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Space systems — Electromagnetic compatibility requirements

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British Standards

National foreword

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The UK participation in its preparation was entrusted by Technical Committee ACE/68, Space systems and operations, to Subcommittee ACE/68/-/1, Design engineering and production, which has the responsibility to:

— aid enquirers to understand the text;

— present to the responsible international/European committee any enquiries on the interpretation, or proposals for change, and keep the UK interests informed;

— monitor related international and European developments and promulgate them in the UK.

A list of organizations represented on this subcommittee can be obtained on request to its secretary.

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Foreword

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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ISO 14302 was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

Introduction

This International Standard addresses the equipment-level requirements, verification and rationale of system-level compatibility concerns used in the development and procurement of complete space systems.

This International Standard includes requirements at all the following levels:

— general system requirements;

— specific system requirements;

— equipment-level electromagnetic interference requirements.

The equipment-level requirements are summarized in Tables 1 and 2.

This International Standard does not include detailed design requirements. Instead, engineering issues to be addressed during execution of the electromagnetic compatibility (EMC) control programme are presented. Requirements in this International Standard may be tailored based on contractual agreements.

This International Standard references civilian equipment-level electromagnetic interference (EMI) test methods to minimize cost and allow the use of standard test methods. This International Standard does not contain EMI test limits. Test limits should be developed based on the environment, power quality definition and operational requirements.

Annex A presents the rationale behind each requirement/test technique, guidance for meeting requirements and test procedures where an acceptable reference is not available. Use of Annex A is advised in order to allow for optimal tailoring of this International Standard for individual programmes.

Space systems — Electromagnetic compatibility requirements

1 Scope

This International Standard establishes performance requirements for the purpose of ensuring space systems electromagnetic compatibility (EMC). The engineering issues to be addressed in order to achieve system-level EMC are identified herein, with guidance and rationale towards achieving specification conformance. The method for the derivation of typical equipment-level requirements from a space-system-level requirement is illustrated.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 7137:1995, *Aircraft — Environmental conditions and test procedures for airborne equipment*

IEC 61000-4-2, *Electromagnetic compatibility (EMC) — Part 4-2: Testing and measurement techniques — Electrostatic discharge immunity test*

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1.1
break-out box
non-flight piece of test support equipment that is connected in-line with a cable that accommodates external connection (usually binding posts) of instrumentation or series/parallel test networks to the wiring in that cable

3.1.2
complete space system
normally the spacecraft or launch vehicle itself, but more generally a suite of equipment, subsystems, skills, and techniques capable of performing or supporting an operational role

NOTE A complete system includes related facilities, equipment, subsystems, materials, services, and personnel required for its operation to the degree that it can be considered self-sufficient within its operational or support environment.

3.1.3
dead-facing
removal of power from a circuit prior to mating/de-mating of the circuit interface (usually to prevent arcing or inadvertent short circuits)

3.1.4
electromagnetic compatibility
EMC
ability of a space equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment

3.1.5
electromagnetic interference
EMI
degradation of the performance of a space equipment, transmission, channel, or system caused by an electromagnetic disturbance

3.1.6
equipment/subsystem
any electrical, electronic, or electromechanical device or integration of such devices intended to operate as an individual unit and performing a specific set of functions

NOTE Generally, a piece of equipment is housed within a single enclosure, while a subsystem may consist of several interconnected units.

3.1.7
faying surface
prepared conductive surface of sufficient area and conductivity that, when joined under pressure contact, ensures a low electrical bond impedance for the required life of the connection

3.1.8
immunity
ability of a device, equipment, or system to perform without degradation in the presence of an electromagnetic disturbance

3.1.9
internal charging
phenomenon caused by penetration of high-energy electrons through spacecraft structures and/or component walls so that these particles are incident on ungrounded metallic or dielectric internal surfaces

3.1.10
intersystem interference
harmful interaction between two different systems

EXAMPLE A launch vehicle docking with a space station.

3.1.11
intrasystem interference
harmful interaction between two different subsystems or between equipment of different subsystems that are all part of the same space system

EXAMPLE Uncommanded operation of a flight control subsystem due to a radio frequency (RF) transmission originating on the same spacecraft.

3.1.12
line impedance stabilization network
LISN
network inserted in the supply mains lead of an apparatus to be tested which provides, in a given frequency range, specified source or load impedance for the measurement of disturbance currents and voltages and which may isolate the apparatus from the supply mains in that frequency range

3.1.13
power quality requirement
requirement developed for the space system that defines the conducted voltage and current noise (from load regulation, spikes, sags, etc.) the power user can expect

3.1.14
procuring activity
agency or organization funding or administering a contract for the development of the space system

3.1.15
radio frequency interference
RFI
degradation of the reception of a wanted signal caused by a radio frequency disturbance

3.1.16
safety margin
ratio of circuit threshold of susceptibility to induced circuit noise under worse-case expected environmental conditions (intrasystem and intersystem)

3.1.17
spacecraft
space vehicle which includes launcher, orbiting platform and probe(s)

3.2 Abbreviated terms

ACS	attitude control system
AM	amplitude modulation
AWG	American wire gage
BCI	bulk current injection
CDR	critical design review
CE	conducted emissions
CISPR	International Special Committee on Radio Interference
COTS	commercial off-the-shelf
CS	conducted susceptibility
DSO	digital storage oscilloscope
EED	electro-explosive device
EGSE	electrical ground support equipment
EMC	electromagnetic compatibility
EMCAB	electromagnetic compatibility advisory board
EME	electromagnetic environment
EMEVP	electromagnetic effects verification plan
EMEVR	electromagnetic effects verification report
EMI	electromagnetic interference
EMISM	electromagnetic interference safety margin
ESD	electrostatic discharge
EUT	equipment under test
FFT	fast Fourier transform
FMEA	failure mode effects analysis
GEO	geosynchronous Earth orbit
HF	high frequency
ICD	interface control document
LEO	low Earth orbit

LISN	line impedance stabilization network
Mil-Std	military standard
NASA	National Aeronautics and Space Administration
PDR	preliminary design review
RDR	requirements definition review
RE	radiated emissions
RF	radio frequency
RFI	radio frequency interference
RFP	request for proposal
r.m.s.	root-mean-square
RS	radiated susceptibility
r.s.s.	root-sum-square
SAE	Society of Automotive Engineers
SMPS	switched mode power supply
TTL	transistor-to-transistor logic
UHF	ultrahigh frequency
VHF	very high frequency
VLF	very low frequency

4 Requirements

4.1 General system requirements

4.1.1 General

The space system shall be electromagnetically compatible among all equipment/subsystems within the space system and with the self-induced and defined external electromagnetic environment during all phases of its mission.

4.1.2 System-level EMC programme

4.1.2.1 General

The procuring activity and prime contractor shall establish an overall EMC programme based on requirements of this International Standard, the statement of work, space system specification, and other applicable contractual documents. The purpose of the EMC programme is to ensure space-system-level compatibility with minimum impact to programme, cost, schedule, and operational capabilities. An EMC programme shall include EMC control documentation and an EMC Advisory Board (EMCAB). The EMC staff responsible for these functions should be appropriate to the size and complexity of the programme. Typical programme milestones and their corresponding EMC data/deliverables are provided in Annex A (see Table A.1). Commercial space programmes having historically successful EMC control and management programmes in place may submit documentation to the procuring activity for an alternate means of equipment-level conformance, providing that the system-level interface requirements of this International Standard are met.

4.1.2.2 Electromagnetic compatibility advisory board

The EMCAB shall be responsible for timely and effective execution of the EMC programme under the general project manager. The prime contractor or developer shall chair the EMCAB, with procuring activity oversight. Other EMCAB members may invite associate contractors or developers and an independent expert of a space engineering certification body. Procuring activities may waive this requirement for systems that do not involve sufficient levels of integration to justify such a board; then the prime contractor shall execute EMCAB functions. The EMCAB shall accomplish its duties and document its activities mainly through the use of the system-level EMC documentation. It is also the responsibility of the EMCAB to solve problems related to EMC as they arise.

4.1.2.3 EMC programme

Details of the EMC programme shall be documented in the EMC control plan or other EMC contract documentation. Initial releases shall document the mechanics of the EMC programme, including basic design guidelines, while subsequent routine updates shall document programme progress. The requirements and approach established by the prime contractor shall be in a contractual document. The contents of the EMC control plan or other EMC contract documentation shall include, but not be limited to, the following:

a) EMC programme management is defined by:

   1) responsibilities of procuring activity, prime and associate contractors, lines and protocols of communication, and control of design changes;

   2) planning the EMC programme, consisting of:

      i) facilities and personnel required for successful implementation of the EMC programme;

      ii) methods and procedures of accomplishing EMC design reviews and coordination (within the EMCAB, if applicable);

      iii) proposed charter;

      iv) details of the operation of the EMCAB, if needed;

   3) programme schedules, including integration of the EMC programme schedule and milestones within the programme development master schedule;

b) system-level performance and design requirements, consisting of:

   1) definition of electromagnetic and related environments; including considerations related to hazards of electromagnetic radiation to fuels, humans, and explosive systems, such as electro-explosive devices (EED's) (see 4.2.9), launch vehicles, interfacing vehicles, and launch site environment, including electronic equipment at the launch site area;

   2) definition of critical circuits;

c) electroexplosive devices, consisting of:

   1) appropriate EED EMC requirements;

   2) design techniques;

   3) verification techniques;

d) subsystem/equipment EMI performance requirements and verification, consisting of:

   1) allocation of design responses at system and subsystem/equipment levels as defined in this International Standard;

   2) allocated EMI performance at the equipment level, including tailored equipment-level requirement of which the control plan is the vehicle for tailoring limits and test methods;

   3) test results from subsystem/equipment level EMI tests shall be summarized:

i) any specification non-conformances judged to be acceptable shall be described in detail and analysis of the non-compliant conditions on overall EMC performance shall be provided as a part of the justifying rationale;

ii) cost, mass, schedule, reliability, system operability, and other factors should also be addressed;

e) EMC analysis:

1) by making predictions of intrasystem EMI/EMC based on expected or actual equipment/subsystem EMI characteristics;

2) by designing solutions for predicted or actual interference situations using equipment-level data as input, impedance coupling (conducted emissions), wire-to-wire, field-to-wire:

i) all coupling modes should be considered to determine or predict EMI safety margin (EMISM) of intra-system EMI/EMC based on specified interface control document (ICD) values or actual (waiver/deviation request) values of equipment/subsystem EMI characteristics;

ii) design solutions should address what filtering, shielding, and grounding need to be applied to achieve these predicted EMISM's;

f) spacecraft charging/discharging analysis;

g) space-system-level EMC verification consisting of an outline of system-level EMC verification plan, including rationale for selection of critical circuits for safety margin demonstration, and instrumentation techniques for both critical and EED circuit and sensitization;

h) method of disposing waivers initial release and subsequent updates of the EMC control plan shall be prepared and submitted in accordance with contractual terms.

4.1.3 Equipment/subsystem criticality categories

The EMCAB shall identify functional criticality for all equipment/subsystems. Functional criticality categories include the following:

a) Category I, safety critical:

EMI problems could result in loss of life and/or loss of space platform;

b) Category II, mission critical:

EMI problems could result in injury, damage to space platform, mission abort or delay, or performance degradation which unacceptably reduces mission effectiveness;

c) Category III, non-critical:

EMI problems could result only in annoyance, minor discomfort, or loss of performance which does not reduce desired spacecraft effectiveness.

4.1.4 Safety margins

Design safety margins shall be established by the EMCAB for both critical functions and EED circuits. Design margins shall consider likely degradation modes of circuits and circuit protection methods over projected spacecraft lifetime.

4.2 Specific system requirements

4.2.1 External electromagnetic environment

The space system shall operate without performance degradation in the electromagnetic environment, not only self-induced but that due to external sources (intersystem EMI) such as other radio frequency sources or plasma effects. The EMCAB shall determine the electromagnetic environment based on mission requirements.

4.2.2 Intrasystem EMC

The space system shall not interfere with key requirements of payloads. Each equipment/subsystem shall operate without performance degradation during concurrent operation of any combination of the remaining equipment/subsystems, subject to mission requirements.

4.2.3 EMI control

The prime contractor shall be responsible for translating system-level EMC goals into equipment/subsystem-level EMI performance requirements. Test limits and test methods may be tailored if required, with procuring activity approval, to meet programme needs. EMI characteristics (emissions and susceptibility) shall be controlled to the extent necessary to ensure intrasystem EMC and compatibility with the predicted external electromagnetic environment. Equipment/subsystem-level EMI performance requirements and test methods shall be in accordance with 4.3 and 5.3.

4.2.4 Grounding and wiring design

4.2.4.1 Grounding

A controlled ground reference concept shall be established for the space system prior to initial release of the EMC control plan or other EMC contract documentation. Both power and signal returns and references shall be considered. Impedance magnitudes of these connections over the affected signal spectrum shall be considered in determining which kinds of power and signals may share common paths (wire or structure). Resistance and inductance values for each element of the ground return circuit architecture may be assigned; the common-mode voltages that develop at circuit reference points can then be computed. These computed values may be compared to conducted susceptibility requirements for equipment.

4.2.4.2 Wiring

Wiring, cable separation, and signal category design guidelines for the space system shall be established.

4.2.5 Electrical bonding

4.2.5.1 General

Electrical bonding measures shall be implemented for management of electrical current paths and control of voltage potentials to ensure required space system performance and protection of personnel. Bonding provisions shall be compatible with other requirements imposed on the space system for corrosion control.

4.2.5.2 Power current feeder and return paths

If the structure is used as the current return path, bonding provisions shall be provided so that current paths of electrical power sources are such that the total direct current (d.c.) voltage drops between the power subsystem point of regulation and the electrical loads are within applicable power quality standard tolerances.

4.2.5.3 Shock and safety hazard

To prevent shock hazards to personnel, all exposed conductive items subject to fault condition charging shall be bonded as necessary to limit potentials to prevent shock to personnel. In order to clear faults or provide against accidental discharge of fault current to ground through a conductor, all exposed conductive items, which could become charged due to an electrical fault condition, shall be bonded to the ground subsystem. Bonding impedance shall be sufficiently low to ensure enough current to clear the fault by tripping a circuit protection device.

4.2.5.4 Antenna counterpoise

Antenna structures relying on a counterpoise connected to (or implemented on) the spacecraft skin shall have an RF bond to structure such that RF currents flowing on the skin have a low impedance path to and through the counterpoise.

4.2.5.5 RF potentials

All electronic and electrical items, which could experience degraded operation or could degrade the operation of other electronic or electrical items in response to external electromagnetic energy, shall be bonded to the ground subsystem with a faying surface bond to present a low impedance at the frequencies of interest. For composite materials, bonding shall be alternating current (ac) accomplished at impedance levels consistent with the materials in use. Where vibration or thermal isolation is required, bond straps may be used. The bond straps shall be as short as possible and maintain a low inductance path. Bond straps should only be used as a last resort.

4.2.5.6 Static discharge

Any isolated conducting items shall be bonded to the ground subsystem in order to avoid a differential build-up of charge that would result in an electrostatic discharge, unless it is shown that there would not be enough charge build-up to cause a hazard.

4.2.5.7 Explosive atmosphere protection

Conducting elements in the vicinity of explosive and flammable materials shall be bonded to the ground subsystem such that arcing or heat rise due to fault currents or lightning currents (either directly applied or induced) is insufficient to cause ignition of the flammable substance. In space plasma environments, fault currents may occur across pins of separated (exposed pins) connectors. Dead-facing shall be employed before demating connectors in an explosive atmosphere and in a plasma environment of thrusters.

4.2.6 Antenna-to-antenna (RF) compatibility

The space system shall exhibit RF compatibility among all antenna-connected equipment/subsystems. This requirement is also applicable on an intersystem basis when there will be a required intersystem interface. The RF compatibility analysis, if used in lieu of a test, shall include the effects of intermodulation products.

4.2.7 Lightning

The space system shall be protected against both direct and indirect effects of lightning such that the mission can be completed without degradation of performance after exposure to the lightning environment. Use test procedure ISO 7137:1995, 3.8 (Section 22) for demonstrating compatibility with the lightning indirect-effects environment and test procedure ISO 7137:1995, 3.10 (Section 23) for the direct-effects environment. Protection may be a combination of operational avoidance of the lightning environment and electrical overstress design techniques.

4.2.8 Spacecraft and static charging

4.2.8.1 General

The space system shall control and dissipate build-up of electrostatic charges both from prelaunch ground sources and from on-orbit energetic plasma environments to the extent necessary to protect against personnel shock hazard, fuel ignition hazard, radio frequency interference (RFI) and destruction of dielectric materials due to static discharge.

4.2.8.2 Plasma-generated/payload-induced differential charging/discharges

Plasma/payload-induced differential charging, occurrence of electrical discharges and degrading effects upon the space system nominal performances shall be minimized to prevent such occurrences by design and integration precautions. Because the elimination of all discharges cannot be guaranteed, the full system shall be hardened and verified so that no malfunctions, degradation of performances, or deviation from identified parameters beyond tolerances given by corresponding specifications occur when the spacecraft is exposed to repetitive electrostatic arc-discharges representative of expected transient phenomena.

4.2.8.3 Internal charging

If the orbit parameters are such that the incident electron flux is high enough to cause internal charging, hardening techniques shall be applied to minimize the charging of these surfaces, preventing them from reaching the electrostatic discharge (ESD) discharging threshold.

4.2.8.4 Charging of fluid lines

All pipes, tubes, and hoses that carry fluids shall have a method of discharging the fluid and its transport system without producing arcs.

4.2.9 Hazards of electromagnetic radiation

The space system shall be designed so that fuels, humans, explosive systems, and electronically actuated thrusters are not exposed to unsafe levels of electromagnetic radiation. All four concerns shall address the entire electromagnetic environment, including interference sources from possible external transmitters.

4.2.10 Life cycle considerations

Electromagnetic environment (EME) protection designs shall include full consideration of life-cycle aspects of the protection.

EXAMPLE Life cycle considerations include identification of protection components and processes, reliability, maintainability and serviceability, verification or inspection requirements.

Space system protection shall include, but not be limited to, the following life-cycle considerations.

a) Reliability:

   The EME protection scheme shall be at least as reliable as the equipment, subsystem, or spacecraft it protects.

b) Maintainability:

   The EME protection schemes shall either be accessible and maintainable or shall be designed to survive the design lifetime of the space system without mandatory maintenance or inspection. Bonding, shielding, or other protection techniques, which can be disconnected, unplugged, or otherwise deactivated during maintenance shall be addressed in maintenance documentation, including required actions to restore their effectiveness. Those protection schemes likely to be repaired during the space system life cycle shall have their performance so specified that it can be tested or inspected as needed.

c) Serviceability:

On potentially repairable systems, protection schemes shall be serviceable or replaceable without degradation of the initial level of protection.

4.2.11 External grounds

A method shall be implemented on space systems to permit connection of grounding cables for charge equalization prior to implementing other procedures or the application of power across the interface.

4.2.12 Spacecraft d.c. magnetic emissions

The spacecraft magnetic moment and resulting diurnal and secular disturbance torques shall be limited to values with the control authority of the attitude control subsystem (ACS). Static and dynamic magnetic fields from all spacecraft-generated sources shall not exceed the sensitivity level of the spacecraft instrumentation.

4.3 Equipment-level EMI requirements

4.3.1 General

System-level EMC requirements shall be sub-allocated to equipment-level EMI requirements. Equipment-level EMI requirements shall be derived for each space system development based on, but not limited to, the following considerations in 4.3.2 to 4.3.17. Where applicable, appropriate test procedures listed in ISO 7137 shall be used as default techniques. Matrices showing equipment-level requirements, their applicability, and the test procedure reference specification are provided in Tables 1 and 2. Immunity requirements, which simulate effects of RF transmissions, shall utilize modulation schemes that simulate actual spacecraft RF transmissions.

Test procedure ISO 7137:1995, 3.6 (Section 20) defines modulation requirements.

4.3.2 Power bus conducted interference, time and frequency domain, source induced

This requirement shall apply to the electrical power subsystem only. The requirement is based on the power bus being loaded resistively. Power bus voltage ripple shall meet power quality requirements at all levels of loading. Consideration shall also be given to control of conducted emissions for the purpose of limiting power bus radiated emissions.

4.3.3 Power bus conducted interference, load induced, frequency domain

This requirement shall be imposed on equipment/subsystems operating from a power bus that can be shared with payloads. When developing the conducted emissions requirements, the sum total of all load-induced power bus voltage ripple shall meet power quality requirements. Differential and common mode ripple noise requirements shall be imposed on each equipment/subsystem such that the noise contribution from subsystems will not exceed the power quality specification. Conducted noise limits shall also consider the RF radiated noise effects on victims such as receivers.

Table 1 — Equipment-level test applicability matrix (emissions)

Test type	Requirement/ verification clause	Applicability	Test procedure reference	Alternate method Mil-Std-461[1]
Power bus conducted interference, time and frequency domain, source induced	4.3.2/5.3.2	Required for electrical power subsystem	Guidelines in A.2.3.2	—
Power bus conducted interference, load induced, frequency domain	4.3.3/5.3.3	Required	ISO 7137:1995, 3.7 (Section 21.3a) (voltage ripple, 150 kHz to 30 MHz)	CE101 and CE102
Control of long duration load induced switching transients	4.3.4.2/5.3.4.2	Case-by-case[a]	Guidelines in A.2.3.4.2	—
Control of fast load induced switching transients	4.3.4.3/5.3.4.3	Required	Guidelines in A.2.3.4.2	—
Power bus load induced time domain ripple	4.3.5/5.3.5	Case-by-case[a]	Guidelines in A.2.3.5	—
Signal cable conducted interference, frequency domain	4.3.6/5.3.6	Case-by-case[a]	ISO 7137:1995, 3.7 (Section 21.3b)	—
Antenna connection port spurious emissions	4.3.7/5.3.7	Required for antennas	Guidelines in A.2.3.7	—
Magnetic field radiated emissions	4.3.8/5.3.8	Case-by-case[a]	Guidelines in A.2.3.8	RE101
Radiated electric field emissions	4.3.9/5.3.9	Required	ISO 7137:1995, 3.7 (Section 21.4)	RE102

[a] Case-by-case means the procuring activity or EMCAB shall specify the applicability.

Table 2 — Equipment-level test applicability matrix (immunity)

Test type	Requirement/ verification clause	Applicability	Test procedure reference	Alternate method Mil-Std-461[1]
Immunity to audio frequency power-line ripple	4.3.10/5.3.10	Required	ISO 7137:1995, 3.4 (Section 18) Guidelines in A.2.3.10	CS101
Immunity to power-line switching transients	4.3.11/5.3.11	Required	ISO 7137:1995, 3.3 (Section 17)	—
Immunity to the conducted effects of radiated electromagnetic fields	4.3.12/5.3.12	Case-by-case[a]	ISO 7137:1995, 3.6 (Section 20.4)	CS114
Immunity to audio frequency radiated magnetic fields	4.3.13/5.3.13	Case-by-case[a]	Guidelines in A.2.3.13 ISO 7137:1995, 3.5 (Section 19.3.1)	RS101
Immunity to radiated electromagnetic fields	4.3.14/5.3.14	Required	ISO 7137:1995, 3.6 (Section 20.5)	RS103
Immunity to magnetic fields induced signals to cabling	4.3.15/5.3.15	Case-by-case[a]	ISO 7137:1995, 3.5 (Section 19.3.2 and 19.3.4)	—
Control of antenna port immunity to out-of-band interference	4.3.16/5.3.16	Receivers	Depends on receiver type	—
Immunity to electrostatic discharge	4.3.17/5.3.17	Required or handling procedure	IEC-61000 4-2	—

[a] Case-by-case means the procuring activity or EMCAB shall specify the applicability.

4.3.4 Power bus load-induced switching transients

4.3.4.1 General

Effects from two types of switching transients shall be controlled. These are long-duration transients (of millisecond duration) and fast transients (of sub-millisecond duration).

4.3.4.2 Control of long-duration load-induced switching transients

Transient inrush current shall be limited so that the power subsystem is able to maintain voltage levels within power quality specification tolerances.

4.3.4.3 Control of fast load-induced switching transients

Switching transient envelopes shall be controlled so the power quality specification can provide accurate envelopes of normal transients. Both magnitude and duration of turn-on, turn-off, and mode-switching transients shall be controlled. Each transient can be evaluated separately unless they are frequently repeating transients, in which case they will be measured in the frequency domain.

4.3.5 Power bus load-induced time domain ripple

This requirement may be imposed in addition to 4.3.2. The envelope of time domain peak-to-peak ripple developed across the power source impedance by the test article shall be controlled so the power quality specification provides an accurate accounting of load-induced effects.

4.3.6 Signal cable conducted interference, frequency domain

Cable bundle common mode current shall be controlled at mission-peculiar frequencies when needed to avoid interference with in-band receivers and other sensitive electronics.

4.3.7 Antenna connection port spurious emissions

Control of antenna port spurious emissions shall be imposed for antenna-antenna RF compatibility. When specifying limits and frequency ranges, the following issues shall be considered:

a) sensitivity of possible victim receiver subsystems (receiver, transmission line, antenna) including out-of-band response;

b) exclusion of transmit frequency and information carrying modulation bandwidth (for transmitters, transceivers);

c) highest and lowest intentional frequency used by space system receivers;

d) antenna port attachments, gain/loss characteristics.

4.3.8 Magnetic field radiated emissions

The a.c. magnetic field emissions shall be limited to levels that do not degrade operation of any part of the space system. This is to protect sensitive hardware, such as very low frequencies (VLF) receivers or low-frequency magnetic field measuring experiments.

4.3.9 Radiated electric field emissions

Radiated electric field emissions of any equipment/subsystems shall be controlled. Frequency bands used by spacecraft/payload receivers and launchers shall receive special emphasis. Additionally, equipment/subsystems procured for a reusable system shall meet radiated electric field emission requirements from the frequency range of intended payload sensitivity through receiver bands. Limits shall reflect possible victim receivers operationally required sensitivity, gain, direction, and location of the victim's antenna.

4.3.10 Immunity to audio frequency power-line ripple

Equipment shall be immune to audio frequency ripple at levels allowed to exist by the governing power quality specification and according to the conducted emissions levels. Appropriate margins shall be applied between allowable bus ripple and equipment susceptibility.

4.3.11 Immunity to power-line switching transients

Equipment shall be immune to power bus load-induced switching transients, as identified in the power quality specification.

4.3.12 Immunity to the conducted effects of radiated electromagnetic fields

Equipment operating in a space system subjected to intentional RF transmission shall be immune to common mode currents coupled onto equipment connected cables and power conductors. This requirement is only applicable in bands where intentional RF transmission is likely or expected. This requirement may be met by performing bulk current injection tests at frequencies up to 400 MHz.

4.3.13 Immunity to audio frequency radiated magnetic fields

Immunity to magnetic fields shall be controlled if there an a.c. magnetic field environments is generated that could disturb the space system equipment.

4.3.14 Immunity to radiated electromagnetic fields

Equipment immunity to unintentional and intentional transmitted RF fields shall be controlled to the degree necessary to ensure space-system-level EMC. Special emphasis shall be given to bands where spacecraft transmitters operate and in bands where transmitters external to the space system illuminate it at sufficient intensity that immunity shall be controlled.

4.3.15 Immunity to magnetic fields induced signals to cabling

When high-density cabling is used on a space system, induced signal susceptibility testing may be used to verify immunity from cable coupling. When used, the audio frequency magnetic field coupling and transient coupling shall be applied.

4.3.16 Control of antenna port immunity to out-of-band interference

Control of radio receiver response to out-of-band interference shall be imposed. Responses to spurious signals, as well as cross and inter-modulation effects, shall be controlled.

4.3.17 Immunity to electrostatic discharge

An ESD control process for equipment immunity and handling shall be implemented. Actual levels of ESD qualification shall reflect the entire life-cycle environment of the equipment, from final assembly through mission completion. Considerations for spacecraft charging are in 4.2.8.

5 Verification

5.1 General system requirements

5.1.1 General

The prime contractor or developer shall have overall responsibility for verifying that all requirements of this International Standard be met. Specific tasks may be delegated to associate contractors via the EMCAB as necessary. Verification shall be accomplished by qualification tests, analyses, inspections, and similarity, as appropriate, subject to procuring activity approval.

5.1.2 System-level electromagnetic effects verification plan (EMEVP)

5.1.2.1 General

The prime contractor or developer shall prepare a space-system-level EMEVP that specifies in detail the methodology to be employed for verifying each electromagnetic effects requirements as well as success criteria for each subsystem and equipment. The detailed plans for space-system-level EMC demonstration shall be provided in this document. Procuring activity approval of the EMEVP shall precede start of qualification testing. EMEVP shall include, but not be limited to system-level verification methods and test conditions.

5.1.2.2 System-level verification methods

The verification activity, if performed by test, can be split between the engineering model and the flight model, depending on the fidelity of the engineering model and the degree of success of the engineering model test campaign. Elements of system verification shall include the methods, procedures, and instrumentation required to document the test results.

5.1.2.3 Test conditions

Required personnel shall be specified, including procuring activity, contractor, associate contractor, and quality control representatives. In addition, required test equipment shall be specified, including a description of unique EMC instrumentation for stimulating and measuring electrical, electronic, and mechanical outputs of equipment and subsystems to be monitored during the test programme, including measured characteristics of any line impedance stabilization networks (LISN's) used for the system-level test.

5.1.3 Electromagnetic effects verification report (EMEVR)

The prime contractor or developer shall prepare an EMEVR. The EMEVR shall provide documentation demonstrating that each requirement of this International Standard has been met. The report shall include each separate test/test objective documented in the report.

NOTE A summary of results and pointers to reports of equipment-level verification is acceptable for lower-level requirements.

5.1.4 Safety margin demonstration of critical/EED circuit

Safety margins that have not been previously determined by equipment-level test or analysis shall be demonstrated at system-level integration, operating the space system suite of equipment/subsystems in a manner simulating actual operations. Monitored circuits shall either be instrumented for direct measurement of induced noise or activating signal-to-noise ratio shall be reduced by the safety margin factor, whichever is technically correct and practical to implement. Safety margin demonstration for something that is susceptible to a time domain circuit (includes EED's) shall use time domain methods to verify safety margins.

5.2 Specific system requirements

5.2.1 External electromagnetic environment

The space system shall be exposed to those external electromagnetic environments identified in conformance to 4.2.1. When exposure of the space system is not feasible, an analysis of equipment and subsystem-level test data may be performed to satisfy this requirement.

5.2.2 Intrasystem electromagnetic compatibility

Intrasystem compatibility shall be demonstrated by a suitable combination of test and analysis. All equipment/subsystems shall meet the requirements of its functional acceptance test procedure, as installed on the platform, prior to system-level EMC testing.

5.2.3 Electromagnetic interference control

Prior verification of equipment/subsystem performance in accordance with the requirements of 4.3 supports the system-level test requirements. Mission-peculiar or specialized test procedures for operation of all matrix equipment shall be included to support test execution.

5.2.4 Grounding and wiring design

5.2.4.1 Grounding

The system-level electrical grounding and isolation shall be verified with respect to the grounding and isolation design by a system-level grounding diagram (one-line diagrams are not sufficient) and test at system assembly.

5.2.4.2 Wiring

Wiring category implementation shall be verified by review of design and inspection.

5.2.5 Electrical bonding

5.2.5.1 General

Conformance to electrical bonding requirements shall be verified by test, analysis, or inspection as appropriate for the particular bonding provision. Compatibility with corrosion control techniques shall be verified by demonstration that the manufacturing processes that address corrosion control have been implemented.

5.2.5.2 Power current feeder and return paths

Bonding for power current paths shall be demonstrated through analysis of electrical current paths, electrical current levels and measurement of bonding resistance levels.

5.2.5.3 Shock and safety hazards

Bonding for shock/safety hazards shall be verified through test, analysis, and inspection as appropriate for the particular application.

5.2.5.4 Antenna counterpoise

Bonding of an antenna counterpoise to structure shall be verified through test, analysis, and inspection as appropriate for the particular application.

5.2.5.5 RF potentials

Verification of milliohm-level bonds imposed for RFI control purposes shall be by special low a.c. voltage output measured by milliohmmeters. Meter voltage output shall be a.c. in order to make an effective measurement without disturbance from galvanic voltages. If only a d.c. meter is available, then two measurements shall be made, with the second measurement having ohmmeter probes reversed from the first measurement and both measurements shall be averaged to determine true bond resistance. If the same bond path is used as a fault return path, it may be tested for that requirement using the system-voltage, high-current ohmmeter, but only after low-voltage, low-current measurements have been completed.

5.2.5.6 Static discharge

Bonding of discharge elements, thermal blankets, or metallic items requiring a bond for static potential equalization shall be verified by test at assembly into structure.

5.2.5.7 Explosive atmosphere protection

Bonding of conducting elements in the vicinity of possible explosive atmospheres shall be verified by a combination of analysis, test, and inspection. Dead-face design shall be verified by inspection of drawings and control logic and by test as appropriate.

5.2.6 Antenna-to-antenna (RF) compatibility

An analysis shall be prepared as part of the EMC Control Plan which shall identify risk frequencies. These shall be checked to demonstrated compatible operation. In general, each culprit and victim pair shall be operated in such a manner as to maximize likelihood of interference. This shall be subject, however, to the restriction that operating modes are simulations of mission operations. Demonstration that a victim receiver is compatible with the culprit shall consist of the ability to receive an intended signal at its low signal condition. Lack of intermodulation interference shall be verified by a combination of analysis and test.

5.2.7 Lightning

Lightning protection for both direct and indirect effects shall be verified by a suitable combination of test, analysis and inspection as appropriate.

5.2.8 Spacecraft and static charging

5.2.8.1 General

Adequate control of static charging effects shall be verified by test, analysis, or inspection, as appropriate.

5.2.8.2 Plasma/payload-induced differential charging/discharges

Adequate control of induced differential charging/discharging effects shall be verified by a suitable combination of test, analysis, and inspection as appropriate.

5.2.8.3 Internal charging

Adequate control of internal charging effects shall be verified by test, analysis, or inspection as appropriate.

5.2.8.4 Charging of fluid lines

Adequate control of charging on fluid lines shall be verified by showing the conductivity of the fluid, the fluid lines, and/or the additives is sufficient to prevent arcing.

5.2.9 Hazards of electromagnetic radiation

Safety with regard to RF effects fuels, human, explosive devices (including EED's), and flight/engine/thruster controls shall be demonstrated by a suitable combination of test, analysis and inspection.

5.2.10 Life cycle

System design features implemented for EMC purposes shall be inspected for conformance to life cycle requirements for reliability, maintainability, and serviceability. Demonstrations of serviceability, testability, and the ability to detect degradations shall be performed. Maintenance methodology and tools shall be identified in the EMEVR and appropriate maintenance publications.

5.2.11 External grounds

Proper placement and marking of space system external ground provisions shall be verified by inspection. Conformance to bonding requirements shall be verified by test.

5.2.12 Spacecraft d.c. magnetic emissions

Conformance to these requirements shall be demonstrated by a combination of analysis and test.

5.3 Equipment-level EMI testing

5.3.1 General

To the maximum extent possible, ISO 7137 test procedures shall be used for verifying conformance to 4.3.1 to 4.3.17. See Table 1 and Table 2 for specific ISO 7137 test procedure references. This is to minimize test cost (minimize procurement of test equipment not commonly available at EMI test facilities). In some cases, standard test procedures may be inappropriate for the EMC requirement. Also, in some cases, standard EMI test methods do not address space-related EMC issues. These special concerns are documented in 5.3.2 to 5.3.17. Alternate standards may be used as long as the 1-m antenna-to-equipment-under-test (EUT) test distance for radiated emissions measurements, peak detection, and equipment are positioned on a ground plane similar to that of actual flight. Specifications that do not meet this criteria shall be reviewed by the procuring organization.

Emissions testing that requires sweeping a band of frequencies shall be controlled as to measurement bandwidth and sweep speed or step size. Sweep speed shall be slow enough to fully charge the smallest intermediate frequency bandpass filter, and step size shall be limited to one-half of the measurement bandwidth. Operation of the test article shall be considered in determining frequency sweep times. Equipment/subsystems that perform a cycle of operations require several iterations of emission scans to catch all possible emissions.

Immunity testing that requires sweeping a band of frequencies shall be controlled as to number of test frequencies and dwell time. If the equipment performs a cycle of operations, the noisiest cycle shall be identified and operated for conducted emissions and radiated emissions frequency domain testing.

Test procedures for equipment-level testing shall be evaluated by the prime contractor.

5.3.2 Power bus conducted interference, time and frequency domain, source induced

Power bus conducted interference, time and frequency domain, shall be verified by test. Time domain voltage ripple shall be measured directly across a resistive load using an oscilloscope. Frequency domain voltage ripple can be measured similarly (see Annex A). The oscilloscope bandwidth shall be compatible with that called out in the power quality standard.

5.3.3 Power bus conducted interference, load induced, frequency domain

Power bus conducted interference, load induced, frequency domain shall be verified by test. The requirement may be stated as a voltage and/or current ripple limit. A frequency domain line impedance stabilization network is specified. The ISO 7137 LISN does not provide adequate control at frequencies below 150 kHz. When conducted emission control is exerted below 150 kHz, it shall be exclusively current control.

Below 150 kHz the bandwidth shall be less than 2 % of tuned frequency, except very near d.c. where the bandwidth requirement is such that noise floor pollution by the local oscillator is controlled to a level at least 6 dB below the specification limit.

5.3.4 Power bus load-induced switching transients

5.3.4.1 Applicability

Both long-duration (drop due to current and resistance) and fast inclusive drop due to change in current with respect to time voltage transient measurement techniques are discussed in 5.3.4.2 to 5.3.4.3.

5.3.4.2 Control of long-duration load-induced switching transients

Inrush current shall be verified by test. Guidelines for measurement are provided in Annex A.

5.3.4.3 Control of fast load-induced switching transients

Fast load-induced switching transients shall be verified by test. Voltage transient limits lasting less than 50 µs may be measured with the same ISO 7137 LISN used for frequency domain voltage conducted emissions measurements. If transient voltages longer than 50 µs are to be measured, then a space system unique source impedance model shall be constructed. In order to measure a time domain transient accurately from onset to steady-state transition, the LISN impedance shall be specified to d.c. The test set-up power source impedance across which the transient is dropped shall exceed the impedance of the expected system power bus wiring. The test set-up and procedural details are offered in Annex A. When the power switch is not contained within the EUT, the turn-off transient data is for information only.

5.3.5 Power bus load-induced time domain ripple

The power bus load-induced time domain ripple shall be verified by test. The default procedure is shown in Annex A. If the bus is a.c. or a guaranteed source impedance over a wider frequency range is necessary, then the Annex A simple approximation to a LISN shall be replaced by a LISN representative of the actual power bus.

5.3.6 Signal cable conducted interference, frequency domain

Signal cable conducted interference, frequency domain shall be verified by test. Compliance with this requirement shall be verified by placing an EMI current probe around each individual cable under test. Alternate methods for verification can be used if agreement is reached with the procuring organization.

5.3.7 Antenna connection port spurious emissions

Antenna connection port spurious emissions shall be verified by test. Whenever possible, conformance shall be verified by direct coaxial/waveguide connection between the antenna port and an EMI meter. Impedance mismatches shall be addressed by impedance transformers or matching networks, and associated losses shall be accounted for. If a directly connected measurement cannot be effected, then a two-antenna test shall be performed. In this case, the test article antenna shall be used, and receive antennas shall as closely as possible simulate possible victim receivers.

5.3.8 Magnetic field radiated emissions

Low-frequency magnetic emissions shall be verified by test. Guidelines for this procedure are in Annex A.

5.3.9 Radiated electric field emissions

Radiated electric field emissions shall be verified by test. Guidelines for this procedure are in Annex A.

5.3.10 Immunity to audio frequency power-line ripple

Immunity to audio frequency power-line ripple shall be verified by test. Guidelines are given in Annex A.

5.3.11 Immunity to power-line switching transients

Immunity to power-line switching transients shall be verified by test. Guidelines for this procedure are in Annex A.

5.3.12 Immunity to the conducted effects of radiated electromagnetic fields

Immunity to the conducted effects of radiated electromagnetic fields shall be verified by test. Specification-level currents/voltages shall be injected via bulk current injection (BCI) clamps, which are described by their insertion loss versus frequency.

5.3.13 Immunity to audio frequency radiated magnetic fields

Immunity to audio frequency radiated magnetic fields shall be verified by test. The preferred approach to conformance demonstration is the Helmholtz coil. If the test article is large, a localized source of magnetic field (hand-held loop) may be used. Both of these sources are calibrated in terms of their physical dimensions and the current they carry. Guidelines for this procedure are in Annex A.

5.3.14 Immunity to radiated electromagnetic fields

Immunity to radiated electromagnetic fields shall be verified by test. The preferred approach is to perform the test in an anechoic chamber.

5.3.15 Immunity to magnetic fields induced signals to cabling

Immunity to magnetic fields induced signals to cabling shall be verified by test.

5.3.16 Control of antenna port immunity to out-of-band interference

Control of antenna port immunity to out-of-band interference shall be verified by test. Verification techniques depend strongly upon the type of receiver being qualified. Techniques shall be submitted in the appropriate section of the EMC control plan prior to test start.

5.3.17 Immunity to electrostatic discharge

Immunity to electrostatic discharge shall be verified by test or controlled by the use of approved handling procedures. Test methods shall be based on those specified in IEC 61000-4-2. Because ESD testing can cause catastrophic failure of test article (and even more insidiously, latent failures), verification is only possible on engineering or prototype models, not the flight article.

Annex A
(informative)

Rationale behind requirements and tests

A.1 General

This annex provides requirement rationale, explanation, and/or guidance where necessary. In addition, test procedures are provided where applicable reference test procedures are not available or complete.

A.2 Rationale for requirements

A.2.1 General system requirements

A.2.1.1 General

EMC implementation should have emphasis in the design phase of a programme rather than after the design is complete. System-level documentation, such as EMC control plans, aids in the technical management of the EMC programme.

A.2.1.2 System-level EMC programme

A.2.1.2.1 General

Typical programme milestones and corresponding EMC data/deliverables are shown in Table A.1.

A.2.1.2.2 Electromagnetic compatibility advisory board

The EMCAB is established to report directly to the programme manager. This provides efficient decision making of design trade-offs that affect other engineering disciplines.

A.2.1.2.3 EMC programme

More specific details of the contents of the EMC programme and EMC control plan are as follows:

a) subsystem/equipment EMI performance requirements and verification:

   1) tailoring should consider, as a minimum:

      i) radiated electromagnetic environment from on-board/external transmitters;

      ii) antenna-connected electronics sensitivity levels;

      iii) assignment of power quality voltage ripple limits among space system electrical/electronic loads;

   1) safety-critical circuit identification;

b) electro-explosive devices (EED);

   1) EED requirements;

i) ISO 14304[2];

ii) other appropriate requirements;

2) design techniques;

i) wiring (including shielding and shield termination);

ii) power, circuitry;

iii) static discharge;

iv) safety margins;

c) verification:

1) safety margin demonstration;

2) requirement;

3) test techniques.

Initial release and subsequent updates should be prepared and submitted in accordance with contractual terms. Normally, the EMC control plan is not finalised until procurement is complete. In some institutions, however, the control plan is a management document that is finalized early in the programme and a design analysis report or other EMC documentation is used for EMC implementation.

A.2.1.3 Equipment/subsystem criticality categories

Programme failure mode effects analysis (FMEA), which is normally produced in the safety organization, may be used to identify equipment/subsystem criticality. The criticality category definitions may vary depending on the safety organization.

A.2.1.4 Safety margins

Safety margins have traditionally been invoked to account for variability in system hardware and uncertainties in verification techniques. Hardware variability is not an important factor at present (1990's) stage of space exploration and exploitation, since systems are acquired in very small quantities. However, space system lifetime degradation is an important factor in variability since maintenance and repair, either routine or emergency, are more complex and expensive. Safety margin establishment should consider circuit and circuit protection lifetime degradation.

EXAMPLE Many space programmes require a 20-dB safety margin between the induced noise in an EED and the EED d.c. no-fire level. If a wire harness shield is used to provide part or all of that margin, then deterioration of the shield termination could easily negate the entire margin. It might be desirable to demonstrate a lower safety margin with an artificially degraded shield termination (pigtail instead of 360° peripheral termination).The traditionally used margin for non-EED safety critical circuits is 6 dB.

An example of a circuit threshold of susceptibility is a transistor-to-transistor logic (TTL) circuit that may have logic “1” levels of 2,5 V to 5 V, and logic “0” levels from 0 V to 1 V. A 6-dB safety margin implies a 0,5 V limit for induced noise for logic “0” level.

A.2.2 Specific system requirements

A.2.2.1 External electromagnetic environment

Environments that the EMCAB should consider are ground-based RF transmitters, RF transmissions from other spacecraft, plasma (including geomagnetic storms), and electromagnetic effects due to travelling through the Earth's magnetic field.

Table A.1 — Programmatic guidelines for EMC design

Programme milestones[a]	EMC data/deliverables
Request for proposal (RFP) issue	— Define EMC performance specifications. — Define system interface requirements. — Define known operational environments. — Establish EMCAB (contractors are included when contract begins).
Requirements definition review (RDR)	— Define system-level EMC requirements. — Define power distribution system requirements. — Define conducted emissions and radiated emissions equipment-level requirements. — Define conducted and radiated susceptibility equipment-level requirements. — Define system-level verification methods for margin demonstration. — Define preliminary power distribution and grounding/isolation architecture.
Preliminary design review (PDR)	— Complete EMI environmental study-radiated and conducted requirements in ICD's. — Present power distribution and grounding/isolation architecture drawing. — Define power conditioning (power converter) physical locations. — Define all loads and locations of single point grounds. — Submit first EMC control plan or EMC contract documentation identifying EMC control techniques. — Assign the cable design engineering function and responsibility for box/system interconnect issues. — Breadboard test results for power line conducted emissions — need not pass, but defines filtering needs. — Identify items of risk. — Define connector layouts/power wiring and signal routing/shielding considerations. — Describe proposed commercial off-the-shelf (COTS) use (if any). — Identify transient suppression locations. — Identify electrostatic charging approach/issues.
Critical design review (CDR)	— Review of engineering model test data. — Perform verification of ICD requirements. — Submit revised EMC control plan. — Provide closure list of EMC outstanding issues. — Define system tests or demonstrations for system EMC assurance.
Flight hardware delivery and test	— Support as required. — Implement the waiver process as needed.
First flight article systems tests	— Review flight unit test data. — Perform EMC compliance verification. — Resolve compliance verification discrepancies with project. — Review need for update in final EMC control plan.

[a] Programmatic milestones may change depending on programme structure.

A.2.2.2 Intrasystem electromagnetic compatibility

Equipment/subsystems that will not be operated concurrently may be exempted from this requirement. An example would be co-channel operation of two radios, one in transmit mode and one in receive mode.

A.2.2.3 Electromagnetic interference control

Any general and comprehensive EMI controls are of necessity a collection of the most severe requirements drawn from a large and varied user community. As such, applicability to and impact of these requirements on space system effectiveness, cost, mass, and schedule should be considered.

A.2.2.4 Grounding and wiring design

A controlled grounding concept is of critical importance in cost-effectively achieving system-level EMC. Such issues as the use of space system structure for current return or the use of a wire return (allowing for the possibility of twisted feeder and return) and the wiring configuration for single-ended, multi-conductor and balanced signals have a strong bearing on the interference control techniques. These system-level practices should be established prior to inception of the equipment EMC design process. At a more detailed level, the EMCAB should decide reasonable trade-offs between circuit sensitivity, EMI immunity concerns, and wiring protection techniques such as twisting, shielding, filtering, and separation. Cable separation and signal grouping requirements/strategies are a part of the EMC control plan. Low-level and/or high-impedance signals may require hardening/buffering prior to wire transmission over cable interfaces. See NASA Handbook 4001[3] for additional information on unmanned spacecraft grounding.

A.2.2.5 Electrical bonding

A.2.2.5.1 General

SAE ARP 1870[4] may be used as a guide for bonding techniques.

A.2.2.5.2 Power current feeder and return paths

When structure is used as the current return path, consideration should be given to the need for a mission-unique LISN.

A.2.2.5.3 Shock and safety hazard

Typically, to prevent shock hazards, potential between equipment and the ground subsystem should be limited to 30 V d.c. or 10 V a.c. (r.m.s.).

An example of an unintentional ground might be personnel making a ground connection to equipment via a metallic hand tool. Possible arcing and high current flow could result in a safety problem unrelated to shock hazard. Attention should be paid to charged battery systems and illuminated solar arrays.

A.2.2.5.4 Antenna counterpoise

A low-impedance bond on an antenna counterpoise prevents spacecraft structure RF currents from inducing noise potentials across the counterpoise. An example of how this requirement applies is a spacecraft skin about a quarter-wave stub antenna working against the skin, but this requirement does not apply to antenna elements separate from spacecraft skin, such as a horn-fed microwave dish.

A.2.2.5.5 RF potentials

The traditional value used for a workmanship check on a faying surface bond is 2,5 mΩ between metallic surfaces. The purpose of this requirement is to facilitate termination of cable shields and filter line-to-ground shunt elements. Nevertheless, for the RF impedance, inductance plays a major role. RF voltages across the bond strap should be taken into account by physical geometry design.

A common design criteria for bond straps is to have no greater than a 5:1 length-to-width ratio.

A.2.2.5.6 Static discharge

There are several reasons for avoiding electrostatic discharges:

— to prevent an ignition source in an explosive atmosphere;

— to avoid RFI to high frequency (HF)/very high frequency (VHF)/military ultrahigh frequency (UHF) 225 MHz to 400 MHz radios;

— to prevent damage to spacecraft structure and ESD-sensitive electronics, and to prevent personnel shock hazard.

When there is no credible hazard or no risk to the mission that could result from an ESD, this requirement could be waived.

A.2.2.5.7 Explosive atmosphere protection

Dead-facing is necessary when sufficient current flows in a circuit that a demating could result in a spark of sufficient energy to ignite an explosive atmosphere. Traditionally, such calculations have tended to be very conservative, using 10 dB or 20 dB safety margins.

A.2.2.6 Antenna-to-antenna (RF) compatibility

An example of an intersystem interface is a launch vehicle docking with an orbiting space station.

A.2.2.7 Lightning

In order to minimize the impact of programme cost and mass, consideration should be given to the portion of the mission profile during which lightning activity is possible, protection schemes based on ground-based protection and the extent of launch window available.

A.2.2.8 Spacecraft and static charging

A.2.2.8.1 General

A protection plan for spacecraft charging should include:

a) developing design guidelines with the purpose of reducing or eliminating the detrimental effects attributed to spacecraft charging;

b) performing computer analyses to model the charging level of the spacecraft and to determine how spacecraft-charging related effects might interfere with mission goals and objectives.

An important aspect of this plan is to establish the appropriate electron environments for the particular satellite orbit and the phase of the solar cycle. See NASA Reference Publication 1396[5] for additional information.

A.2.2.8.2 Plasma/payload-induced differential charging/discharges

In some regions of space, there are energetic plasma environments, of which the electron content is the driver for space charging. The charging can occur on the surface for electron energies of 0 keV to 20 keV, with resultant discharges. NASA TP-2361[6] discusses this surface charging.

A.2.2.8.3 Internal charging

Charging can occur on interior parts of the spacecraft if the electron energies are above 200 keV. Additional grounding and/or shielding can be required typically for cables, circuit boards, device radiation shields, if located outside the spacecraft structure and/or separated by space environment by thin equivalent aluminium cover and/or used as uncovered boards containing electronic circuits. See NASA Handbook 4002[7] for additional information.

A.2.2.9 Hazards of electromagnetic radiation

ANSI C95.1[8] may be used as a reference for human exposure thermal concerns. ISO 14304 may be used as a reference for explosive system designs.

A.2.2.10 Life cycle

The equipment/subsystem/spacecraft performance should be no worse off with a failed EME protection scheme than with no EME protection scheme at all. This implies that line-to-ground (shunt) filter elements fail open, and in-line (series) filter elements fail short. Software filtering, where possible to implement, is preferable to passive filtering or can be used in addition to passive filtering to decrease attenuation requirements, increase reliability, or a combination of both.

For irretrievable systems, such as geosynchronous satellites or planetary probes, lifetime design has to be considered since maintenance is not an option.

A.2.2.11 External grounds

Charge equalization is necessary when mating separate parts of a space system or when mating separate space systems. A typical resistance used for the initial contact with structures isolated from the space system is 10 kΩ to limit current in the electrostatic discharge between the attached item and the contacting structure. Grounding jack bonds to space system structure should be built to maintain performance for the life of the space system.

A.2.2.12 Spacecraft d.c. magnetic emissions

A.2.2.12.1 General

The space vehicle magnetic moment is used to determine the impact of the space vehicle on two main areas:

— the attitude control system (ACS);

— the magnetic sensors in scientific payloads.

The ACS effort required to balance this effect, thus the torque about the centre of gravity, should be the most important parameter.

Functionally, the space vehicle may be using a magnetic sensor either as part of the ACS or as part of its payload; thus, the field intensity at that sensor location should be the most important parameter. The ACS sensors are not as critical in terms of an accurate value being required and the scientific payloads are more critical as the magnetic content of the spacecraft could de-sensitize the mission.

The first activity is to identify the driving requirements, i.e. whether it is for ACS torque budget or for magnetic cleanliness due to on-board sensitivity.

A.2.2.12.2 ACS budget reasons

Perform the following:

a) make a magnetic budget based on major equipment;

b) assign a general magnetic moment requirement to equipment, categorizing it by type.

EXAMPLE Permanent magnets inside, standard electronic equipment or inherent large current loop topology.

A.2.2.12.3 Sensor reasons

Perform the following:

a) calculate the maximum allowable disturbance at its location from known sensor constraints (which becomes the overall space vehicle requirement);

b) assign equipment level requirements according to the same categories as a), ensuring every unit is specifically called out;

c) adopt a magnetic cleanliness programme and if very low magnetic content is essential

   1) ensure no “perm-up” of space vehicle or components during manufacture or integration,

   2) use nonmagnetic materials in as many components as possible, and

   3) use tools made of non-ferrous material or demagnetize them before use.

A.2.2.12.4 Magnetic dipole typical values

The magnetic dipole moment of the spacecraft should be less than 30 A·m^2 at the beginning of life for all nominal configurations.

A.2.2.12.5 Specific cases and tailoring

A.2.2.12.5.1 Depending on the attitude control actuators and the altitude of the spacecraft, the maximum value of magnetic dipole momentum may be tailored. The value of 30 A·m^2 is a common value both for geosynchronous Earth orbit (GEO) and low Earth orbit (LEO) orbits. The requirement should be tailored for out-of-magnetosphere probes in the interplanetary magnetic field intensity (H-field).

A.2.2.12.5.2 For magnetic systems such as magnetic unloading systems with magnetic moment exceeding 30 A·m^2, the issues of torque balance determination should be especially analysed.

A.2.2.12.5.3 For spacecraft on equatorial orbits with a north-south stabilized axis, which is the general case for geosynchronous spacecraft, the requirement applies only for the projection of the momentum on the equatorial plan, fixed in spacecraft axis.

A.2.2.12.5.4 For geosynchronous 3-axis stabilized spacecraft, the solar array magnetic torque has a null mean in a 24-h period in spacecraft axis. The contribution of the solar array may be specified separately and the general requirement can be written as:

— Solar array: 20 A·m^2

— Spacecraft structure: 10 A·m^2

A.2.2.12.5.5 For electrical propulsion, some electrical thrusters use electromagnets with high-level magnetic momentum during firing. The magnetic component of the resultant parasitic torque due to the electrical propulsion can be neglected with respect to other components (misalignment, for example). Therefore, the general requirement does not apply in this configuration. Magnetic compatibility between torquers and sensitive equipment should be analysed.

A.2.2.12.5.6 For magnetic torquers for attitude control, the general requirement does not apply when magnetic torquers used for magnetic control are in the “ON-state”. Magnetic compatibility between torquers and sensitive equipment should be analysed. A radiated susceptibility to d.c. An H-field requirement for sensitive equipment should be defined after system analysis.

A.2.2.12.5.7 Fields at nearby hardware may be as much as 0,2 mT to 0,5 mT when current is applied to torquer bars with a moment of 30 A·m^2. Care should be taken to decrease the stray magnetic field from such torquers during design.

A.2.3 Equipment-level EMI requirements

A.2.3.1 General

Many equipment-level EMI requirements are customarily specified in the frequency domain. The reason for this is that frequency-tunable electronics are most commonly the victims of EMI. Employment of stringent frequency domain equipment-level EMI requirements should closely match the system's intentional electromagnetic spectrum usage.

The tailoring of intelligent system/mission-specific requirements is the backbone of a cost-effective EMC programme.

Usually tailoring implies taking exception to some portion of a suite of traditional requirements. For multiple mission or reusable space vehicles, the process should be to apply the entire set of all possible EMI controls to the space system procurement. The reason for the more stringent set of requirements for the space system suite of equipment is that future missions cannot be foreseen during the original procurement process. It is sensible to build maximum flexibility into a space system that will be used for extended periods. Finally, a robust EMC design of a space system allows maximum relaxation of EMI requirements levied on payloads that the space system will carry.

For space systems, it is the very act of levying an equipment-level EMI performance requirement that generates cost and schedule impact, not the actual type of limit (commercial or military). This is because in a single item procurement, all expense and time are in design and conformance verification. Actual cost of parts procured for the purpose of complying with requirements is negligible compared to the design/conformance verification.

NOTE A single day in an EMI test facility may cost at least $ 1 500 as of 1996.

There is a common misconception that levying commercial standards is more cost effective than military or aerospace standards because commercial equipment generally costs less than military or aerospace equipment. This is a totally invalid comparison. Commercial equipment costs less because of sales volume relative to smaller military/aerospace procurements. Engineering design is optimized to reduce recurring costs when designing for large production runs. Small procurements cannot afford nonrecurring costs of a design optimized for low recurring costs. The only way to take advantage of low commercial costs is to buy a purely commercial item in which nonrecurring, engineering costs have been spread over thousands of articles. As soon as a special requirement is levied on the commercial article, cost savings are lost. In the same manner, when procuring a new single item procurement, it is the number, not the type, of EMI requirements levied, which determine the cost. The cost-effective approach is to levy only those requirements absolutely necessary.

These modulation schemes, required in ISO 7137, are consistent with test equipment capabilities and are applicable to audio, video, radar, and many information links. When testing flight or engine controls, or other critical subsystems with small physical bandwidths of operation, the 1-kHz modulation should be augmented by another lower frequency square wave modulation within the test article's bandwidth.

A.2.3.2 Power bus conducted interference, time and frequency domain, source induced

The power source designer does not normally know the exact filter characteristics, capacitor and inductor values, of the power loads; therefore, the assumption is made for the voltage ripple requirement that the power bus is loaded resistively. Resistive loading should allow the full rated current of the power source to be demonstrated.

Electronics tunable over the range of VLF to HF that are included in the space system or, in the case of a reusable space system power bus, might at any time be included in a payload, should have stringent ripple control through the HF band. Conducted emissions are typically controlled below HF and sometimes into a portion of the VHF band.

A.2.3.3 Power bus conducted interference, load-induced, frequency domain

The total of all load-induced ripple can be allocated on a percentage load basis to the total bus current; that is, the ripple voltage budget can be allocated on a volts per ampere basis. This approach yields an optimum limit for each piece of equipment, resulting in lower system masses for filter components. Furthermore, limit non-conformances may be viewed in a total system setting. If another equipment conducted emission in-band to the specification non-conformance is below the limit by the same or greater amount than the non-conformance, the non-conformance may be waived. If conducted emission currents are to be controlled by the equipment-level requirement, then the voltage ripple limit is adjusted for the power bus impedance to yield allowable current emissions. The budgeted ripple current limit is given in amperes of ripple current per ampere of load current. If conducted emission control is exerted below 10 kHz, it should be specified as a current limit, or a special bus impedance simulation should be developed uniquely for the programme and be adjustable for different load currents.

A.2.3.4 Power bus load-induced switching transient

A.2.3.4.1 General

The effects of two types of switching transients merit consideration. The first effect, termed a long-duration transient, is line voltage sag on the order of milliseconds due to an insufficiently stiff power source. This is an important consideration for a space system whose power subsystem relies on solar cells or any other current limited source. The second effect, termed a fast transient, is due not to the power source impedance but to the reactance of the power bus wiring. In this case the relevant factor is the time rate of change of the load current draw more than the magnitude of the current drawn that is the culprit.

A.2.3.4.2 Control of long-duration load-induced switching transients

Inrush current control should only be exerted if the current of the power subsystem is limited enough that individual load cycling can reasonably be expected to result in bus voltage sags. Inrush current limits should consider the power source stored energy capacity, its capability to supply transient current in excess of its steady-state maximum. This will determine magnitude and duration of the inrush current limit. Figure A.1 illustrates a sample limit. Transient current limits are normalised to steady-state current draw. The curve is often approximated by a stair-step to ease conformance verification. Inrush current is measured from a stiff source; i.e. one in which voltage across the power source does not drop significantly when energizing the test article. Therefore, the test power source should not simulate the space system power subsystem. The point of the requirement is to control and measure the test article transient current with the power bus voltage kept constant in order to calculate the test article load characteristics during the inrush event.

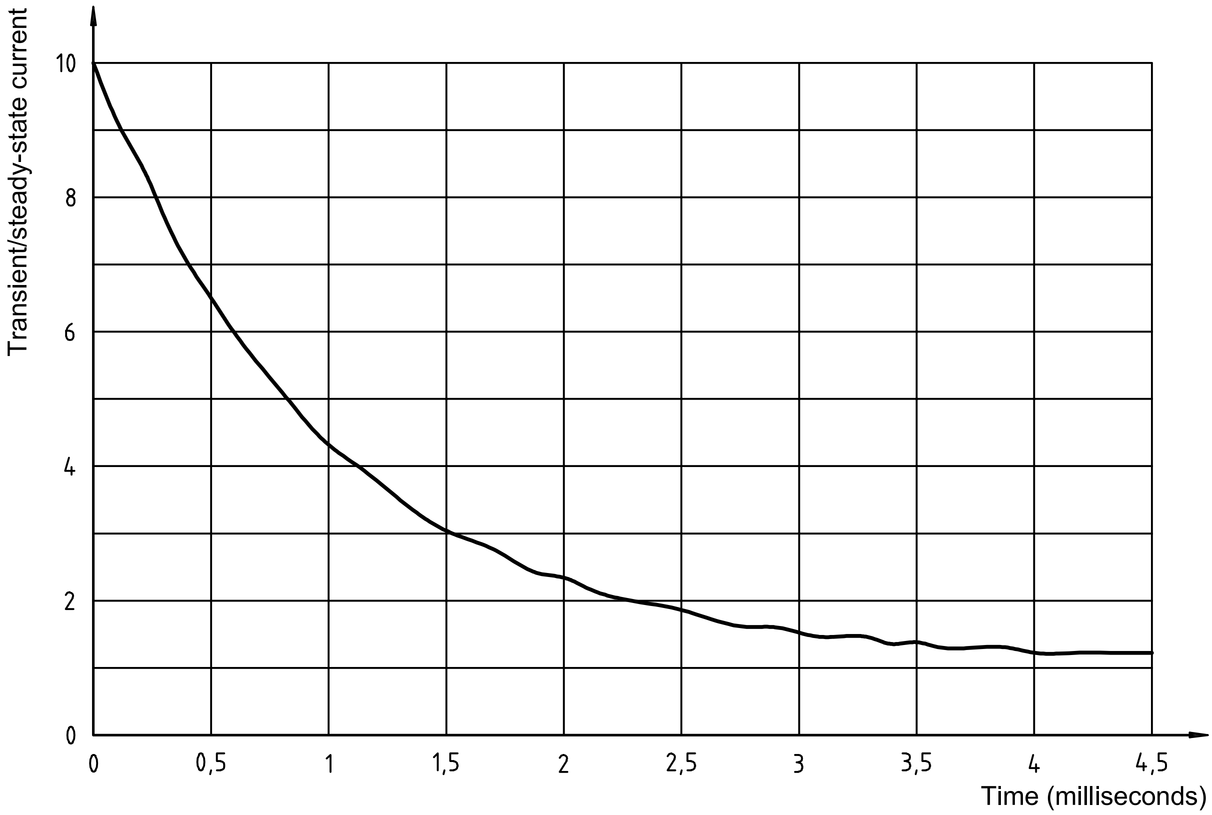


Figure A.1 — Transient inrush current sample limit

A.2.3.4.3 Control of fast load-induced switching transients

The limit for fast load-induced switching transients should be set such that low-power loads may meet the limit without the use of a soft-start switch. The limit is a trade-off between requiring a soft-start switch and requiring large amounts of energy storage in victim power supplies. The test set-up power source impedance across which the transient is dropped should exceed the impedance of expected system power bus wiring. Turn-off transients should be limited only in magnitude. The turn-off transient waveform is solely a function of source impedance and time rate of change of the switched current. The designer has no other recourse to passing the test besides limiting the switch rise-time. If the switch is external to equipment, the designer has no means to meet the requirement, and the EMCAB should be careful about levying a reasonable requirement that will not generate numerous waiver requests. For a structure return bus, the inductance is on the order of 1 μH/m, whereas for an aboveground return, the inductance is less than 300 nH/m. Usually a value of 50 Ω is used for the LISN inductor bypass resistance in order to model high-frequency transmission line characteristics of a power bus. Transient durations of longer than 50 μs are typically measured against a current limit, for the same reason that steady-state conducted emissions are specified as a current below 10 kHz. Voltage control longer than 50 μs requires a programme-specific bus impedance simulation.

The criteria commonly used to identify frequently repeating transients are transients $>$ 10/s.

A.2.3.5 Power bus load-induced time domain ripple

True r.m.s. ripple should be controlled to a level defined by the power quality ripple limit multiplied by the ratio of test article load current divided by total power source available current. The measurement instrument, preferably a digital storage oscilloscope with true r.m.s. capability, bandwidth should match that of the power quality specification when it states a certain ripple voltage with a specified bandwidth. Specified bandwidth corresponds to digital storage oscilloscope (DSO) effective repetitive bandwidth. The DSO single-shot bandwidth should be able to capture a 100-ns waveform. If the equipment under test operates off an a.c. bus, then some means of nulling or reducing the power frequency waveform is necessary.

Another reason for performing this test is to verify stability of power bus with the equipment interface. Switched mode power supplies (SMPS's), which are common on space system power buses, draw a current waveform spectrum that occupies a band at which the power bus is a high impedance. If an adequate local low-impedance voltage source is not provided by the SMPS designer, large voltage oscillations across the power source may occur.

A.2.3.6 Signal cable conducted interference, frequency domain

Control of common mode currents on signal cables is an effective means of controlling radiation at frequencies below 1 GHz. This requirement refers to net current flowing in an entire bundle, in flight configuration.

A point of departure for determining a signal cable conducted emission limit is the conducted emission limit placed on power bus loads. The common mode emissions limit for signal cables needs to be only as required to control radiated emissions threats to receivers and/or cable coupling. This test adds programme cost and should only be done as an aid to troubleshooting because of the large number of cables on some equipment.

A.2.3.7 Antenna connection port spurious emissions

Antenna port spurious emissions may be measured either by injection at the connection of the antenna port to an EMI meter via coaxial cable or wave guide or by measuring radiated emissions from the subsystem antenna connected to the port (simulation of *in situ* condition). The former method has the advantage of simplicity and measurement accuracy, while the latter method more accurately accounts for antenna out-of-band gain and transmission line losses. The latter method is also indicated if the antenna is hardwired to the antenna port or if the transmit power out is too high to filter or to eliminate it otherwise from the EMI meter input in a direct connection.

A.2.3.8 Magnetic field radiated emissions

Control may be exerted either via directly limiting magnetic field emissions, zoning, or a combination of both. Zoning refers to separation of potential victims and culprits. Because low-frequency magnetic emissions from equipment enclosures fall off rapidly with distance, it may be most economical to limit magnetic emissions at a distance larger than the traditional 7 cm from the EUT. This is facilitated via zoning.

A.2.3.9 Radiated electric field emissions

Because traditional space system test methods measure field emissions at 1 m, the limit should be adjusted downward if any possible victim antenna or antenna-connected unshielded transmission line can be placed closer to the EUT than 1 m. Limits should reflect possible victim receivers operationally required sensitivity. Limits should also reflect the equipment proximity to the victim. If the space system is such that

a) there exists a clearly defined electromagnetic environment inside and outside of a shielded enclosure,

b) all antennas are mounted externally, and

c) shielded transmission lines connect internal receivers to bulkhead-mounted RF connectors,

then radiated emission limits imposed on internal equipment should reflect shielding/shading expected from the space system enclosure.

This limit is relaxed from the limit on externally installed equipment mounted in immediate proximity to victim antennas or unshielded transmission lines. If a space system contains a broadband source (ion thruster for example), care should be taken to characterize the noise over the bandwidth of the communications receiver bandpass. Internal use of a wireless intercom would necessitate a more stringent internal than external radiated emission limit in the band occupied by that transceiver subsystem.

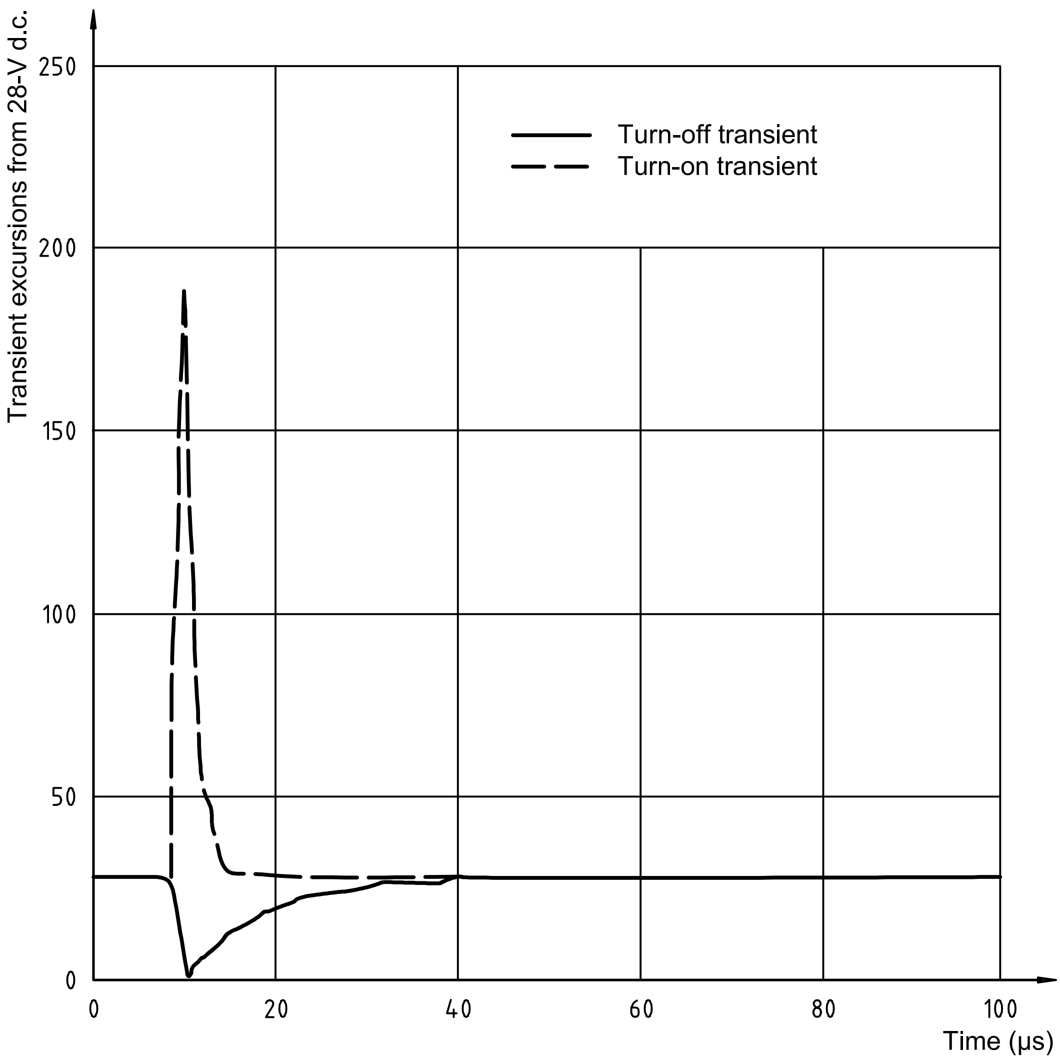
A.2.3.10 Immunity to audio frequency power-line ripple

The purpose of this requirement is to evaluate immunity of equipment to audio frequency power-line ripple. RF ripple immunity is evaluated using bulk current injection on power and signal lines as specified in 5.3.12.

A.2.3.11 Immunity to power-line switching transients

Although power quality specifications often show symmetrical (with respect to nominal voltage) positive and negative (turn-off and turn-on) waveforms, this is not an accurate representation. The turn-off transient is typically shorter in duration and higher in amplitude and source impedance than the turn-on transient if the switch time is shorter than 1 µs. The turn-off transient magnitude may be estimated by multiplying the maximum load current that might be switched in 1 µs by 50 Ω. The turn-on transient is the response of the power bus source impedance simulated circuit to the largest load that might be turned on without the benefit of a soft-start switch.

Figure A.2 shows a qualitative comparison of turn-on and turn-off transients from a 4-A load with a 100-µF input capacitor in parallel with a 7-Ω resistor operating from a 28-V d.c. bus. The source impedance is modelled by the CISPR 50 µH, 50-Ω LISN. Details of this LISN can be found in CISPR 16-1[9].



100 µF// 7 Ω, switched in 100 ns, from 50 µH, 50 Ω CISPR LISN.

Figure A.2 — Switching transient envelopes on a 28-V d.c. bus

A.2.3.12 Immunity to the conducted effects of radiated electromagnetic fields

The coupled current limit may be computed from a knowledge of the field intensity, cable length, cable height above the ground plan and termination impedance. For the configuration assumed under ISO 7137, the limit is 1,5 mA/V·m at frequencies above which the cable length is one-half wavelength. At lower frequencies, the limit decreases linearly with frequency. It is suggested that a correlation be made by test to verify the 1,5 mA/V·m injection factor in critical applications. It is customary, for the sake of simplicity, to invoke a single limit based on a frequency independent maximum field intensity and the longest possible cable length for the space system. Care should be taken to ensure such simplifying assumptions do not result in a severe over test.

A.2.3.13 Immunity to audio frequency radiated magnetic fields

This requirement is normally applied to equipment designed to process audio frequency (30 Hz to 100 kHz) signals at microvolt levels. It can also be applied as an interface control, together with a companion magnetic emission limit, when two pieces of equipment, that operate in immediate proximity, are qualified by separate contractors.

The limit should be chosen such that the total impact to design for immunity and emission control is minimized. If, as is typical, the space system complement of victims requiring such protection is limited, the effort should be slanted towards maximum immunity levels and minimal control of magnetic emissions. Limits may be determined analytically if the victim is a magnetometer-type device; i.e. one which measures magnetic fields and whose sensitivity is specified. In this case, the culprit magnetic emissions should be less than the signal to be measured. If the sensor is mounted remotely from possible culprit emitters, immunity of the sensor-connected equipment should still be controlled. Because magnetic field intensity from small sources decreases rapidly with distance, zoning is a complementary approach to controlling susceptibility. See A.3.3.8.

If there are requirements for low-intensity magnetic field locations, the space vehicle integration will define such locations and environments and verify by test or analysis that these equipment threshold sensitivity levels are not exceeded.

A.2.3.14 Immunity to radiated electromagnetic fields

A very important consideration in radiated immunity limit setting for spacecraft is that many antennas used are extremely directional. When setting immunity limits, the side-lobe power density that can actually illuminate space system equipment/subsystems should be considered. This important caveat does not apply to electromagnetic fields originating on other platforms and which could possibly illuminate the space system with an antenna main lobe.

If the space system is such that there exists a clearly defined electromagnetic environment inside and outside (a shielded enclosure) and all antennas are mounted externally, then the radiated immunity limit imposed on internally mounted equipment should reflect the amount of shielding/shading expected from the space system enclosure. This limit is necessarily reduced from the limit on externally installed equipment mounted in immediate proximity to culprit antennas. This requirement should take into account also the close proximity of equipment and cables and their unintentional radiated fields.

NOTE The internal use of a wireless intercom necessitates a more stringent internal than external radiated immunity limit in the particular band occupied by that transceiver subsystem.

A.2.3.15 Immunity to magnetic fields induced signals to cabling

The limits for induced magnetic fields to cabling are normally set in accordance with typical system culprit cable signals (both current levels and transients levels are defined). Also, any circuits sensitive to magnetic coupling (cable to cable) should be identified. A test should be imposed only if sources are determined to be of a magnitude that would induce cross talk in sensitive circuits. Magnetic torquers may be the source of such fields.

A.2.3.16 Control of antenna port immunity to out-of-band interference

The requirement is easily tailored to the necessary pass band of a tuned super heterodyne receiver. For non-traditional receivers, such as frequency hoppers and spread spectrum receivers, tailored limits and test methods should be devised that address pertinent technical issues. Repetitive broadband RFI may be especially detrimental to spread spectrum receivers.

A.2.3.17 Immunity to electrostatic discharge

Due to the potentially destructive nature of ESD testing, especially the possibility of inducing latent failures, and the small production runs inherent in space system procurements, serious consideration should be given to the ESD control process, especially the type and degree of verification desired.

A.3 Verification

A.3.1 General system requirements

A.3.1.1 General

The selection of test, analysis, inspection, similarity, or some combination to demonstrate a particular requirement is generally dependent on the degree of confidence in the results of the particular method, technical appropriateness, associated costs and availability of assets.

A.3.1.2 System-level electromagnetic effects verification plan (EMEVP)

A.3.1.2.1 System-level verification methods

Typical system-level verification activities include:

a) methods to be used to select critical circuits to be monitored for conformance to degradation criteria and safety margin;

b) procedures used for developing failure criteria and limits, i.e. when checking receivers for interference, it is important to check for quieting on clear channels in addition to verifying capability to copy signals of a known strength;

c) means of verifying radiated and conducted compatibility at the system level;

d) methods of verifying power line conducted margin in differential and common modes especially for distribution outputs and critical circuits;

e) methods of verifying common-mode margin for cable bundles, especially on cable bundles with critical circuits and bundles routed close to sensors or critical circuits;

f) means of verifying RF self-compatibility (compatibility between transmitters, receivers, and the whole spacecraft in all their modes of operation) (see 5.2.6);

g) means of verifying design adequacy of spacecraft electrification (static electricity, spacecraft charging) and the programme required lightning protection (advance planning to procure safety-margin sensitized or instrumented EEDs is crucial to timely execution of EMC verification);

h) means of simulating and testing electro-explosive subsystems and devices (EEDs);

i) verifying electrical power quality and methods for monitoring d.c. and a.c. (as applicable) power buses;

j) means of verifying EMC at interfaces such as the interface of the launch vehicle;

k) effects of cavity resonances.

A.3.1.2.2 Test conditions

Parameters necessary to specify the test conditions include:

a) test conditions for all electronic and electrical equipment installed in or associated with the space system and sequence for operations during tests, including switching (see Note 1);

b) implementation and application of test procedures including modes of operation and monitoring points for each subsystem and equipment;

c) use of approved results from laboratory interference tests on subsystems and equipment;

d) methods for reporting/recording data readout and analysis;

e) test locations and descriptions of arrangements for simulating operational performance in cases where actual operation is impractical;

f) configuration of equipment/subsystems modes of operation to ensure victim equipment/subsystems are tested in most sensitive modes, while culprit equipment/subsystems are tested in noisiest modes (see Note 2);

g) details concerning frequency ranges, channels, and combinations to be tested specifically, such as image frequencies, intermediate frequencies, local oscillator frequencies, transmitter fundamental and harmonically related frequencies, and receiver bandwidths and sweep rates for measurement equipment (subsystem susceptibility frequencies identified during laboratory testing should be included).

NOTE 1 An intrasystem compatibility culprit/victim matrix is part of the system verification.

NOTE 2 Any individual equipment/subsystem can be both a culprit and victim and therefore might need to be tested in multiple modes of operation.

A.3.1.3 Electromagnetic effects verification report (EMEVR)

Typical requirements for an EMEVR are as follows:

a) identification of specific objectives, including applicable requirements and EMEVP references;

b) description of the test article, including serial number, configuration, and drawings/photographs as appropriate;

c) description of any fixes or configuration changes to the article resulting from verification failures;

d) summary of results including an executive summary stating the degree of conformance to requirements;

e) description of any deviations from test facilities, analysis techniques or tools and inspection aids in EMEVP;

f) description of any deviations from procedures in EMEVP;

g) test set-up diagrams and photographs, as appropriate;

h) list of test equipment, including calibration information, as appropriate;

i) recorded data or logs, including instrument readings, correction factors and reduced results (methods of data reduction should be described; if the value of the data has been compromised due to test conditions, the reason and impact on results should be stated);

j) identification of ambient and other test conditions.

A.3.1.4 Safety margin demonstration, critical/EED circuit

When the activating signal-to-noise ratio is reduced by the safety margin factor, no direct measurement of monitoring circuit is necessary. Proper equipment/subsystem operation demonstrates the existence of a safety margin. Typical techniques for EED circuits include substitution of sensitized EEDs (bridge-wire fuses at one-tenth of real EED no-fire current) and thermocouple or other temperature-measuring attachments to real bridge-wires.

A.3.2 Specific system requirements

A.3.2.1 External electromagnetic environment

For the sake of a technically valid test, a field illumination of 3 dB spot diameter should be sufficient if the proper antenna is selected for this immunity test. For large systems, sectorized testing may be performed.

A.3.2.2 Intrasystem electromagnetic compatibility

A useful way to check for intrasystem EMC is by implementing a compatibility matrix. The compatibility matrix shows all combinations of individual equipment/subsystems which should be considered in order to verify overall intrasystem compatibility. An example of the compatibility matrix-basic format is shown in Table A.2. Test procedures for operation of all matrix equipment should be included to support test execution. Any special support equipment required to exercise culprits/victims should also be considered. Prior to demonstration of any particular culprit/victim pair compatibility, it should have been previously determined that the culprit is operating correctly and that the victim operates correctly when the culprit is not energized.

Table A.2 — Intrasystem compatibility test demonstration matrix

Culprit/victim	Equipment A	Equipment B	Equipment C	Other equipment	Equipment N
Equipment A	n/a[a]	test	test	test	test
Equipment B	test	n/a[a]	test	test	no test[b]
Equipment C	test	no test[b]	n/a[a]	test	test
Other equipment	test	test	test	n/a[a]	test
Equipment N	test	no test[b]	test	test	n/a[a]

a "n/a" means not applicable.

b "no test" means that these two pieces of equipment can never operate simultaneously or in such a manner as to cause interference; therefore, no demonstration is required.

A.3.2.3 Electromagnetic interference control

A successful system demonstration test is required to provide baseline data for comparison with the system-level EMI test results.

A.3.2.4 Grounding and wiring design

Verification of intentional current flow in structure and/or shields is controlled according to the design. This will require power grounding and isolation measurements with respect to structure.

A.3.2.5 Electrical bonding

A.3.2.5.1 General

Verification of metallic and conductive composite structures may normally be accomplished by inspection with a proven bonding process. Verification of dielectric surfaces treated with conductive finishes usually requires testing of surface resistivity and electrical contact to a conductive path.

A.3.2.5.2 Power current feeder and return paths

Adequate power voltage at all loads with power subsystem fully loaded is the final verification of power bus current sourcing capability.

A.3.2.5.3 Shock and safety hazards

The system should be designed so it is possible, through the use of devices such as break-out boxes, to verify that safety requirements are met. Redundancy options that by design are intended to prohibit shock and maintain safety should be exercised. National safety standards should be met as well.

A.3.2.5.4 Antenna counterpoise

This verification may be met by operation of the system in a compact range to verify proper antenna system performance.

A.3.2.5.5 RF potentials

Low-voltage output is necessary on the milliohmmeter so that bond measurements simulate the effect of bonds on induced EMI currents. If a high-voltage source is used, it may pierce an oxide or contaminant layer that a milliampere, millivolt EMI signal would find a very high impedance. Therefore, higher voltage fault current testing should not be performed until after the low-voltage RF bond testing is completed. This test sequence is necessary because it is possible for the same bond to fail the RFI bond requirement, while passing the fault current requirement, even though the fault current bond reading is within the limit specified for the RFI bond. A low-voltage output meter has a maximum output voltage of 20 mV with a typical output of 200 µV and test currents ranging from 1 µA to 10 mA.

A.3.2.5.6 Static discharge

Verify that bonds satisfy the requirement to prohibit formation of potentials that would be the source of static discharge. Inspection of surface treatment on all structure-connected materials should be performed to ensure adequate bonding can be maintained.

A.3.2.5.7 Explosive atmosphere protection

Verification of bonding for explosive atmospheres includes analysis of the flammable substance ignition point. Fuel hazard criteria are normally based on peak power.

A.3.2.6 Antenna-to-antenna (RF) compatibility

In the absence of a real or simulated signal for reception, the receiver should be checked for not just absence of noise but also for quieting, if applicable. If a suitable signal source for exercising the victim receiver is not available and the receiver is such that its operation cannot be evaluated without that source, then the receiver may be disconnected from its antenna feed and be replaced by a similar noise figure test receiver system. This test receiver may be used to quantify the RFI level present at the receiver input, which may be compared to victim receiver sensitivity. However, this test cannot simulate any noise rejection capabilities inherent in the victim receiver. Each receiver should be operated without its intentional signal source and with other sources operating at maximum power/antenna pointing. This guarantees, in general, maximum sensitivity at the receiver to disturbances.

A.3.2.7 Lightning

The tests procedures listed in ISO 7137 are equipment level. The SAE ARP 5412[10] provides some recommendations for complete vehicle testing. There is a separate SAE standard dedicated to test methods, which contains extensive information on lightning verification.

A.3.2.8 Spacecraft and static charging

A.3.2.8.1 General

An important step in implementing a spacecraft charging effects protection plan is the application of computer modelling to estimate the extent and likelihood of electric charge build-up on spacecraft surfaces.

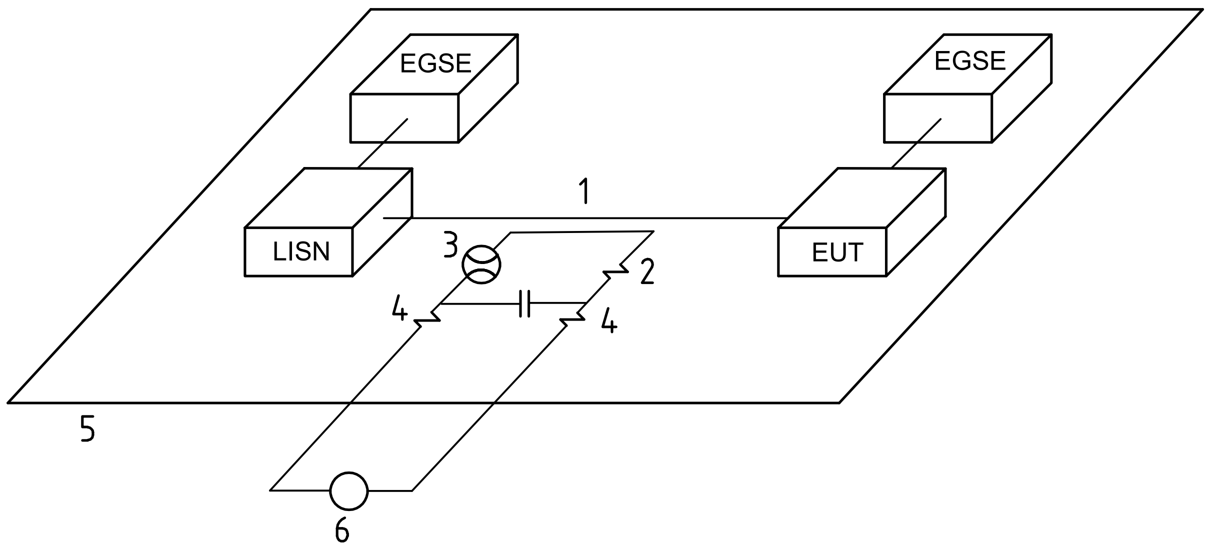
A.3.2.8.2 Plasma/payload-induced differential charging/discharges

The verification of induced differential charging is recommended by test. Verification by test can be executed with radiated ESD sources; the pulse energy is selected on the basis of specific mission charging/discharging risk.

EXAMPLE Low Earth orbit and geosynchronous Earth orbit.

The conducted ESD source is to be used if expected anomalies in payloads will inject current into the structure.

A suggested test method is shown in Figure A.3.



Key

1 discharge circuit
2 damping resistor
3 spark gap
4 choke resistor
5 ground plane
6 high voltage source

Figure A.3 — Spacecraft charging ESD immunity test

The following list contains specified current parameters for Figure A.3.

a) Spark gap

The typical value is 6 kV. Hermetically sealed, pressurized envelope over-voltage spark gap with fast breakdown time is preferred. An air gap should not be used.

b) Capacitance

The typical value is 100 pF, high-voltage capacitor with low inductance.

c) Damping resistor

The typical value is 47 Ω, which may be adjusted at critical damping depending on value of the capacitance and self-inductance of the discharge circuit.

d) Choke resistor

This part is used to prevent high-frequency component of discharge from flowing in uncontrolled paths. The minimum value is 10 Ω. With this precaution, the discharge parameters are not dependent on length and position of high-voltage source wires.

e) High-voltage source

The source could be d.c. In this case, a choke resistor of more than 10 MΩ is used. However, for safety reasons, an ESD generator as in IEC 61000-4-2 is preferred. It will be used in air discharge mode but with permanent connection of the discharge tip to one of the choke resistors and the discharge return connection being connected to the second choke resistor.

f) Discharge circuit

The circuit should be floating and tightly coupled 20 cm along the harness of the EUT.

g) Transient current pulse

The aim is to obtain a value of 30 A for 30 ns duration at mid-height.

A.3.2.8.3 Internal charging

Testing for internal charging is exceedingly difficult. Analysis and implementation of design techniques, such as shielding with proper thickness of grounded aluminium, are necessary.

A.3.2.8.4 Charging of fluid lines

If possible, fluid additives should be used to control the resistivity of the fluid line. Any fluid lines composed of metallic braid (external or internal) should provide for a positive bond of this metallic braid.

A.3.2.9 Hazards of electromagnetic radiation

ANSI C95.1 may be used as a guide for human-exposure-related measurement procedures. The national safety regulations take precedence.

A.3.2.10 Life cycle

Built-in test capability, test ports, resistance measurements, continuity checks, transfer impedance measurements and transfer function measurements are some of the means available for use in periodic surveillance of system integrity. For non-retrievable spacecraft, good design practices are essential such as reliable shielding effectiveness, termination and bonding implementation methods.

A.3.2.11 External grounds

Proper placement and marking of space system external ground provisions should be verified by inspection. Compliance with bonding requirements should be verified by test.

A.3.2.12 Spacecraft d.c. magnetic emissions

A.3.2.12.1 Budget reasons

A.3.2.12.1.1 As the total moment for the space vehicle is not so critical, it can be calculated in a simple way. This method is to consider the major contributors (equipment which has a known high-magnetic content), add their moments as scalar values and add the total of the other contributors after processing by a simple statistical consideration of their vector direction; e.g. use of root-sum-square (r.s.s.).

A.3.2.12.1.2 Verify equipment against these requirements by similarity or “rough” test.

A.3.2.12.1.3 Calculate the total moment from major units plus statistical distribution (r.s.s.) sum of the remaining equipment.

A.3.2.12.2 Sensor reasons

A.3.2.12.2.1 The driving factor in this case is the sensitivity of the sensor to magnetic fields. This sensitivity becomes the requirement for the maximum allowable disturbance from the total space vehicle made up from its component parts. Starting from the unit measured magnetic moments for three orthogonal axes, it is possible to convert these into field strengths and translate these results to the sensor location. Once all units are measured and added into the calculation, the total magnetic field will be known at the sensor location. This method relies on good equipment-level measurements and equipment being located far enough away from the sensor to take advantage of the inverse cubic law.

A.3.2.12.2.2 Verify each equipment by testing in a Helmholtz compensating coil arrangement.

A.3.2.12.2.3 Calculate the magnetic flux density (B-field) or magnetic moment vector at the sensor location as a combination of all test results. This should provide a very accurate result.

A.3.2.12.2.4 As an optional, confirm system level calculation by performing test on the fully integrated space system.

A.3.3 Equipment-level EMI testing

A.3.3.1 General

It is highly desirable to verify prior to test start that the EMI test equipment as set up to conduct the given measurement is capable of measuring 6 dB below the applicable specification limit.

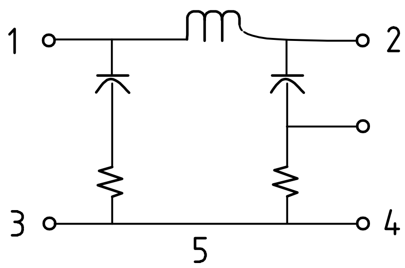
Optimal control of the number of sweep frequencies and the dwell time for immunity testing will reflect the nature of the test article, and the most efficient way to exercise this control is at the EMCAB level. Test frequencies should be logarithmically spaced.

A.3.3.2 Power bus conducted interference, time and frequency domain, source induced

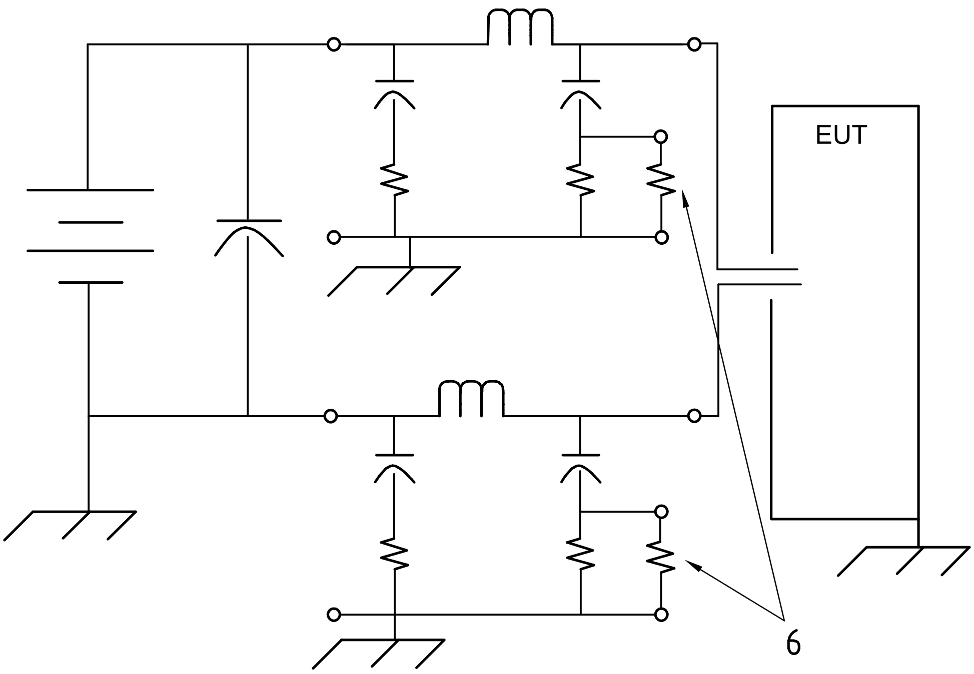
Frequency domain voltage ripple can also be measured using a digital storage oscilloscope with a fast Fourier transform (FFT) capability or with an interface to a computer performing the FFT. Because noise on the purely resistively loaded power subsystem can only be periodic in nature, it is sufficient that the DSO repetitive bandwidth meet the power quality bandwidth requirement. For power quality purposes, it is sufficient that for single shot events, the DSO be able to capture a 100-ns transient. If a 50-Ω input EMI meter is used, then a high-pass filter should be provided that blocks power frequency voltage from destroying the meter. Alternatively, frequency domain ripple current can be measured, if the limit is expressed that way. Then an EMI current probe may be used, which inherently provides the high-pass filter function. If frequency domain conducted emissions limits are imposed to control radiated emissions, then a current probe should be used. Such measurements are likely to be imposed as a common mode requirement; therefore, the current probe will be placed around both feeder and return lines.

A.3.3.3 Power bus conducted interference, load induced, frequency domain

A frequency domain LISN is shown in Figure A.4 a). Figure A.4 b) shows a LISN-based conducted emission test set-up. Resistors connected to the LISN EMI ports are 50 Ω. Current control is needed below 150 kHz. This is because it is impossible to standardize a single source impedance at such low frequencies. If it is necessary to control conducted emissions below 150 kHz, then the instructions of SAE ARP 1972[11] may be used as a guide.



a) Topology



b) LISN-based voltage conducted emission test set-up

Key

1 power input

2 power output

3 power source reference

4 EMI port

5 LISN frequency domain

6 EMI instrument 50 Ω

Figure A.4 — Topology of a CISPR LISN and LISN-based voltage conducted emission test set-up

A.3.3.4 Power bus load-induced switching transients

A.3.3.4.1 Applicability

A.3.3.4.1.1 Direct current

Most space system power buses have historically been d.c. buses. This simplifies transient measurements. On a d.c. bus, timing of the transient is unimportant and the transient waveform is clearly discernible. The supply may be made as stiff as desired (for short durations) through bypassing the test article power input with large values of line-to-line electrolytic capacitance.

A.3.3.4.1.2 Alternating current

On an a.c. bus, the transient amplitude is dependent upon voltage magnitude at the onset of transient condition. It is necessary to synchronize transient onset with a.c. waveform peak in order to guarantee worst-case transient capture. The actual power-switching device should be capable, however, of operating on an a.c. bus. Especially on an a.c. current inrush measurement, it is difficult to differentiate inrush current magnitude from normal variation in current due to line voltage periodic fluctuation.

A.3.3.4.2 Control of long-duration load-induced switching transients

Inrush current is measured from a low-impedance source; i.e. one in which voltage across the power source does not drop significantly when energizing the test article. Therefore, the test power source resistance should not simulate that of space system power subsystem. The test set-up is shown in Figure A.5. Voltage sag measured across the R series (due to transient inrush current) at the test article power input should be less than or equal to the following quantity:

$$\Delta V_{\mathrm{trans}}\left(V_{\mathrm{nom}}-V_{\mathrm{min}}\right) \leqslant \sqrt{\frac{I_{\mathrm{ss}}}{I_{\mathrm{bus}}}}$$

where

$\Delta V_{\mathrm{trans}}$ is the maximum allowable voltage sag, expressed in volts, during inrush current measurement;

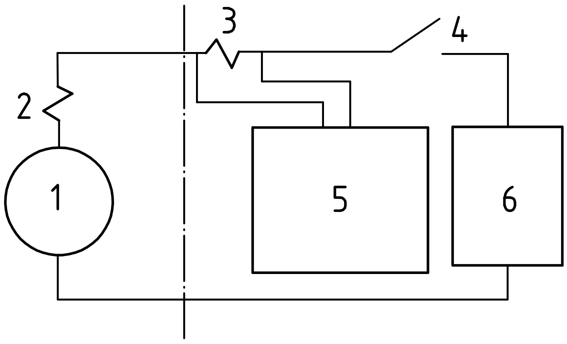
V_{nom} is the power quality specified nominal bus voltage, expressed in volts;

V_{min} is the power quality specified minimum bus voltage, expressed in volts;

I_{ss} is the test article steady-state current draw, expressed in amperes;

I_{bus} is the space system power bus maximum steady-state current load, expressed in amperes.

If a load operates from an a.c. bus, then the switch should close within 10 % of the a.c. waveform peak voltage. Either polarity is acceptable as long as the test article operates as a full-wave rectifying load. The sum of internal and series resistance should accommodate the requirement for maximum voltage sag stated above. The test article input power capacitors should be discharged prior to transient measurements. Bypass capacitance across the output of a d.c. power source can effectively reduce the internal resistance.



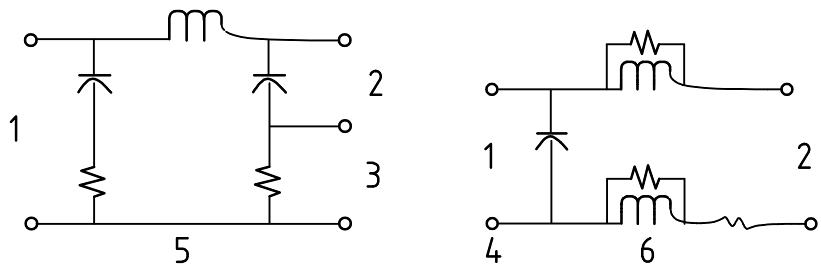
Key

1	$V_{ac/dc}$	4	switch
2	$R_{internal}$	5	digital storage oscilloscope (differential input)
3	R_{series}	6	test article

Figure A.5 — Current inrush test set-up

A.3.3.4.3 Control of fast load-induced switching transients

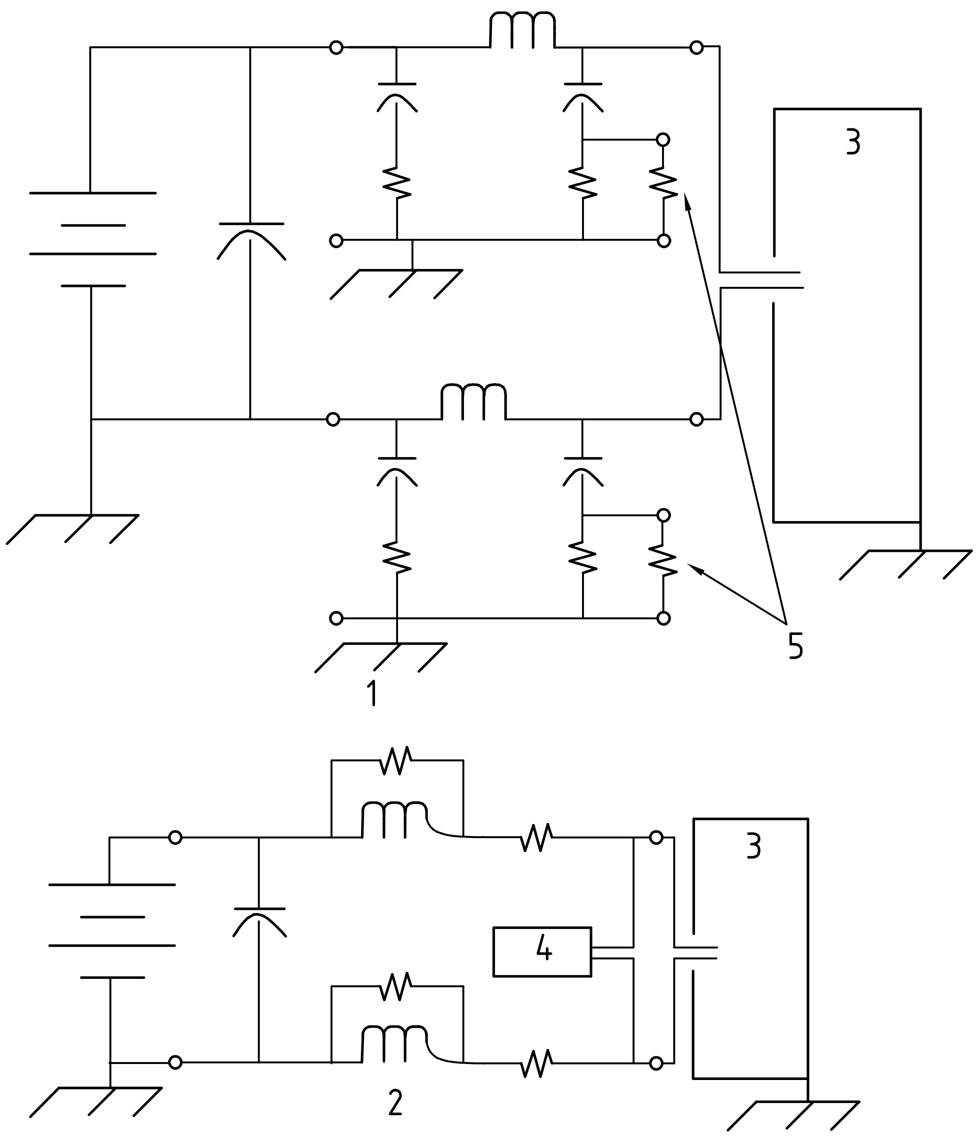
Frequency domain conducted emissions (CE) requirements have a lower frequency limit below which the LISN impedance is undefined. Figure A.6 a) illustrates a time domain LISN (and contrasts topology with the CISPR LISN). A time domain LISN has no line-to-ground components and hence exerts no control over power source common mode impedance. This is acceptable when measuring time domain transients or line-to-line ripple in aboveground current return power buses, because these are differential mode phenomena. Figure A.6 b) shows measurement test set-ups using the two types of LISN. If the frequency domain test set-up is used for a time domain test, a DSO should replace the EMI meter. A 50-Ω load should still be provided at each EMI port. Consideration should be given to making a balanced line-to-line measurement to avoid measuring common mode effects at the EMI port. Note that the frequency domain LISN does not adequately control the impedance (resonance occurs) below 150 kHz.



Key

1	power input	4	return
2	power output	5	frequency domain LISN
3	EMI port	6	time domain LISN

a) Topology



Key

1 frequency domain CE measurement

2 time domain CE measurement

3 EUT

4 DSO

5 50 Ω EMI meter

b) Modelling of frequency and time domain CE

Figure A.6 — Time domain LISN

A.3.3.5 Power bus load-induced time domain ripple

The measurement instrument bandwidth (digital storage oscilloscope with true r.m.s. capability) should match that of the power quality specification when it states a certain ripple voltage with a cited bandwidth. DSO repetitive bandwidth should meet or exceed the bandwidth required in the power quality specification. DSO single shot bandwidth should be able to capture a 100-ns waveform. If equipment operates off an a.c. bus, then some means of nulling or reducing the power frequency waveform is necessary. The source impedance across which ripple is measured should be controlled over bandwidth required by the power quality specification.

Because both peak-to-peak and r.m.s. values of ripple voltage are ascertained, a true r.m.s. readout is required to perform this test. For a test article powered from a d.c. bus and a power quality specification requiring time domain ripple measured with no more than a 10-MHz bandwidth (100-ns waveform capture), a simple source impedance may be constructed according to the worst-case inductance and the following equation:

$$L = \frac{d^2 N^2}{0{,}45d + l}$$

where

L is the inductance, expressed in nanohenrys (nH);

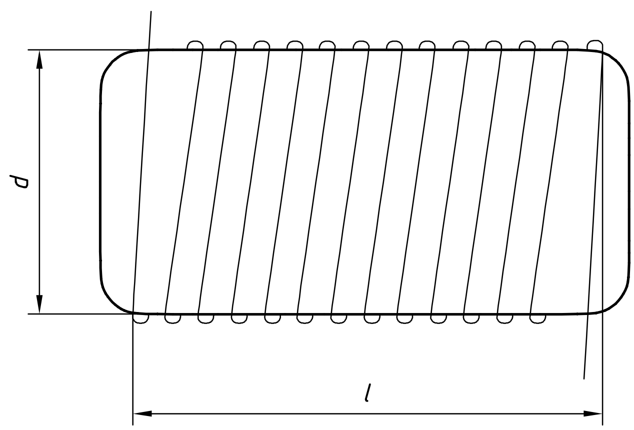
d is the coil diameter, expressed in millimetres (wire-centre-to-wire-centre);

l is the coil length, expressed in millimetres;

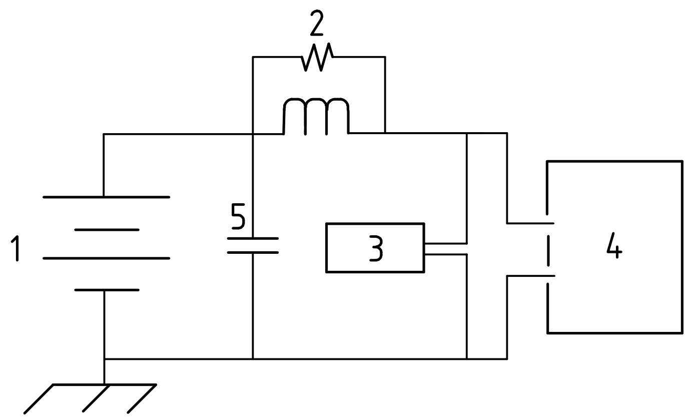
N is the number of turns.

This inductance may be bypassed by a quarter-watt resistance of 50 Ω in order to provide a controlled high-frequency bus impedance. Figure A.7 a) shows physical implementation of the above inductance equation. The test set-up for measuring time domain ripple for d.c. equipment is shown in Figure A.7 b). The DSO input impedance in this case should be 1 Ω or greater. The power source impedance should be sufficiently stiff that ripple voltage measured on the source side of the inductor/resistor combination is negligible with respect to the specification limit.

The test set-up for an a.c.-powered test article is shown in Figure A.7 c). In this set-up, the DSO input impedance should be 50 Ω. In addition, it may be necessary to reduce further the power frequency voltage waveform at the LISN port by high-pass filtering between the EMI port and the DSO 50-Ω input port. A filter which provides at least 40 dB of rejection at 400 Hz (increasing at lower frequencies) and negligible insertion loss above 100 kHz is diagrammed in Figure A.7 d). It is built into a metallic box with coaxial connectors to be inserted in line between the LISN EMI port and the DSO. Because the a.c. line voltage is attenuated and current limited by the LISN d.c. blocking capacitor, AWG 22 wire is sufficient to wind the inductor, and a 2,5-cm diameter ferrite core is suitable.



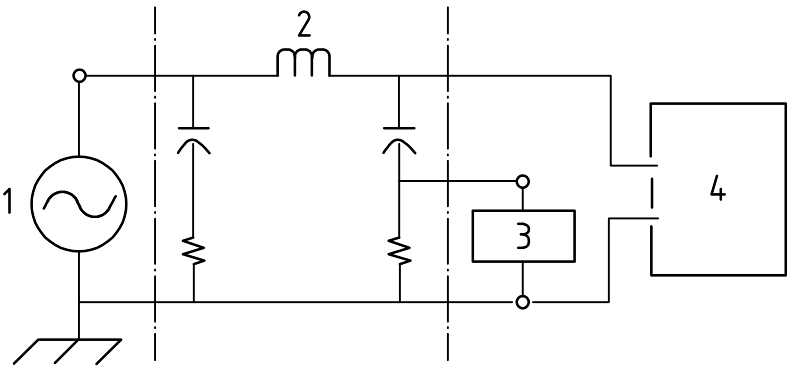
a) Choke winding



Key

1 d.c. power source
2 source impedance
3 DSO
4 test article
5 as required

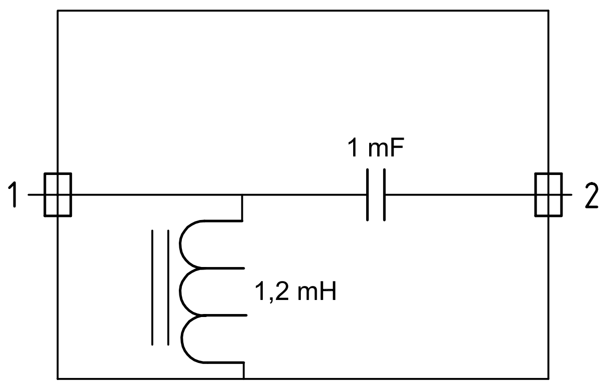
b) CE test set-up for d.c., time domain



Key

1 a.c. power source
2 LISN
3 DSO
4 test article

c) CE test set-up for a.c., time domain



Key

1 LISN EMI port
2 DSO 50-Ω input port

d) Power frequency rejection filter

Figure A.7 — Power bus load-induced time domain ripple equipment

A.3.3.6 Signal cable conducted interference, frequency domain

This test should be performed as a bulk current measurement, preferably 5 cm from the equipment under test. As a guide, the BCI test method should be used but do not install the injection probe. Only the measurement probe should be installed.

A.3.3.7 Antenna connection port spurious emissions

Transmitters should be protected from the damaging effects of transmitting into a high-voltage standing wave ratio load. A notch filter is required when testing a transmitter in transmit mode.

If excellent fidelity is observed in the selection and placement of antennas, then the limit may be expressed in terms of power received at the EMI meter rather than the effective field intensity, which is derived from the desired power at the receiver.

A.3.3.8 Magnetic field radiated emissions

Low-frequency magnetic emissions are measured with an electrostatically shielded loop antenna or an a.c. magnetometer. The sensor size depends on the loop to test article separation. For test separations of less than 10 cm, an air core loop should be 13 cm in diameter. Sensor diameter of a hand-held a.c. magnetometer should be no larger than 13 cm. The type of wire, number of turns, and magnetic material used should be such as to yield adequate measurement system sensitivity when connected to the EMI meter. Air core loops are inefficient at low frequencies and require very sensitive EMI receivers below 1 kHz. For larger sensor-test article separations, sensor size should simulate that of victim circuits.

A.3.3.9 Radiated electric field emissions

If the test bandwidth significantly differs (more than a factor of 1,5 difference) from victim bandwidth, narrowband/broadband discrimination may be required. The peak detector function should be used, except (in special circumstances) where separate narrowband/broadband discrimination is performed; in this case, narrowband data may be evaluated against the limit with an average detector. When trying to match the characteristics of the victim space system antenna during testing, the test antenna should match the polarization of the space system antenna. Also, to improve test quality, both polarizations, horizontal and vertical, should be used.

Table A.3 indicates test antennas that should be used for the protection of various types of spacecraft or payload attached antennas.

Table A.3 — Antenna selection guide

Victim antenna type	Test antenna type
Electrically short rod (*E*-field probe) 20 Hz to 10 kHz	104-cm rod or short dipole, actively matched
Electrically short rod (*E*-field probe) 10 kHz to 30 MHz	104-cm rod, active or passive
Wire-type antennas (quarter wave stub, dipole, Yagi, broadband dipole, log periodic), tuned or near tuned 20 MHz to 1 GHz	Dipole, biconical
Aperture antennas, typically horns and horn-fed dishes, used above 500 MHz	Double-ridge guide horns, standard gain horns, may use log periodic array to 1 GHz

A.3.3.10 Immunity to audio frequency power-line ripple

For this test, specification-level voltage should be measured across the input power terminals of the test article. The injected signal is unmodulated. Ripple generator impedance should be the greater of 0,5 Ω or the expected power source impedance at and below 1 500 Hz. The source impedance will increase with increasing frequency above 1 500 Hz. The requirement is met when either of the two following conditions prevails:

a) the test article functional performance is not degraded unacceptably when specification-level voltage appears across its input power terminals;

b) the test article functional performance is not degraded unacceptably when ripple generator injects that current, which it can deliver into load impedance at specification-level voltage, regardless of the voltage developed at the test article power input terminals.

NOTE If a stiff power source is not used, this test may degrade the power quality sufficiently to look as though the EUT is susceptible.

Modulated signals may also be used. Placement of a line-to-line capacitor across a power source aids in the development of voltage across the test article.

A.3.3.11 Immunity to power-line switching transients

The test procedure ISO 7137:1995, 3.3 (Section 17) requires a transformer-coupled series injection of the transient. This test method may need to be varied to reflect the actual source impedance and characteristics of the transients for a space system as given in the power quality specification. NASA H-29919D[12] is a good reference for transient immunity.

A.3.3.12 Immunity to the conducted effects of radiated electromagnetic fields

Attention should be paid to the insertion loss requirements of the chosen test standard. Power supplied to a BCI clamp in order to generate specification limit current flowing in a 50 Ω system may be calculated from insertion loss:

$$P = I_{\text{lim}} + I_L - 73$$

where

P is the desired power level, expressed in decibel times metres (dB·m);

I_{lim} is the specification limit, expressed in decibel times microamperes (dB·μA);

I_L is the BCI clamp insertion loss, expressed in decibels (dB).

It is this pre-calculated power, which should be applied to a BCI clamp and monitored. In addition, the actual injected current should be monitored via placement of a current probe around the cable under test. An over-current limit of 10 dB above the specification limit can be imposed in this fashion.

A.3.3.13 Immunity to audio frequency radiated magnetic fields

This is not a normally required test except on scientific spacecraft using magnetometers or on spacecraft using magnetic torquers.

The following equations allow calibration of the field in terms of current and physical dimensions, subject to the limitation that the coil diameters are electrically short and the potential developed across the coil is negligible (inductive reactance is small). Equation (1) applies to a Helmholtz coil, and Equation (2) applies to a hand-held coil.

$$B = \frac{8\mu NI}{125d} \tag{1}$$

$$B = \frac{\mu NId^2}{2\left(d^2 + r^2\right)^{3/2}} \tag{2}$$

where

B is the magnetic induction field, expressed in teslas (T);

μ is the permeability of free space and is equal to 4×10^{-7} H/m;

N is the number of turns;

I is the current, expressed in amperes (A);

d is the coil diameter, expressed in metres;

r is the distance along axis from loop, expressed in metres.

An important difference between the two coils is that the inside of a Helmholtz coil field is uniform, whereas the field drops off with distance from a hand-held loop. Furthermore, the hand-held loop expression is true only on the axis; field variation is complex at points not on the axis. A test performed in a Helmholtz coil is much more repeatable and provides a worse-case exposure, relative to the hand-held coil.

A.3.3.14 Immunity to radiated electromagnetic fields

Mode-tuned techniques should not be used unless the test article is static in time (no cyclic routines, only steady-state conditions). The mode-tuner should be stepped rather than continuously rotated. For large and complex test articles, mode tuning will likely save time in initially determining if susceptibilities occur. Initially, when the susceptibility is unknown, aspect angle uncertainty of test procedure ISO 7137-3.6 (Section 20.5) is high and may result in long test times for successive illuminations. Mode tuning may be a useful diagnostic technique as a precursor to the more formal and accurate technique of test procedure ISO 7137-3.6 (Section 20.5).

When trying to match the characteristics of the culprit space system antenna during testing, the test antenna should match the polarization of the space system antenna. Also, to improve test quality, both polarizations (e.g. horizontal and vertical) should be used because, in an under-damped test chamber, the polarization at the test article can be different from the test antenna polarization.

A.3.3.15 Immunity to magnetic fields induced signals to cabling

The transient portion of this test is sometimes performed by routing the wires containing the transient voltage parallel to the cables of the equipment under test.

A.3.3.16 Control of antenna port immunity to out-of-band interference

Verification techniques depend strongly upon the type of receiver being qualified. Mil-Std-461E CS03, CS04, CS05, and CS08 test methods may be used as a guide when qualifying traditional superheterodyne receivers.

A.3.3.17 Immunity to electrostatic discharge

Normally, manufacturer's handling procedures for equipment-level ESD protection are acceptable.

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[8] ANSI C95.1[2], *American national standard safety levels with respect to human exposure to radiofrequency electromagnetic fields, 300 kHz to 100 GHz,* Institute of Electrical and Electronics Engineers, Inc., 345 East 47th Street, New York, NY 10017

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[13] CISPR 22, *Information technology equipment — Radio disturbance characteristics — Limits and methods of measurement*

[14] IEC 60050-161, *International Electrotechnical Vocabulary. Chapter 161: Electromagnetic compatibility*

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1) In preparation.

2) Or other country's national standard. In case of conflict, national safety regulations prevail.

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