

Standard

Electromagnetic Compatibility Requirements for Space Equipment and Systems

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Standard

Electromagnetic Compatibility Requirements for Space Equipment and Systems

Sponsored by

American Institute of Aeronautics and Astronautics

Approved

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Abstract

This document, when followed in its entirety, will yield a robust electromagnetic capability design suitable for high-reliability space missions. This document specifies general design practices and sets recommended verification and validation requirements for space vehicles and launch vehicles.

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Foreword

This standard has been developed under the sponsorship of the Chief Engineer's office of the United States Air Force Space and Missile Systems Center (SMC) and under the auspices of the AIAA Electromagnetic Compatibility (EMC) Committee on Standards. It is one in a series of standards planned to codify industry best practices to ensure the very highest level of performance and reliability for the next generation of high-reliability space systems. It follows in the footsteps of MIL-STD-1541A, "Electromagnetic Compatibility Requirements for Space Systems and Equipment," but has been thoroughly updated to reflect current industry design practices.

The starting point for this document was "Electromagnetic Compatibility Requirements for Space Systems and Equipment," TOR 2005(8583)-1, 8 August 2005, developed by Mark W. Dunbar of the Electrical and Electronic Systems Engineering Department, Electronics Engineering Subdivision at The Aerospace Corporation. However, as a result of committee deliberations, this standard draws most of its content from MIL-STD-461F and MIL-STD-464A. Additional requirements deemed necessary for high-reliability space systems have been added by the committee.

The intent is to address approximately 80% of space systems. For missions that do not require all the provisions of this standard, or which may need additional requirements, it is understood that tailoring may be performed to balance performance, risk, and cost to suit the needs of a particular program.

The final product reflects the best EMC design and verification practices for high-reliability space systems.

At the time of approval, the members of the AIAA EMC Committee on Standards were:

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James Lukash, Co-Chair	Lockheed Martin
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The above consensus body approved this document in September 2009.

The AIAA Standards Executive Council (Mr. Amr El Sawy, Chairman) accepted the document for publication in October 2009.

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1 Scope

This standard is applicable for the procurement of space systems, including spacecraft, space vehicles, launch vehicles, ground systems, and associated equipment/subsystems.

This standard establishes performance and verification requirements for the purpose of ensuring space systems electromagnetic compatibility (EMC), including all electromagnetic environmental effects. Engineering issues that must be addressed in order to achieve system-level EMC are identified herein, with guidance and rationale toward achieving specification compliance.

2 Tailoring

When viewed from the perspective of a specific program or project context, the requirements defined in this standard may be tailored to match the actual requirements of the particular program or project. Tailoring of requirements shall be undertaken in consultation with the procuring agency where applicable.

NOTE Tailoring is a process by which individual requirements or specifications, standards, and related documents are evaluated and made applicable to a specific program or project by selection, and in some exceptional cases, modification and addition of requirements in the standards.

3 Applicable Documents

The following documents contain provisions that, through reference in this text, constitute provisions of this standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies.

AFSPCMAN 9-710, Vol. 3	<i>Range Safety User Requirements Manual, Volume 3 – Launch Vehicles, Payload, and Ground Support Systems Requirements</i>
AFSC DH 1-4 (4 th Ed, Rev 1)	<i>AFSC Design Handbook 1-4</i>
AIAA S-113-2005	<i>Criteria for Explosive Systems and Devices on Space Launch Vehicles</i>
ANSI/IEEE C95.1-2005	<i>Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz</i>
JSC-28596 (2000)	<i>NASA Standard Initiator User's Guide</i>
MIL-HDBK-83575 (1998)	<i>General Handbook for Space Vehicle Wiring Harness Design and Testing</i>
MIL-STD-331C	<i>Fuse and Fuse Components Environmental and Performance Tests</i>
MIL-STD-461F	<i>Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment</i>
MIL-STD-464A	<i>Electromagnetic Environmental Effects Requirements for Systems</i>
MIL-STD-889B	<i>Dissimilar Metals</i>
MIL-STD-1576 Valid Notice 1	<i>Electroexplosive Subsystem Safety Requirements and Test Methods for Space Systems</i>

4 Vocabulary

4.1 Acronyms and Abbreviated Terms

A	Ampere
AC	Alternating current
AIAA	American Institute of Aeronautics and Astronautics
ANSI	American National Standards Institute
CE	Conducted emissions
CM	Common mode
cm	Centimeter
CRES	Corrosion resistant steel
CS	Conducted susceptibility
CSV	Comma separated value(s), comma separated variable(s)
CW	Continuous wave
dB	Decibel
dB μ A	Decibel referenced to one microamp
dB μ V	Decibel referenced to one microvolt
DC	Direct current
DoD	Department of Defense
DoDD	Department of Defense Directive
E3	Electromagnetic environmental effects
EED	Electrical explosive device
EGSE	Electrical ground support equipment
EID	Electrically initiated device
EMC	Electromagnetic compatibility
EME	Electromagnetic environment
EMI	Electromagnetic interference
EMISM	Electromagnetic interference safety margin
EMP	Electromagnetic pulse
EMV	Electromagnetic vulnerability
ESD	Electrostatic discharge

EUT	Equipment under test
f_0	Tuned frequency
GFE	Government furnished equipment
GHz	Gigahertz
GPI	Ground plane interference
GPS	Global Positioning System
HERF	Hazard of electromagnetic radiation to fuel
HERO	Hazard of electromagnetic radiation to ordnance
HERP	Hazard of electromagnetic radiation to personnel
IF	Intermediate frequency
I&T	Integration and test
kHz	Kilohertz
LISN	Line Impedance Stabilization Network
LV	Launch vehicle
MHz	Megahertz
mA	Milliamp
mV	Millivolt
NASA	National Aeronautics and Space Administration
NDI	Non-developmental Items
NTIA	National Telecommunication and Information Administration
PRD	Program Requirements Document
pps	Pulses per second
p-static	Precipitation static
RE	Radiated emissions
RF	Radio frequency
RFI	Radio frequency interference
RRD	Range Requirements Document
RS	Radiated susceptibility
RSS	Root-sum-square
RMS, rms	Root-mean-square
SV	Space vehicle
TOR	Technical Operating Report

μF	Microfarad
μH	Microhenry
μs	Microsecond
V_{ac}	Volts alternating current
V_{dc}	Volts direct current
V_{rms}	Root-mean-square of voltage
XFMR	Transformer

4.2 Terms and Definitions

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

Critical circuits

circuits that can impact the ability to complete the mission, cause injury, or cause loss of life or property if function is lost or degraded

Electromagnetic Compatibility Criticality Categories

descriptions of worst-case potential criticality of the effects of interference-induced anomalies to dictate electromagnetic interference safety margins for system and equipment designs

NOTE This document uses:

Category I: Serious injury or loss of life, damage to property, or major loss or delay of mission capability or any autonomous actions that lead to loss or delay of mission capability

Category II: Degradation of mission capability, including any loss of autonomous operational capability

Category III: Loss of functions not essential to mission

Electrically Initiated Devices (EIDs)

single unit, device, or subassembly that uses electrical energy to produce a non-reversible explosive, pyrotechnic, thermal, or mechanical output

EXAMPLES electroexplosive devices (EED) (such as hot bridgewire, semiconductor bridge, carbon bridge, and conductive composition), exploding foil initiators, laser initiators, burn wires, fusible links, wax pellets, non-explosive initiators, or solenoids

Electromagnetic Compatibility (EMC)

capability of a space system, etc., to perform its mission without degradation due to electromagnetic interference between equipment and subsystems

Electromagnetic Environmental Effects (E3)

impact of the electromagnetic environment (EME) upon the operational capability of systems, subsystems, and equipment

NOTE Encompasses all electromagnetic disciplines, including electromagnetic compatibility; electromagnetic interference; electromagnetic vulnerability; electromagnetic pulse; hazards of electromagnetic radiation to personnel, ordnance, and volatile materials; and natural phenomena effects of lightning, p-static, and space system charging.

Electromagnetic Interference (EMI)

degradation of equipment/subsystem performance due to unintentional electromagnetic interaction with another part of the space system

Electromagnetic susceptibility

undesirable unit level response to external electromagnetic stimulus such as external radiated fields

Electromagnetic Vulnerability (EMV)

adverse system response to external electromagnetic stimulus such as external radiated fields

Equipment/subsystem

electrical, electronic, or electromechanical device or integration of such devices intended to operate as an individual unit to perform a specific set of functions

NOTE May consist of several interconnected equipments.

Intrasystem

interaction between two different subsystems or between equipment of different subsystems that are all part of the same space system, etc.

EXAMPLE uncommanded operation of a flight control subsystem due to a radio frequency transmission originating on the same space system

Multipaction

radio frequency (RF) resonance effect occurring only in a high vacuum where RF field accelerates free electrons resulting in collisions with surfaces creating secondary electrons that are accelerated resulting in more electrons and ultimately a major discharge and possible equipment damage

NOTE Definition taken from MIL-STD-464A (3.12).

Radio Frequency Interference (RFI)

interference from radio reception

NOTE RFI is a subset of the more general term EMI.

Safety margin

margin between noise induced in a circuit under all possible modes of operation and the normal (desired) signal level

Spacecraft

an assemblage of subsystems and components making up a satellite bus (i.e., space vehicle without the payload)

Space vehicle

an integrated assembly of spacecraft and payload/s

System

suite of equipment, subsystems, skills, and techniques capable of performing or supporting an operational role

NOTE A system includes all 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.

5 General Requirements

The system shall be electromagnetically compatible among all subsystems and equipment within the system and with environments caused by electromagnetic effects external to the system. Verification shall be accomplished as specified herein on actual flight hardware or representative systems, in flight representative configurations, and operational modes. Safety-critical functions shall be verified to be electromagnetically compatible within the system and with external environments prior to use in those environments.

Verification shall address all life-cycle aspects of the system, including (as applicable) normal in-service operation, checkout, storage, transportation, handling, packaging, loading, unloading, launch, and the normal operating procedures associated with each aspect.

5.1 System

The space vehicle and launch vehicle shall be designed to achieve electromagnetic compatibility (EMC) among all equipments/subsystems within the space vehicle/launch vehicle and with the self-induced and external electromagnetic environment. For all system-level tests, a “test as you fly” philosophy shall be followed. See Annex A for further details.

5.2 Units and Subsystems

Each equipment/subsystem shall operate without performance degradation during concurrent operation of any combination of the remaining equipment/subsystems, subject to mission requirements.

5.3 Ground Equipment

Ground equipment shall operate without performance degradation in its intended operating environment and shall not cause interference to other equipment. Space vehicle and launch vehicle electrical ground support equipment (EGSE) shall be designed such that it will not produce interfering emissions or be susceptible to the factory, the processing facility, and launch-site test environment; the interfacing space vehicle/launch vehicle, subsystems, components, or science instruments. Coordination with range safety is required.

5.4 Limits

All limits in this document are RMS (root-mean-square) unless otherwise indicated. Limits labeled in decibels (e.g., dBμV) refer to RMS equivalent of the peak of the modulation envelope.

6 Detailed Requirements—System

6.1 EMI Safety Margins (EMISMs)

6.1.1 Purpose

The purpose of these requirements is to ensure the intrasystem and intersystem EMC of space systems over their entire service lives.

6.1.2 Applicability

This requirement applies at the system level. This includes, but is not limited to, intrasystem-conducted interfaces, intrasystem unintentional radiated interfaces, intrasystem intentional radiated interfaces (antenna-connected equipment), intersystem radiated interfaces (external RF environment), and EIDs. General applicability is also provided in Table 1 and Sections 6.2.5, 6.2.5.1, and 6.2.5.2.

6.1.3 Basic Requirement

All systems and subsystems shall have EMISMs as given in Table 1.

Table 1 — EMI safety margins

Applicability	Test	Analysis ^a
Category I or II critical circuits (reference Section 4.2)	6 dB	12 dB
EID interfaces, RF level referenced to DC no-fire level ^b	20 dB ^b	20 dB ^b
EID interfaces, RF level referenced to RF no-fire level ^{c,d}	12 dB	12 dB
All other equipment, subsystems and systems, including Category III critical circuits	0 dB	0 dB
^a When verification is based only on analysis, the procuring agency will define the acceptable level of EMISM required and approve the analysis method that is used. ^b MIL-STD-1576, para. 4.4.1a; JSC-28596A, para. 11.0a; AFSPCMAN 9-710 Vol. 3, para. 13.3.1.6; AIAA S-113-2005, paras. 5.3.4.2.4, 5.3.5.3, 5.3.5.4, 5.3.5.5 ^c Thresholds from JSC-28596A or measured values based on Military Standard Methodology shall be used. ^d Method 4303, MIL-STD-1576, FB-2210 Monograph on Computation of RF Hazards, July 1968, is an acceptable method. Results greater than 0 dBs using this method are acceptable, as described in the monograph.		

6.2 Intrasystem Electromagnetic Compatibility

The system shall be electromagnetically compatible within itself such that system operational performance requirements are met. Compliance shall be verified by system-level test, analysis, or a combination thereof.

Antenna-to-antenna compatibility shall be demonstrated by a system level test, analysis, or a combination thereof.

6.2.1 Passive Intermodulation (PIM)

Space vehicle design shall ensure that RF transmissions from on-board or external transmitters, when incident on the platform, do not result in unintentional signals as a result of PIM, which can interfere with on-board receivers. Compliance shall be verified by system-level test, analysis, or a combination thereof.

6.2.2 Multipaction

Space and launch vehicle equipment and subsystems shall be free of multipaction effects. Compliance shall be verified by test and analysis.

6.2.3 Deployment, Staging, and Separation Events

Space vehicle and launch vehicles that experience deployment, staging, separation, or docking event(s) shall verify compatibility. A test or demonstration of compatibility before, during, and after the deployment, staging, separation, or docking event is the preferred verification method, when practicable.

6.2.4 Plugs-Out Test

Space vehicles and launch vehicles shall verify compatibility with all electrical umbilicals disconnected from the space vehicle or launch vehicle. RF links, air conditioning, cooling, and other connections are allowed. A safety ground strap to facility ground is allowed to preclude electric shock hazard to personnel. See Annex A for guidance on the application of the safety ground.

6.2.5 Demonstration of Receiver Safety Margin

Various types of on-board receivers perform critical functions on many space vehicles. Proper operation (6 dB safety margin) of the receivers installed on a fully integrated space vehicle shall be verified in a credible manner. Verification by test may be performed either at the RF front end, or at the base band output, depending upon which technique works best for the program.

6.2.5.1 RF Front-End Margin Assessment

The transmission line from the antenna may be disconnected at the space vehicle receiver, and connected instead to an EMI receiver system (via a calibrated cable) that has greater than or equal sensitivity, compared to the space vehicle receiver. The level of RFI coupled from the intentional and unintentional emissions of the space vehicle may then be analytically compared to the lowest level of RF signal predicted for the up-link transmission.

6.2.5.2 Base Band Margin Assessment

In this technique, the critical space vehicle receiver system is completely undisturbed. A simulated up-link transmission is established with an RF field intensity at the space vehicle antenna that is 6 dB below that expected from the worst-case level received during the mission. Margin has been demonstrated if the simulated signal (with an input level 6 dB below the worst-case on-orbit level) is properly received and acted upon by the space vehicle receiver. In some cases, there may not be adequate receiver sensitivity to perform this test, and the RF front-end margin assessment should be an alternate choice.

6.3 External Electromagnetic Environment

To ensure that system operational performance requirements are met and system safety is preserved, space and launch vehicle systems shall be electromagnetically compatible with their anticipated radiated RF environment.

The anticipated radiated RF environment shall be determined by analysis or by direct measurement, and shall be defined throughout the life cycle of the space or launch vehicle system. As a minimum, this includes the integration, transportation, launch-site integration, launch, and orbital operations. Anticipated sources shall include external sources, such as ground-based radar systems, and internal sources, such as vehicle-mounted transmitters. The operational status of the space vehicle and launch vehicle during system verification using a simulated RF environment shall replicate operational scenarios (e.g., survival, without damage in an "off" state; operational, without malfunction in "on" state, or a combination that reflects intended usage).

System shielding shall be used to calculate verification field levels only if test or analytical data are available and that data are acceptable to the procuring agency. Shielding effectiveness of fairings or other physical structures shall be assumed to be 0 dB unless there is acceptable test or analytical data available on the specific structure used for a specific mission.

Verification shall be performed by test or by analysis. Verification by analysis requires appropriate supporting unit/subsystem test data and approval by the procuring agency.

Specific radiated RF environments should be supplied by the procuring agency. If an environment is not supplied, or if none is available, the levels provided in Tables 2 and 3 shall be used. Appropriate consideration shall be given to system capabilities before flight hardware is exposed to the environmental levels specified herein, including, but not limited to, a potential for damage to RF receivers. Test levels or methods may be modified to reduce system damage as long as the predicted RF environment is maintained and if accepted by the procuring agency.

Table 2 — Ground operations through launch and SV/LV separation

Frequency	Environment Level V/m (Peak)	Modulation
2 MHz to 18 GHz	20	Pulse Modulated (on/off ratio of 40 dB minimum) 1 kHz rate with a 50% duty cycle
18 GHz to 40 GHz (required only if specified in the procurement spec)	20	CW (no modulation)
2.0 GHz to 2.5 GHz	100	CW (no modulation)
5.4 GHz to 5.9 GHz	100	Pulse Modulated (on/off ratio of 40 dB minimum) 1 kHz rate with a 1 μ s pulse width
NOTE 1 Pre-launch includes integration and test (I&T) and transportation to the launch facility.		
NOTE 2 The pre-launch RF environment requires coordination with the range, (e.g., Program Requirements Document (PRD), Range Requirements Document (RRD), etc.); levels at some ranges may be higher than shown here.		

Table 3 — On-orbit

Frequency	Environment Level V/m (Peak)	Modulation
2 MHz to 18 GHz	20	Pulse Modulated (on/off ratio of 40 dB minimum) 1 kHz rate with a 50% duty cycle
18 GHz to 40 GHz (required only if specified in the procurement spec)	20	Pulse Modulated (on/off ratio of 40 dB minimum) 1 kHz rate with a 50% duty cycle
2 GHz to 4 GHz	50	Pulse Modulated (1 μ s pulse width, 1 kHz rate)
5.5 GHz to 5.9 GHz	50	Pulse Modulated (1 μ s pulse width, 1 kHz rate)

6.3.1 Electrical Ground Support Equipment (EGSE)

The anticipated RF environment for EGSE shall be determined by analysis or by direct measurement, and shall include levels experienced during system integration and test, transportation, and launch-site integration. It shall be the contractor's responsibility to ensure that EGSE will operate as intended in the anticipated environment.

6.4 Lightning

Immunity from indirect effects of lightning shall be shown based on the protective measures at the launch site and a lightning attachment near to the protection system. This requirement applies only to the pre-

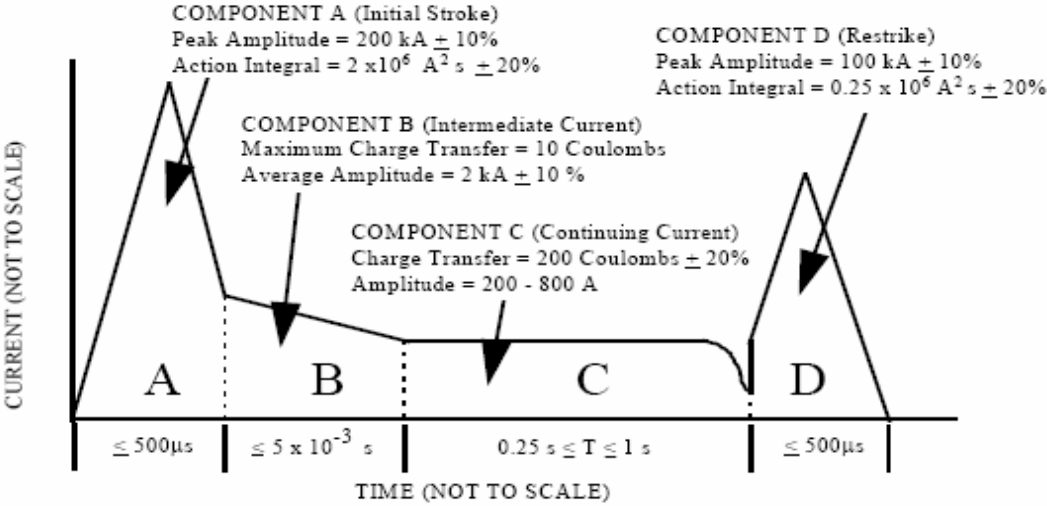
launch configuration; it does not apply to flight. Verification shall be by inspection, demonstration, analysis, test, or a combination thereof.

If the site has a system to detect lightning-induced fields and/or currents, those data shall be used to assess SV and LV damage to lightning.

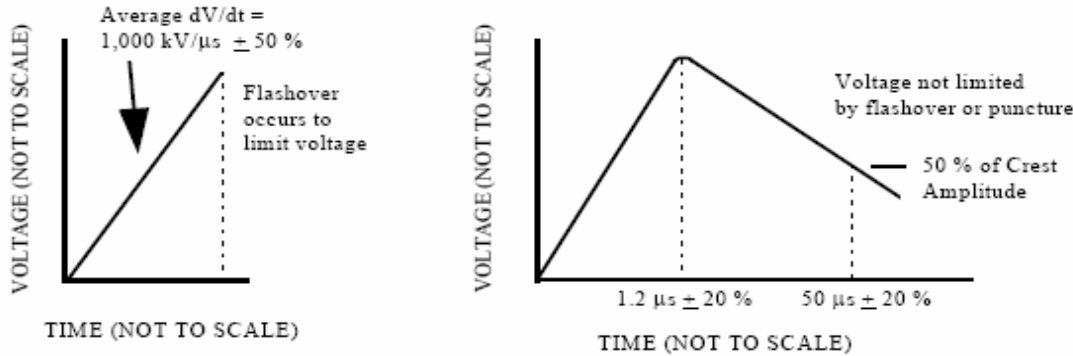
Actual levels coupled to equipment are configuration- and site-dependent and should be evaluated to determine damage levels and retest criteria for the SV and LV in the event of a direct strike to the launch pad, its lightning protection system (if present), or other nearby strikes. The source current and waveforms describing the lightning event are described in Table 4 and Figures 1 and 2.

Table 4 — Lightning stroke waveform parameters

Current Component	Description	$i(t) = I_0 (\epsilon^{-\alpha t} - \epsilon^{-\beta t})$ (t is time in seconds)		
		I_0 (A)	α (s ⁻¹)	β (s ⁻¹)
A	Severe stroke	218,810	11,354	647,265
B	Intermediate current	11,300	700	2,000
C	Continuing current	400 for 0.5 s	Not applicable	Not applicable
D	Restrike	109,405	22,708	1,294,530
D/2	Multiple stroke	54,703	22,708	1,294,530
H	Multiple burst	10,572	187,191	19,105,100



ELECTRICAL CURRENT WAVEFORMS



ELECTRICAL VOLTAGE WAVEFORMS

Figure 1 — Lightning direct effects environment

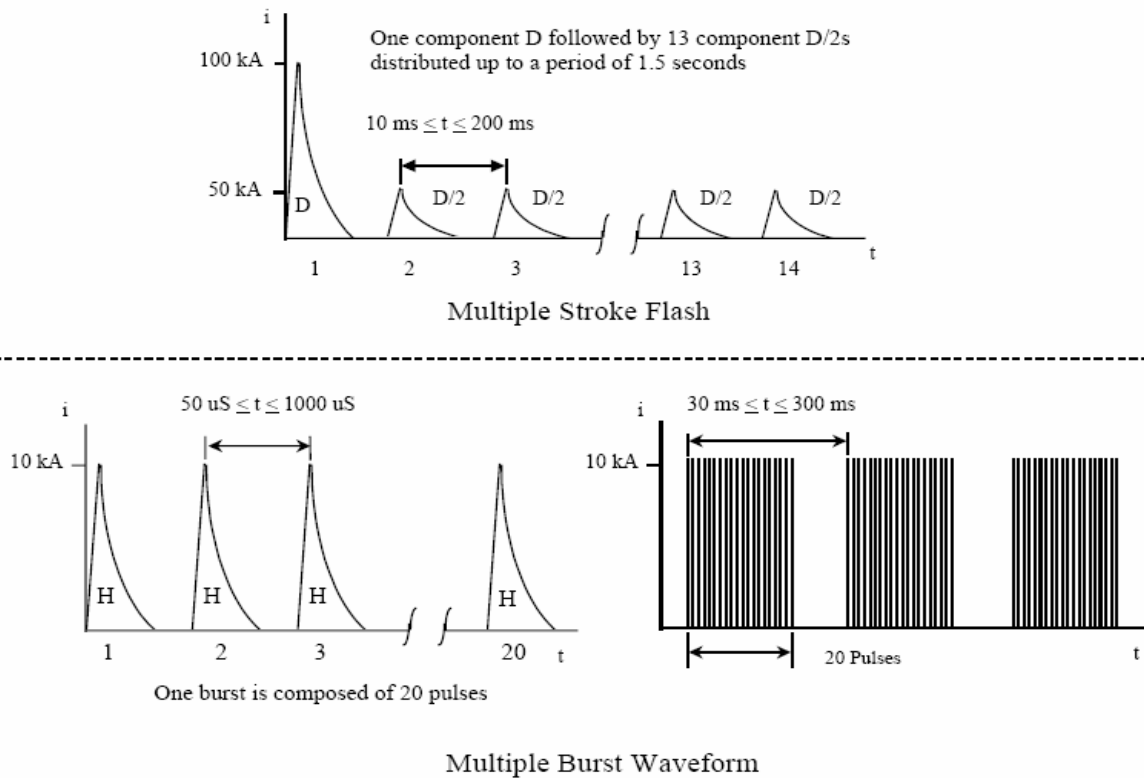


Figure 2 — Lightning indirect effects environment

6.5 Electromagnetic Pulse (EMP)

The procuring agency may impose EMP requirements. This requirement is beyond the scope of this document, and the contractor shall work with the procuring agency to define the requirements and verification. If applicable, the system shall meet its operational performance requirements after being subjected to the EMP environment. Compliance shall be verified by system-, subsystem-, and equipment-level tests, analysis, or a combination thereof.

6.6 Subsystems and Equipment Electromagnetic Interference (EMI)

Individual subsystems and equipment shall meet interference control requirements (such as the conducted emissions, radiated emissions, conducted susceptibility, and radiated susceptibility requirements of Section 8 of this standard) so that the overall system complies with all applicable requirements of this standard. Compliance shall be verified by tests that are consistent with the individual requirement (such as testing in accordance with Section 8 of this standard). Because space systems vary widely in mission and equipment complement, the equipment-level requirements and test methods may often be profitably tailored so as to minimize the cost and schedule impact of EMC design.

6.7 Non-Developmental Items (NDI), Government Furnished Equipment (GFE), and Commercial Items

NDI, GFE, and commercial items shall meet EMI control requirements suitable for ensuring that system operational performance requirements are met. Compliance shall be verified by test, analysis, or a combination thereof.

6.8 Magnetic Field Environment

Subsystems and equipment used aboard space vehicles shall not be degraded when exposed to external or internal AC or DC magnetic sources in the operational environment. Subsystems and equipment used aboard space vehicles shall not contribute AC or DC magnetic field emissions beyond limits required by the platform. Compliance shall be verified by test, analysis, or a combination thereof.

6.8.1 Magnetic Dipole Moment

Magnetic dipole moment shall be limited as required by the platform. Compliance shall be verified by test, analysis, or a combination thereof.

6.9 Electrostatic Charge Control

To protect personnel from shock hazards, and to prevent performance degradation or damage to electronics, subsystems, or equipment, the system shall control and dissipate the build-up of electrostatic charges caused by precipitation static (p-static) effects, fluid flow, air flow, exhaust gas flow, personnel charging, charging of LV (including pre-launch conditions) and SV (in the energetic space plasma environments), and other charge-generating mechanisms to avoid fuel ignition and ordnance hazards. Compliance shall be verified by test, analysis, inspections, or a combination thereof.

6.9.1 Triboelectric Charging

The system shall control triboelectric charging, including p-static interference to antenna-connected receivers and other systems onboard the SV or LV, such that system operational performance requirements are met. The system shall protect against puncture of structural materials and finishes and shock hazards from charge accumulation. Compliance shall be verified by test, analysis, inspection, or a combination thereof.

6.9.2 Electro-Explosive Devices (EED)

Electro explosive devices shall not be inadvertently initiated or dudged by a 25 kV electrostatic discharge caused by personnel handling. Compliance shall be verified by test (such as MIL-STD-331), discharging a 500 PF capacitor through a 500 Ω resistor to the EED (pin-to-pin and pin-to-case).

6.10 Electromagnetic Radiation Hazards (EMRADHAZ)

The system design shall protect personnel, fuels, and ordnance from hazardous effects of electromagnetic radiation. Compliance shall be verified by test, analysis, inspection, or a combination thereof.

6.10.1 Hazards of Electromagnetic Radiation to Personnel (HERP)

For man-rated systems only, the system-designed exposure to personnel shall comply with ANSI/IEEE C95.1. Compliance shall be verified by test, analysis, or a combination thereof.

6.10.2 Hazards of Electromagnetic Radiation to Fuel (HERF)

Fuels shall not be inadvertently ignited by radiated EMEs. The EME includes onboard emitters and the external EME (see Section 6.3). Compliance shall be verified by test, analysis, inspection, or a combination thereof.

6.10.3 Hazards of Electromagnetic Radiation to Ordnance (HERO)

Ordnance shall not be inadvertently initiated or dudged by radiated EME. The EME includes onboard emitters and the external EME (see MIL-STD-464A, Section 5.3). Compliance shall be verified by test, analysis, inspection, or a combination thereof. Inspection alone is inadequate.

6.11 Life Cycle, E3 Hardness

The system operational E3 performance will consider the rated life-cycle of the system, and shall include, but not be limited to, the following: degradation, maintenance, repair, surveillance, and corrosion control. Further guidance can be found in Annex A. No formal verification is required.

6.12 Electrical Bonding

Electrical bonding measures shall be implemented for management of electrical current paths and control of voltage potentials to ensure required space system performance and to protect both personnel and platform. Bonding provisions shall be compatible with other requirements imposed on the space system for corrosion control. Compliance shall be verified by test, analysis, inspection, or a combination thereof, for the particular bonding provision.

6.12.1 Power Current Return Path

For the electrical power sources of systems using structure for power return currents, bonding provisions shall be provided for current return paths such that the total voltage drops between the point of regulation for the power system and the electrical loads are within the tolerances of the applicable power quality standard. Compliance shall be verified by analysis of electrical current paths, electrical current levels, and bonding impedance control levels.

6.12.2 Antenna Installations

Antenna structures relying on a counterpoise connected to (or implemented on) space system 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. Compliance shall be verified by test, analysis, inspection, or a combination thereof.

A low impedance bond prevents space system structure RF currents from inducing noise potentials across the counterpoise.

For instances in which the procuring agency has approved that specific controls are not established for a system, the following DC bonding levels shall apply throughout the life of the system:

- a) 10 mΩ or less from the equipment enclosure to system structure, including the cumulative effect of all faying surface interfaces;
- b) 15 mΩ or less from cable shields to the equipment enclosure, including the cumulative effect of all connector and accessory interfaces; and
- c) 2.5 mΩ or less across individual faying interfaces within the equipment, such as between subassemblies or sections.

Compliance shall be verified by test, analysis, inspection, or a combination thereof.

6.12.3 Prevention of 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 less than 30 V_{dc} or 10 V_{ac} between item and ground subsystem. However, as a minimum, in order to clear faults or provide against accidental discharge of fault current to ground through a fortuitous conductor, all exposed conductive items, which could become charged due to an electrical fault condition, shall be bonded to the ground subsystem. Bond magnitude shall provide enough current to clear the fault by tripping a circuit protection device. Verification shall be by inspection or measurement.

6.12.4 Control of RF Potentials

All electronic and electrical items with the capability to respond to electromagnetic energy shall be bonded to the ground subsystem with a faying surface bond of DC resistance of 2.5 mΩ or less for metallic interfaces. Where composite materials are used, bonding shall be accomplished at impedance levels consistent with the materials in use. Verification shall be by measurement.

6.12.5 Bonding for Static Control

Isolated conducting items subject to frictional charging shall be bonded to the ground subsystem in order to avoid a differential build-up of charge that would result in an electrostatic discharge. Compliance shall be verified by test, analysis, or a combination thereof.

6.12.6 Bonding in Explosive Atmospheres

Conducting elements in the vicinity of explosive or flammable materials shall be bonded to the ground subsystem such that arcing due to fault currents and lightning currents and/or induced heat rise from these events is insufficient to cause ignition of the flammable substance. Compliance shall be verified by test, analysis, or a combination thereof.

6.12.7 External Grounds

For the purpose of preventing shock, and/or inadvertent ignition of ordnance, fuel, and flammable vapors damaging to hardware or personnel, the system, and associated subsystems, shall provide external grounding provisions to control electrical current flow and static charging. Compliance shall be verified by test, analysis, inspections, or a combination thereof.

6.12.8 Servicing and Maintenance Equipment Grounds

Servicing and maintenance equipment shall have a permanently attached grounding wire suitable for connection to earth ground. All servicing equipment used to handle or process flammable fuels, fluids, explosives, oxygen, or other potentially hazardous materials shall have a permanently attached grounding wire for connection to the system. Compliance shall be verified by inspection.

6.13 TEMPEST

Emanations from classified information processing equipment shall not compromise U.S. national security. Compliance shall be verified by test, analysis, inspection, or a combination thereof.

6.14 EM Spectrum Compatibility

Systems, subsystems, and equipment shall comply with the DoD, national, and international regulations for the use of the electromagnetic spectrum (such as NTIA "Manual of Regulations and Procedures) as appropriate for the equipment development stage.

6.15 System Circuit and Structure Reference

The system electrical return network shall be designed to ensure the system is self-compatible. A detailed description of the return network design shall be documented and maintained in the program documentation system. The description shall consist of a system-level schematic of return referencing, including structure. That schematic shall be such that the chassis reference for each circuit can be determined in conjunction with unit or subsystem schematics and assemblies. Compliance shall be verified by inspection.

6.16 Return Current Control

Return currents shall be controlled in the system structure such that system performance is achieved.

6.17 Wiring

Wire categorization, separation, and shielding shall be addressed in the design. MIL-HDBK-83575 shall be used if no other categorization and separation guidance is available.

6.18 Material Properties

Material properties should be considered in the design of surface coatings, thermal blankets, and dielectrics to facilitate electrostatic control. Material properties of surface coatings and of dissimilar metals also should be considered when designing electrical bond interfaces. Whereas corrosion will result in degraded electrical bonds, surface coatings used to prevent corrosion may inhibit good electrical bonding. Use of Mu-metals, special metal alloys with a high permeability used for magnetic shielding, may require special attention, to avoid permanent magnetization that will affect magnetic dipole moment.

6.19 Data Formats

For new designs or tests, it is preferred that test data be made available in tabular electronic form in addition to emission plots, i.e., comma separated values (CSV) format.

6.20 Tailoring Guidance for Contractual Application

Application-specific criteria may be derived from operational and engineering analyses on the system being procured for use in specific environments. When analyses reveal that a requirement in this standard is not appropriate or adequate for that procurement, the requirement should be tailored and incorporated into the appropriate documentation. Annex A provides tailoring guidance.

7 General Requirements—Units and Subsystems

The requirements of MIL-STD-461F, Section 4, shall apply, except as modified below. The changes are summarized in Table 5.

Table 5 — Exceptions to MIL-STD-461F Section 4

MIL-STD-461F Section 4 Paragraph	Reason for Exception
4.2.2 Filtering (Navy Only)	Not applicable to spacecraft or launch vehicles.
4.2.4 Non-Developmental Items (NDI)	Modify as follows: Requirements of this standard shall be met when applicable and warranted by the intended installation and platform requirements.
4.2.4.1.1 Selected by contractor	Modify as follows: When it is demonstrated that a commercial item selected by the contractor is responsible for the system failing to meet the contractual system level EMI requirements, either the commercial item shall be modified or replaced or interference-suppression measures shall be employed, so that the equipment or subsystems meet the contractual EMI requirements.
4.2.4.2 Procurement of equipment or subsystems having met other EMI requirements	Not applicable (addressed in system-level requirements section, paragraph 6.7).
4.2.5 Government Furnished Equipment (GFE)	Not applicable (addressed in system-level requirements section, paragraph 6.7).
4.2.6 Switching Transients	Not applicable as written. MIL-STD-461F does not control single-event switching transients, whereas this standard does. The switching transient requirements may be found in paragraph 8.7 of the box level requirements section.
4.3.1 Measurement Tolerances	Applicable with following modification: investigation of non-compliances may require frequency tolerances much smaller than 2%.
4.3.4 Ambient Electromagnetic Level	Applicable with the following modification: ambient test measurements shall be included as part of the EMI test report.
4.3.6 Power Source Impedance	See full discussion in paragraph 7.9.
4.3.8.6.2 Input power leads	Amend paragraph 4.3.8.6.2 as follows: "The length of primary power cable from the LISN to the EUT shall be one meter instead of the MIL-STD-461F 2 - 2.5 meters. Further, it shall not be shielded, unless the installation's power cabling is shielded from the power source to the unit.
4.3.9.3 Susceptibility monitoring	A suitable method of monitoring each performance parameter necessary to qualify the equipment shall be employed to detect the threshold(s) of susceptibility if or when exceeded. This may be provided by a built-in-test function or other indication to monitor the EUT performance, preferably in real-time. Prior to the start of each susceptibility test, the pass/fail criteria shall be predetermined, and the course of action to follow, should susceptibility occur, shall also be predetermined. This will involve coordination of the E3 staff of the EUT supplier and the procuring agency.
4.3.10.1 Detector	Applicable. Note, see guidance in Annex regarding testing in notched limit bands.
4.3.10.2 Computer-controlled instrumentation	Paragraph 4.3.10.2 is modified as follows: A summary of all pertinent EMI receiver settings directed by software for computer controlled receivers shall be included with all emissions graphs. As a minimum the following information shall be included, Start Frequency, Stop Frequency, Step Width, Detector, Measurement Dwell time, I.F. Bandwidth and transducer description/nomenclature.
4.3.10.3.1 Bandwidths	In addition to the MIL-STD-461F required bandwidths and detector, as defined in MIL-STD-461F paragraphs 4.3.10.1 and 4.3.10.3.1, additional

MIL-STD-461F Section 4 Paragraph	Reason for Exception
	bandwidths and detectors may be required on a program-specific basis. In frequency bands where the limit has been specifically tailored to protect a platform receiver, the measurement will need to be performed twice. One measurement will use the MIL-STD-461F paragraph 4.3.10.1 and 4.3.10.3.1 detector and bandwidth, and that measurement must meet the nominal (untailored) limit in that band. A second measurement shall use a bandwidth commensurate with that of the protected receiver, as identified by the procuring agency. That measurement must meet the tailored limit in that band. At the procuring agency's discretion, the detector used to measure against the tailored limit may be different from the default peak detection of MIL-STD-461F paragraph 4.3.10.1.
4.3.10.3.2 Emission identification	Modify to read as follows: Identification of emissions with regard to narrowband or broadband categorization is not applicable.
4.3.10.3.3 Frequency scanning	Paragraph 4.3.10.3.3 of MIL-STD-461F is modified as follows: The analyzer/receiver is allowed to sweep as fast as possible while still making a calibrated measurement, with the analyzer/receiver in max hold mode, and constantly scanning for a period of time equal to that prescribed for a single scan in MIL-STD-461F paragraph 4.3.10.3.3.
4.3.10.3.4 Emission data presentation	Paragraph 4.3.10.3.4 is appended as follows: Additional resolution may be required in limit notches. Outages recorded in notched bands are required to be recorded and presented with the same or better resolution than the bandwidth specified for the measurement of the notch.
4.3.10.4.1 Frequency scanning	See paragraph 7.17 and Table 6.
4.3.10.4.3 Thresholds of susceptibility	Should a EUT fail to meet its susceptibility requirements at the full test level, the threshold(s) of susceptibility shall be determined in accordance with MIL-STD-461 procedures. In the event the supplier proposes to deliver the EUT as prototype flight equipment without further modification and re-test, sufficient test data shall be gathered to support the processing of a waiver using the program's established process. Unless deemed different by the procuring agency (see 4.3.9.3), the information below shall be provided: Onset of susceptibility defined as degradation in one or more EUT performance parameters beyond product specification limits or levels. EUT transition from soft upset (EUT returns to normal operation upon removal of the immunity stimulus) to hard upset (operator intervention required to reset to normal operation after removal of immunity stimulus), should it occur at or below the full required susceptibility test level. Description of degradation of performance with full test level applied. If very sensitive technologies in the EUT result in unavoidable low levels of susceptibility (cannot shield large optical aperture, for example), application of this additional reporting requirement shall be explicitly obtained from the procuring agency (where further modification is not possible to improve immunity) to avoid possible damage of the EUT as flight hardware.
4.3.11 Calibration of measuring equipment	Modify to include ISO/IEC-17025 as an acceptable calibration standard.