electric field (e.g. Radio Plasma Wave experiment).

5.1.3.2 Tailoring of ECSS-E-ST-20-07C

5.1.3.2.1 Tailoring of RE and RS requirements – Overview

a. Intra-spacecraft radiated compatibility

The objective of the RE/RS requirements is to ensure that the intentional and non-intentional emissions of the spacecraft do not disturb the sensitive units and the TT&C subsystem.

1. Intentional emission

This emission is mainly due to the side lobes of the Tx antennas which could transmit high power density on the external units and attenuated by the structure (through the apertures) for internal units. A specific notch in the Tx frequency band is assessed and corresponds to the RS requirement. This level is determined to ensure a positive EMC margin (at least +6 dB). It is also specific to each mission and depends on the RF power, Tx frequency band and mechanical accommodation.

2. Non intentional emission

This is mainly due to common mode currents induced on the harnesses and RF leakage on the unit housing or S/C structure which radiate low level EM field on the sensitive units or in the sensitive bands of the on-board RF receivers.

Specific notches are established and included in the RE requirements, to cover the Rx band(s) of the TT&C subsystem and the susceptible bands of sensitive units (e.g. E-field payload sensors, VHF or UHF receivers).

b. **Spacecraft compatibility with the launcher**

In order to ensure the compatibility between the spacecraft and the launch vehicles & launch sites, the following requirements need to be established:

- spacecraft radiated emission requirements ensuring that the spacecraft emissions do not interfere with the launcher RF receivers;
- spacecraft RS requirements ensuring that the launcher/launch site Tx emissions do not interfere with the spacecraft;

In the derivation of spacecraft RE and RS requirements related to the launch, the specific case of a spacecraft transmitting RF TM signals (TCR) under the launcher fairing should be taken into account, as well as its compatibility with the companion spacecraft in case of double launch.

5.1.3.2.2 RE and RS requirements at transmit and receive frequencies

a. **Radiated emission limits in receive frequency bands**

The purpose of a RE notch requirement is to protect a receiver frequency band from unwanted in-band spurious emissions.

A typical receiver sensitivity mask is shown in Figure 5-1.

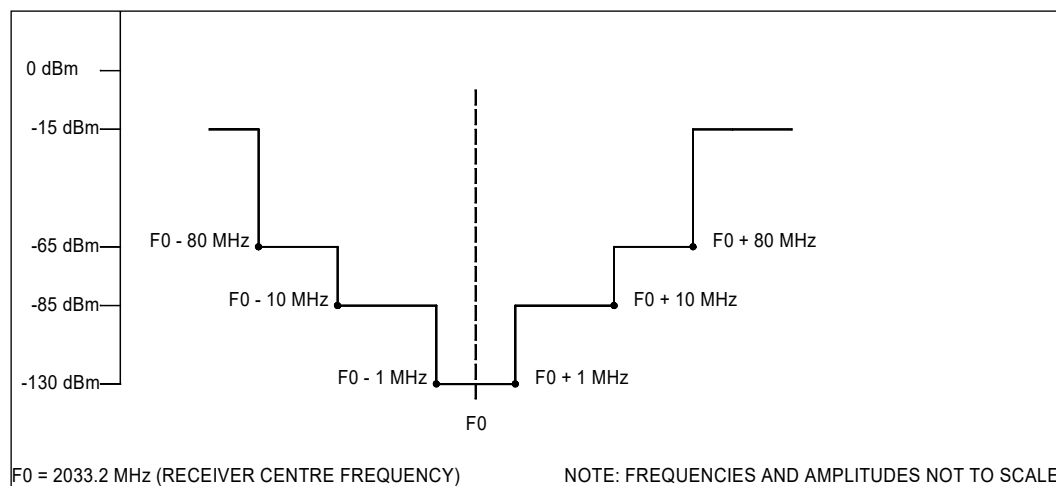


Figure 5-1: Example of receiver sensitivity mask (ESS Rosetta S-Band receiver)

1. **RE limits in Rx frequency bands for externally mounted units**

The coupling between an external unit and a receive antenna, illustrated in Figure 5-2, is a difficult problem which in general requires a full wave simulation; however, for the early derivation of RE requirements, it is practical to use the Friis transmission equation, bearing in mind its limits of applicability.

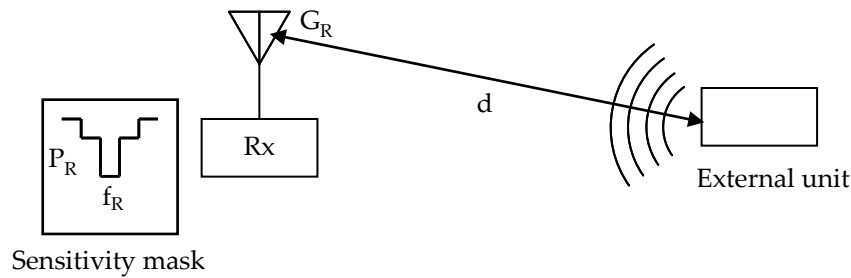


Figure 5-2: Coupling of an external unit to an antenna connected receiver

The general case that takes into account the distance between a given external unit and a receive antenna can be treated as follows.

According to the Friis transmission equation, the spurious RF power P_R received by the Rx antenna is:

$$P_R = P_E G_E \times G_R \left(\frac{\lambda}{4\pi d} \right)^2$$

P_R	Spurious power received by Rx antenna from interfering external unit [W]
G_R	Gain of the Rx antenna in the direction of the interfering unit [no unit]
P_E	Spurious power radiated by the interfering unit [W]
G_E	Gain of the interfering unit in the direction of the receive antenna [no unit]
d	Distance between the interfering unit and the receive antenna [m]

This is in dB:

$$P_E G_E [\text{dBm}] = P_R [\text{dBm}] - G_R [\text{dBi}] + 20 \log \frac{4\pi d}{\lambda}$$

This is compared with the field emitted by an interfering unit:

$$E_0 = \frac{1}{d_0} \sqrt{\frac{Z_0}{4\pi} P_E G_E}$$

E_0	RE limit for the RE test of the interfering unit [V/m]
d_0	Test distance of the for the RE test [m], usually 1 [m]

This is in dB:

$$E_0 [\text{dB}\mu\text{V/m}] = P_E G_E [\text{dBm}] - 20 \log(d_0) + 105$$

Substituting $P_E G_E$:

$$E_0 [\text{dB}\mu\text{V/m}] = P_R [\text{dBm}] - G_R [\text{dBi}] + 20 \log \frac{4\pi}{\lambda} + 20 \log \left(\frac{d}{d_0} \right) + 105$$

Or:

$$E_0 [\text{dB}\mu\text{V/m}] = P_R [\text{dBm}] - G_R [\text{dBi}] + 20 \log(f) + 20 \log \left(\frac{d}{d_0} \right) - 43$$

The above formula allows deriving the RE requirement as a function of the maximum allowed received spurious power. In some cases, the assumption $d = d_0$ is taken to simplify the procurement process (cf. example here below); however, projects are known

where each external unit was assigned a different requirement taking into account its location relative to the receive antenna.

For the ESS Rosetta Receiver, the in-band RE requirement was derived as follows, considering $d = d_0$:

$E_0 = -130 - 2 + 20 \log(2033,2 \cdot 10^6) - 43 = 11,4 \text{ dB}\mu\text{V/m}$

$P_R \quad -130 \text{ dBm (receiver in-band sensitivity)}$

$G_R \quad 2 \text{ dB}$

This result was corrected by +2dB for the receive path losses and -6dB for the margin. Eventually the following notch requirement was placed for the ESS receive band (Table 5-1):

Table 5-1: Example of RE notch requirement

Frequency Range	Field Level (peak values)	Measurement Bandwidth	Notes
2030 MHz - 2040 MHz	5 dBμV/m	100 Hz	due ESS Rx, S-band

2. RE limits in Rx frequency bands for internally mounted units
- To analyse the coupling of an internal unit to an antenna connected receiver, it is necessary to take into account the effect of the spacecraft cavity, as shown in Figure 5-3.

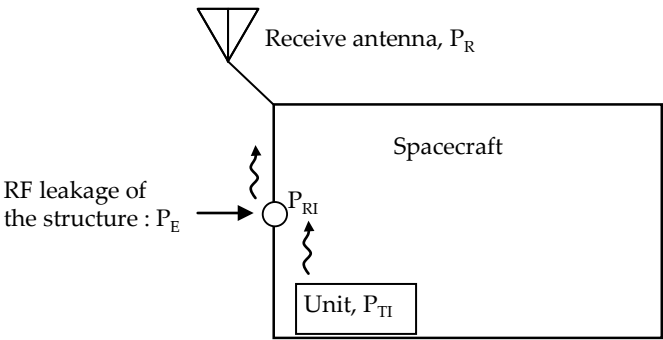


Figure 5-3: Coupling of an internal unit to an antenna connected receiver

- P_R Spurious RF power received at the antenna terminal [W]
- P_E Spurious power radiated by the RF leakage in the spacecraft structure [W]
- P_{TI} Total spurious power radiated in the spacecraft cavity by an internal interfering unit [W]
- P_{RI} Power received at the RF leakage location (aperture) of the spacecraft structure [W]

Assuming the free space propagation, the relation between P_E and P_R is the same as before, namely:

$$P_E[\text{dBm}] = P_R[\text{dBm}] - G_R[\text{dBi}] + 20 \log \frac{4\pi d}{\lambda}$$

Considering the RF leakage as an isotropic interference source, $G_E = 1$.

For the propagation between the internal unit and the spacecraft aperture, the free space losses are not applicable; instead the cavity insertion loss should be considered, so

$$\frac{\langle P_{RI} \rangle}{P_{TI}} = X_C \text{ where } \langle \cdot \rangle \text{ denotes the expected value.}$$

NOTE 1: The oversized cavity theory is described in 5.3.1.3 and 8.1.4.

NOTE 2: $X_C < 1$ and $X_C[\text{dB}] < 0$

In addition, the shielding effectiveness of the spacecraft structure should be introduced to define the relation between the received (P_{RI}) and transmitted (P_E) power at the RF leakage point: $ATT = \frac{P_{RI}}{P_E}$

$$ATT = \frac{P_{RI}}{P_E}$$

NOTE $ATT > 1$ and $ATT[\text{dB}] > 0$

With similar notations as in the previous section, the field emitted by an interfering unit tested in an anechoic chamber is:

$$E_0[\text{dB}\mu\text{V/m}] = P_I G_I[\text{dBm}] - 20 \log(d_0) + 105$$

If G_I is the gain in the direction of maximum emission, then $P_I G_I = P_{TI}$.

$$P_E[\text{dBm}] = P_{TI}[\text{dBm}] + X_C[\text{dB}] - ATT[\text{dB}] = P_R[\text{dBm}] - G_R[\text{dBi}] + 20 \log \frac{4\pi d}{\lambda}$$

Substituting P_{TI} :

$$E_0[\text{dB}\mu\text{V/m}] = P_R[\text{dBm}] - G_R[\text{dBi}] + 20 \log(f) + 20 \log\left(\frac{d}{d_0}\right) - 43 + (ATT - X_C)$$

As $(ATT - X_C)$, in dB is positive, this limit is more relaxed than the one applicable to externally mounted units.

b. Radiated susceptibility limits in transmit frequency bands

In addition to the general radiated susceptibility specification, the on-board emitters radiate high field levels in their transmit frequency band. A specific RS requirement is established, applicable to spacecraft units.

1. RS limits in Tx frequency bands for externally mounted units

For the early derivation of RS requirements, the coupling between a transmit antenna and an external unit, illustrated in Figure 5-4, can be assessed from the Friis transmission equation, bearing in mind its limits of applicability.

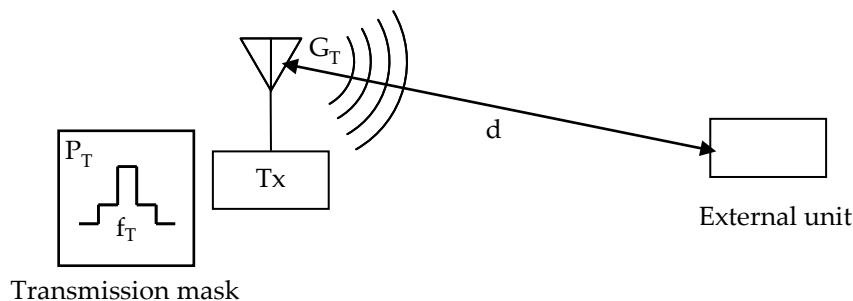


Figure 5-4: Coupling of transmitter connected antenna to an external unit

The level of electric field radiated from the antenna reaching external units is calculated as follows.

$$E[\text{dB}\mu\text{V/m}] = P_T[\text{dBm}] + G_T[\text{dBi}] - 20 \cdot \log d + 105$$

The distance d is taken from in the Mechanical Interface Control Document drawings.

G_T is the gain in the back lobes of the antenna radiation pattern, in the direction of the external unit.

2. RS limits in Tx frequency bands for internally mounted units

Applying a similar approach as described above for the RE notch, the E-field value inside the spacecraft is assessed using the following formula:

$$E[\text{dB}\mu\text{V/m}] = P_T[\text{dBm}] + G_T[\text{dBi}] - 20 \cdot \log d + 105 - \text{ATT}$$

Where ATT is the shielding effectiveness of the spacecraft structure and d is distance between the Tx antenna and the closest considered spacecraft aperture.

5.1.3.2.3 Tailoring of CE and CS requirements

CE requirements are sometimes tailored to adapt to the inherent characteristics of equipment having by design a variable current consumption. Typical examples are cryo-coolers, and pulsing loads (cf. 5.3.1.1.2c).

CE requirements can also be tailored by being extended to higher frequencies than the maximum proposed in the ECSS-E-ST-20-07C, *i.e.* 100 MHz. This can be useful to control the radiated emission from the cables at VHF or UHF receive frequencies (*e.g.* around 400 MHz), cf. 5.4.1.

CS requirements can also be tailored; in particular the CS transient requirements should be adapted to the electrical architecture of the space segment element of interest and to the resulting voltage transients likely to occur on the power lines.

It is also possible to specify differential mode CS on the power lines up to 10 MHz or 50 MHz: this was done on many projects although it is not specified in the ECSS-E-ST-20-07C (cf. 7.4.2).

5.1.3.2.4 Consistency of specifications

As stated in the ECSS-E-ST-20-07C, A.1: there is no single method for achieving EMC. A given project can in principle be carried out with various sets of EMC requirements. This freedom of manoeuvre is limited by:

- The need to take into account the state of the art;
- The absolute necessity of specifying EMC requirements that result in sufficient margins, *i.e.* consistent requirements.

Examples of coupled requirements that require consistency are:

- The requirement of conducted susceptibility to voltage transients specified to power bus users should exceed with margin the voltage transients resulting, for example, from load steps, changes of regulation domain, fault or fuse blowing;
- A possible requirement of susceptibility to low frequency magnetic field (specified to sensitive equipment in the vicinity of noisy equipment) should be consistent with the corresponding emission requirement specified to the noisy equipment of interest (a cryo-cooler, for example), and the distance should be properly taken into account.

In the above examples, the emission and the susceptibility are related to the same physical quantity: voltage in the first case, magnetic field in the second one. It is obviously not always the case. In particular, concerning the conducted compatibility on the power bus, the conducted susceptibility requirements specified to power bus users are expressed as voltage, whereas their emission

requirements are expressed as current, and the two are coupled through the EPS output impedance, at least at low frequencies.

5.1.4 EMC control plan

The ECSS-E-ST-20C (“Space Engineering – Electrical and electronic”), clause 6.2.2, requires that an EMC Control Plan (EMCCP) is written by the supplier for the System PDR. However, if EMC has been identified in the early phases of the project to have major design impact, or to require a major verification effort (with relevant schedule and cost impacts), it is then natural to have the EMCCP written as early as the SRR (or as early as the proposal for phases B, C, D).

The contents of the EMCCP are specified in the Annex A of the ECSS-E-ST-20C.

The EMCCP is the core document of the EMC programme, which according to the ECSS-E-ST-20C, clause 6.2.1, “is based on requirements of this standard, the statement of work, the spacecraft specification, and other applicable contractual documents”.

The Annex A of the ECSS-E-ST-20C specifies that the EMCCP is supposed cover the following areas:

- EMC programme management (organisation, methodology, milestones);
- System level EMC performance and design requirements;
- Subsystem and equipment EMC requirements and verification;
- Subsystem and equipment level EMC tests summary;
- EMC analyses;
- System level EMC verification, including outline of system-level EMC test plan.

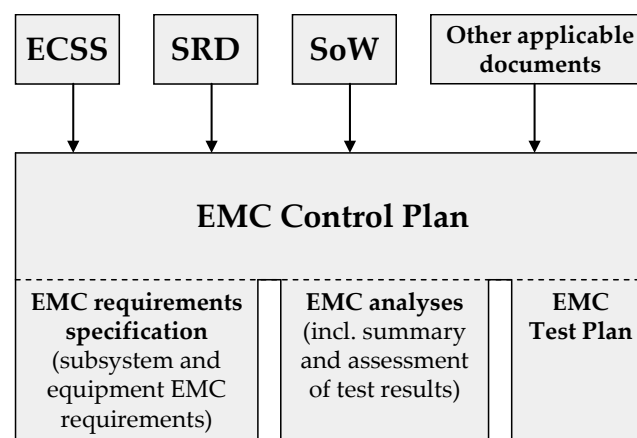


Figure 5-5: Inputs and perimeter of the EMC control plan

In essence, the EMCCP is specified to describe the EMC design and verification approach, but also to contain some elements of this verification (the EMC analyses) and the EMC requirements (cf. Figure 5-5).

In practice, it is usual to have the EMC requirements specification separate from the EMCCP; the same way for the EMC analyses. The EMC requirements specification is sometimes included in the General design and interface requirements document. This is not recommended.

The EMC engineer should ensure the consistency of the EMCCP with other documents such as:

- The Design Development and Verification Plan
- The AIV/AIT Plan
- The Design report

5.2 System level design aspects

5.2.1 Introduction

The prime supplier of a space segment element cannot only rely on EMC performance requirements specified to space segment equipment suppliers to ensure electromagnetic compatibility. Architecture and design aspects specified or implemented at space segment element level are just as important. The ones below are addressed:

- Electrical bonding (5.2.2): state of the art of the methods used minimise voltage differences across the mechanical structure of the space segment element over a wide frequency range;
- Grounding strategies (5.2.3): minimising voltage differences between references and mitigating their effects;
- Cable shields connection rules and methods (5.2.4);
- EGSE grounding strategies (5.2.5): avoiding making them more noisy or susceptible than the space segment element under test, because of detrimental design and installation methods;
- Protection against ESD (5.2.6);
- Magnetic cleanliness (5.2.7);
- RF shielding (5.2.8).

5.2.2 Electrical bonding

5.2.2.1 Electrical bonding overview

Many EMC problems are due to poor attention paid to the mechanical interfaces. Electrical bonding is the process by which elements are electrically connected to form a low impedance path for current flow. The term electrical bonding classifies all those devices used to guarantee the integrity of the reference plane and the needed conductivity between different metallic parts and the reference plane.

As said before, a poor electrical bond can lead to a variety of EMI producing situations. An example, shown in Figure 5-6, occurs when a poor electrical bond reduces the effectiveness of an EMI filter. As the chassis-to-structure bond impedance increases, the capacitive feed-through filter becomes less and less effective against incoming noise currents allowing the noise currents to enter the interior circuitry.

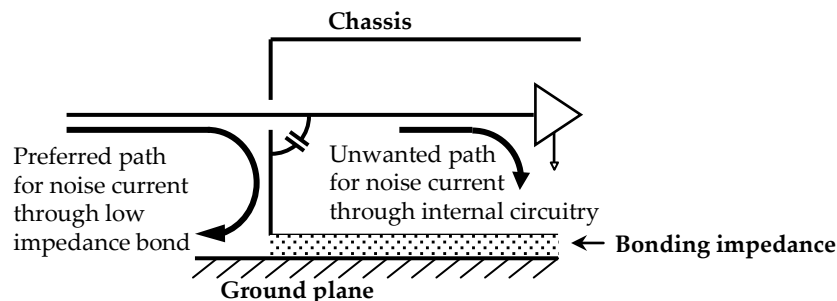


Figure 5-6: Filter decreased efficiency due to poor bonding

Typically, the bonding methods can be classified in two main typologies: direct and indirect. Direct bonding is the preferred one, being the junctions permanently fixed together without needing additional joints. The direct bonding, typically, determines the realization of a lower impedance path

with respect to the indirect one, by increasing the EMC performances. In many cases the indirect bonding is unavoidable (*i.e.* unit installed on partially/not conductive surfaces like CFRP). In these cases, the indirect bonding realization should be carefully studied in order to minimize its impedance. On first instance, it is a good practice to minimize the length of the joints. But also the layout of the joint has impacts on its overall impedance. Solid flat straps, accordingly to experimental results and mathematical/physical models, have a lower reactance with respect to braided and solid cylindrical straps (respectively, one and two order of magnitude higher). For equipment operating at RF, or emitting/sensitive at RF, the use of this kind of solid bonding strap is the preferable solution.

As a general rule, the surfaces to be connected together are clean and without any process of oxidation in act. Also the surface treatments are carefully addressed. In fact, coatings are commonly used in the aerospace industry for corrosion control of metals. The impedance of these coatings can reduce the effectiveness of EMI filters. Clark and Krome [8] have evaluated different coatings applied to electrical bonding surfaces. Based on the results of this study, there are discernable differences in filter operations (up to several hundred MHz) with bond resistance between 0,5 Ω and 5,6 Ω .

In order to satisfy the electrical conductivity requirements it is necessary to bond together dissimilar metals. In order to avoid galvanic corrosion processes, the metals selection guidelines are contained in ECSS-Q-ST-70-71. The galvanic corrosion effects should be carefully considered also in presence of direct bonding between metals and conductive/partially conductive fibre-reinforced materials (*e.g.* carbon fibre composites).

Composite materials like Carbon Fibre Reinforced Plastic (CFRP) are now increasingly being used in spacecraft structures because of their higher stiffness-to-weight and strength-to-weight ratios compared to conventional aluminium. As CFRP is basically a plastic with carbon fibres added to enhance the mechanical properties of the plastic material, it has a significantly lower conductivity compared to metals (typically 10^4 S/m). The lower conductivity directly affects the shielding, bonding and current carrying capability. As a consequence, the Carbon fibre structural parts cannot be used as bonding paths, and alternative grounding networks are used, for example by adding thin metallic grounding foils on top of CFRP surfaces. To properly size the grounding network, two main parameters are considered:

- Skin effect for the minimum thickness;
- Fault current for the minimum cross section.

5.2.2.2 Electrical bonding solutions

5.2.2.2.1 Overview

Two main types of structural panels exist: sandwich panels made of aluminium honeycomb with aluminium face sheets and sandwich panels made of aluminium honeycomb with CFRP face sheets.

Metallic structures not only perform well known mechanical and thermal functions but also electrical functions that are most of time “free of charge” from a weight and integration point of view:

- Functional power current return (only on telecom satellites);
- Functional signal current return (only on telecom satellites);
- Fault current path;
- Low impedance path for EMI currents thus providing an equipotential voltage reference to electronic circuits;
- Electromagnetic shield or screen against EM fields.

- Low impedance path for static charge bleeding: all conductive elements such as thermal blankets aluminium layer and metallic parts without electrical functions, are connected to the structure.

The electrical contact between the unit and the metallic structure is ensured directly by contact and/or by grounding straps. Direct contact is by far the preferred method, cf. 5.2.3.8.

CFRP structures cannot ensure the electrical functions of the metallic structure with the same level of performance because of the lower conductivity of the material. Therefore a grounding network is commonly implemented in order to perform the electrical functions that a CFRP structure cannot easily provide:

- Functional power and signal return is not commonly used on CFRP satellite;
- Fault current path;
- Electronics interconnection network for parasitic current;
- Low impedance path for static charge bleeding: all conductive elements such as thermal blankets aluminium layer, metallic parts without electrical functions such as support brackets, are connected to this network.

This grounding network, commonly made of Aluminium strips or foils is an additional item of the satellite. Some options are likely to entail design and integration effort, weight and complexity penalty. Several families can be distinguished:

- Simple strips directly cut from the roll;
- Shaped strips;
- Shaped foils;
- Al foil co-cured with the CFRP; this last solution has great advantages.

5.2.2.2.2 Strips or foils design

Different sizes of strips can be used, depending on the constraints on structure distortion due to temperature changes and on specified fault current capabilities. A few examples are shown hereafter in Figure 5-7 through Figure 5-10.

a. Narrow strips, fixation by screws

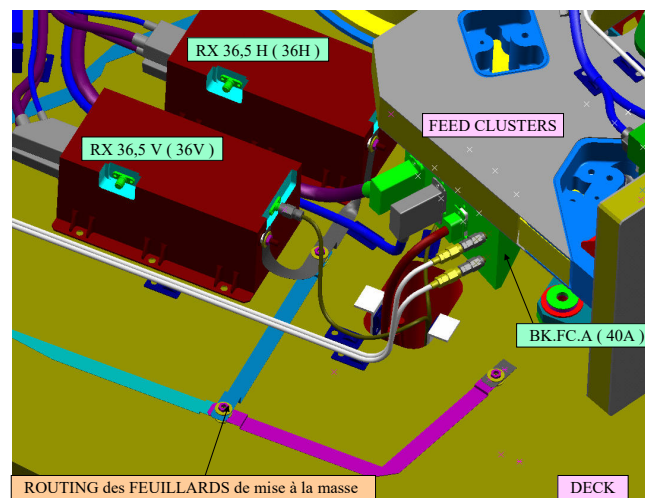


Figure 5-7: Narrow strips, fixation by screws

In this example, the dimensions of the strips are:

- Width : 12 mm
- Thickness : 0,3 mm
- Length : from 10 cm to 30 cm

The connection of two strips is made by screw bolts and washer assembly.

- b. Wide strips, fixation by rivets and screws



Figure 5-8: Wide strips, fixation by rivets and screws

In this example, the thin aluminium foil dimensions are 25 mm wide and 0,3 mm thick.

The junctions between elements are done by multi-point riveting the parts together.

The fixation of the ground rail to the structure is done by flat screws. The grounds of the electronic units are connected by flat straps similar to the ground rail material, using flat screws.

- c. Thick strips, fixation by screws

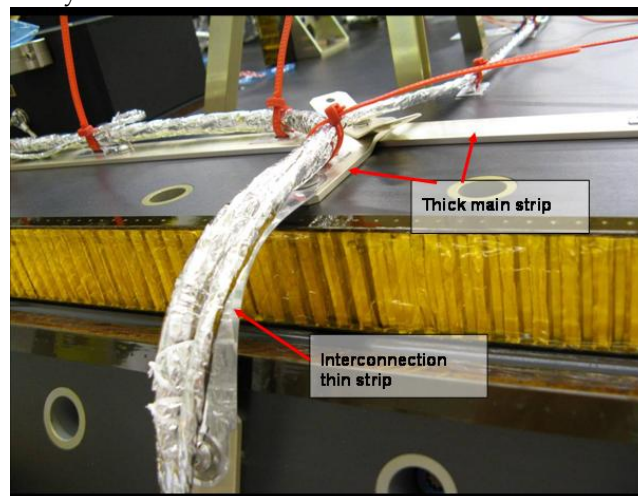


Figure 5-9: Thick strips, fixation by screws

In this example, one 3 mm thick strip is used on the main panel. At the time, the need for such thick strip was justified by the high power consumption of the payload and the relevant fault current requirement.

The fixation of the grounding rails to the structure is done by flat screws.

- d. Shaped grounding strips, fixation by rivets

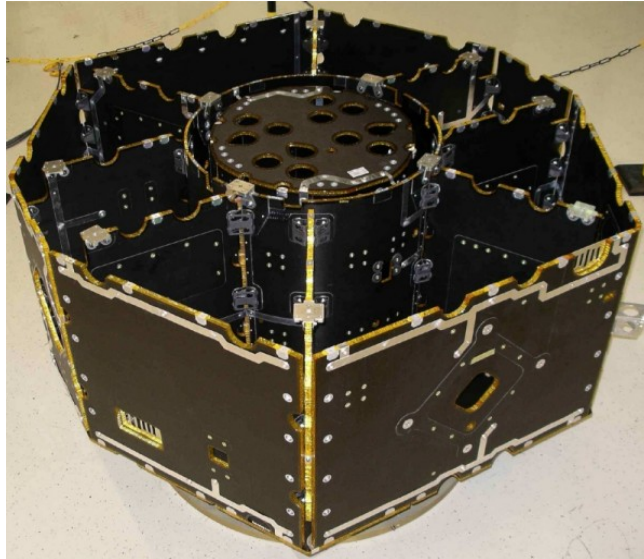


Figure 5-10: Shaped grounding strips, fixation by rivets

In this example, the octagonal structure made of CFRP panels is equipped with shaped grounding strips mainly on top and bottom of each panel.

The strips are 20 mm wide and 0,2 mm thick.

The fixation of the grounding strips to the structure is done by rivets.

5.2.2.2.3 Shaped grounding sheets

Grounding rails built from Al sheets are sometimes used on large satellites. In this case the grounding “rails” are realized as custom made sheet metal cuts, effectively forming grounding planes almost similar to all metal structures, as shown in Figure 5-11. Such design generally arises from the requirement to have the grounding rails following the harness. Issues are the fixation of bonded standoffs e.g. for fixing the harness. Bonding of the standoffs onto the grounding rail is avoided, instead the grounding rail is cut out and the standoff is bonded directly to the CFRP structure. The covering of the structure can be in the order of 50% with a weight impact of several kg on large satellites. Besides the weight impact this technique involves costs in case of late configuration changes.



Figure 5-11: Shaped grounding sheet

5.2.2.2.4 Al foil co-cured with the CFRP

A new technique has been introduced, shown in Figure 5-12, consisting of an aluminium foil of 25 μm laid over the CFRP lay-up before the sandwich panel is cured at $\sim 120\text{ }^{\circ}\text{C}$ in the autoclave.

The foil is black painted in some areas, as required by thermal design. The unpainted areas, the metallic surface is passivated (Alodine treatment or similar).

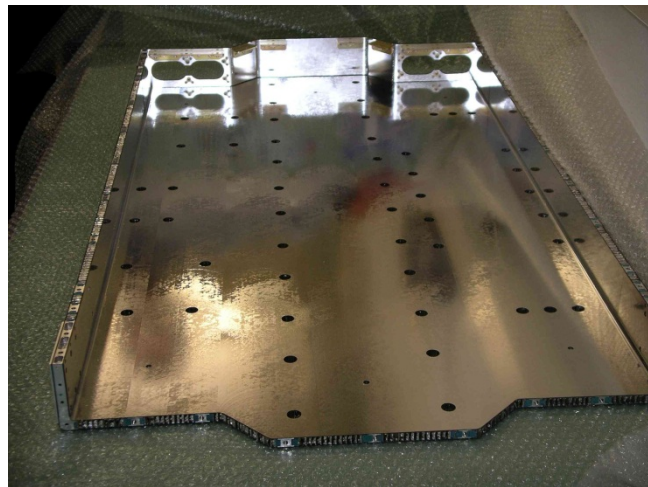


Figure 5-12: SMOS arm panel featuring an external Al foil co-cured with the CFRP

5.2.2.2.5 Grounding network assembly techniques

Several techniques of assembly for the grounding rails are used:

- Assembly with rivets
- Assembly by welding
- Assembly with bolts

The connection of electrical units to the grounding rail is made by dedicated removable straps. It is important to note that this method is not sufficient to ensure a good grounding EMC-wise, cf. 5.2.3.8.

The most common technique is the use of inserts, bolts and washers combining fixation of the “ground reference rail” (GRR) to the structure with assembly of adjacent strips.