Chapter 15

Electromagnetic Interference and Compatibility

15.1 Introduction

All spacecraft systems are required to be compatible with the electromagnetic interference expected from internal and external sources. For decades, the electromagnetic interference (EMI) and electromagnetic compability (EMC) requirements have come from MIL-STD-461. It specified the maximum emission limit of the potential culprit, and the minimum susceptibility level of the potential victim equipment. The companion MIL-STD-462 defined the test methods for verifying that MIL-STD-461 requirements are met, and MIL-STD-463 defined the applicable terms and units. The first two standards are now merged into one, MIL-STD-461. For complying with the EMI/EMC requirements, the contractor of commercial and defense spacecraft is required to develop the following three documents and submit to the customer as deliverables:

1. EMC control plan containing the analysis of expected EMI in the spacecraft versus the imposed requirement, and the steps to be taken for making the two compatible.
2. EMI test plan with detailed test setups, cables to be used, the grounding details, frequency range, point of monitoring, and the pass–fail criteria.
3. EMI test report, summarizing the findings of the tests, and steps to be taken to rectify the failures, if any.

The EMI requirements broadly fall in two general groups, the conducted EMI and the radiated EMI. In addition, some spacecraft-specific requirements may also be imposed. The EMI can enter the equipment either by conduction via wires, or by radiation in space. For verifying that the spacecraft would meet such requirements, the first task is to determine the conducted EMI and the radiated EMI from potential sources, and the degree of coupling to the victim equipments.

15.2 Sources of EMI

In the commercial world, radiated EMI comes from radio and TV towers, mobile radio vans, lightening, and nearby power lines. The conducted EMI comes mainly from power cables. In space systems, the main sources of EMI are:

- Switching large currents or voltages at high frequency, causing large dI/dt and dV/dt
- Electrostatic discharge
- Nuclear detonation

15.2.1 Conducted EMI

Active components, such as switches and diodes, are the main sources of conducted EMI in the switch mode power converter. As was seen in Section 14.4, the switching frequency voltage ripple is primarily influenced by the dynamic impedance of the equipment. The high-frequency EMI, however, arises due to the parasitic ringing in voltage following a current switching. Therefore, refined component models are needed to predict accurate ringing frequency, amplitude overshoot, and rising or falling transients. Such models must be verified by tests. The commercially available circuit modeling tools, such as PSPICE and SABER, may not be accurate enough for the EMI prediction. Specifically, accurate circuit models for the following high frequency components are needed in the applicable frequency range.

- Active components (switches, diodes, etc.)
- Passive components (transformers, capacitor, inductor, resistor, etc.)
- Printed circuits board patterns used in the spacecraft

Accurate models of these components cannot only predict the high-frequency EMI level, but also can identify the cause. An optimized EMI solution can then be achieved before fabricating the hardware.

15.2.2 Radiated EMI

The power system harness is a major source of low frequency electromagnetic radiation and coupling. Around a short wire (< 10% of the signal wavelength), generally one type of field dominates, either the magnetic field (B-field) around high-current lines or the electric field (E-field) around high-voltage lines. The B-field dominates around a typical power cable. It is derived from Ampere's law. In the commonly encountered geometries shown in Figure 15.1, it is given by the following expressions:

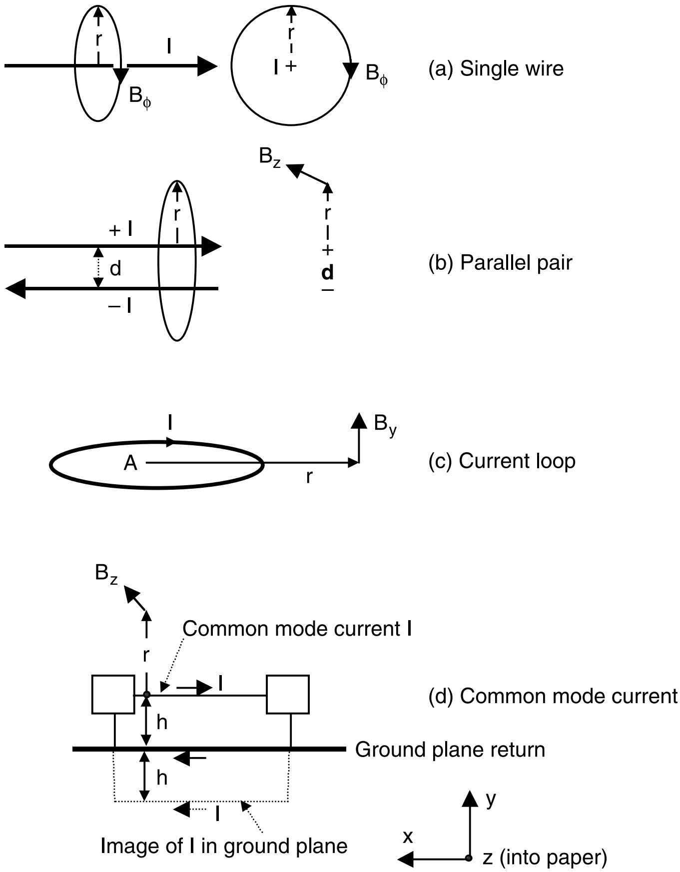


FIGURE 15.1 Magnetic field due to current carrying conductors in various configurations.

For a single wire,

$$B_\phi = \frac{\mu_o I}{2\pi r} \tag{15.1}$$

For a parallel pair,

$$B_{z\ \max\ at\ z=o} = \frac{\mu_o I\, d}{2\pi r(r+d)} \cong \frac{\mu_o I\, d}{2\pi r^2} \tag{15.2}$$

at far distance.

For a current loop,

$$B_{y\ \max\ at\ y=o} \cong \frac{\mu_o I\ \times \text{loop area}}{r^3} \tag{15.3}$$

at far distance.

For a common mode current,

$$B_{z\ \max\ at\ z=o} = \frac{\mu_o I\, 2h}{2\pi\, r(r+2h)} \tag{15.4}$$

The B-field is negligible around a coaxial cable with small eccentricity, and also at some distance from a twisted wire pair carrying a differential mode current. For the wires depicted in Figure 15.1, the B-field falls off as $1/r$ for a single wire, $1/r^2$ for two parallel wires carrying equal and opposite currents, and $1/r^3$ for a current loop.

The high-frequency electromagnetic field travels at the speed of light in the medium of propagation. The field is characterized into two types: the far field and near field in terms of the wavelength λ, which is the ratio of speed of light over frequency.

15.2.2.1 Far field at r > λ/2π

This is also known as the radiation field. It travels long distances in wave motion with a characteristic wave impedance Z_o. In vacuum or air, Z_o is 377 Ω. In coaxial cables it is about 50 Ω. The field strengths, both electric and magnetic, fall off as $1/r$.

15.2.2.2 Near field at r < λ/2π

This is also called the induction field. Its intensity at a point is determined by the characteristic of the source. The E-field falls off as $1/r^2$ if the source impedance $Z_s << Z_o$, and as $1/r^3$ if $Z_s >> Z_o$. On the other hand, the B-field falls off as $1/r^2$ if $Z_s >> Z_o$, and as $1/r^3$ if $Z_s << Z_o$.

15.2.2.3 Transition field at r = λ/2π

At this distance, the field characteristic changes from the near field to the far field.

15.3 Modes of Coupling

The electromagnetic field coupling between the two components can be via one or more of the following parameters:

- Stray capacitance
- Mutual inductance
- Ohmic conduction

The degree of coupling can be quantified in terms of the following parameter:

$$\text{transfer impedance} = \frac{\text{voltage across victim (succeptor)}}{\text{current through culprit (emitter)}} \tag{15.5}$$

Figure 15.2 depicts capacitive coupling between various conductor configurations on a relative basis. The E-field coupling for an ESD type of transient is governed by the mutual capacitance between the source and the victim cable. For two straight conductors shown in Figure 15.3, the circuit analysis leads to the capacitive coupling between conductors 1 to 2 to be

$$\frac{V_2}{V_1} = \frac{j\omega\left[\dfrac{C_{12}}{(C_{12}+C_{2G})}\right]}{j\omega + \dfrac{1}{R(C_{12}+C_{2G})}} \tag{15.6}$$

The B-field coupling between a culprit and a victim cable can be strong around the high-current bus, transformer or motor. The voltage induced is given by $V = -A\ \mathrm{d}B/\mathrm{d}t$, where A is area of the loop formed by the victim cable. If the radiation is sinusoidal at frequency f, then $V = 2\pi fAB$ volts, or V

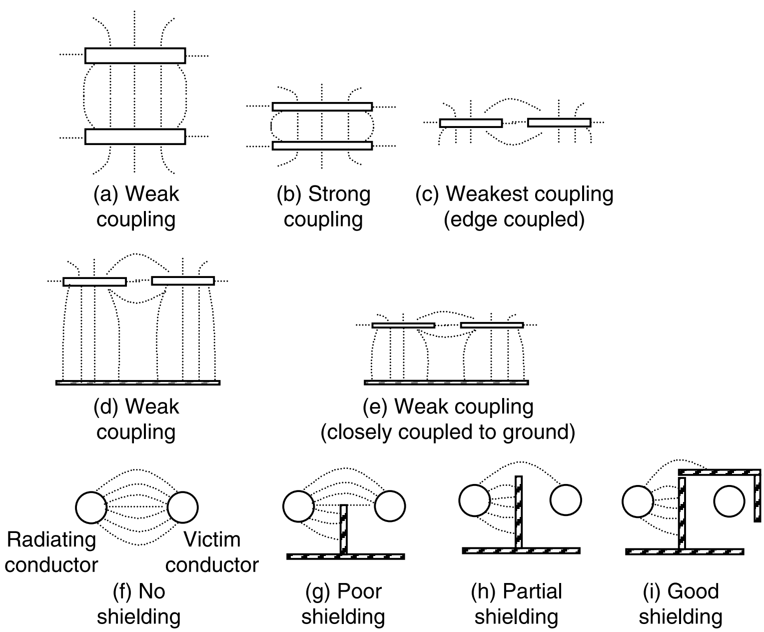


FIGURE 15.2 Capacitive coupling between various conductor configurations.

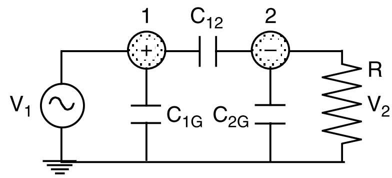


FIGURE 15.3 Capacitive coupling between two straight conductors.

(in dB·μV) = $K + B$ (in dB·μT), where K = constant. In terms of the mutual inductance M, the term V (in volts) is then

$$V = M\mathrm{d}I/\mathrm{d}t = 2\pi f M I \tag{15.7}$$

The total inductive and capacitive couplings between two parallel unshielded wires over a ground plane are determined by the mutual inductance and capacitance, which, in turn depend on the geometry of the cables. The two mutual couplings are shown in Figure 15.4, where C and M are determined from the classical transmission line theory. The capacitive coupling circuit between an unshielded culprit and shielded victim wires is shown in Figure 15.5. At very low frequency, the capacitive coupling is

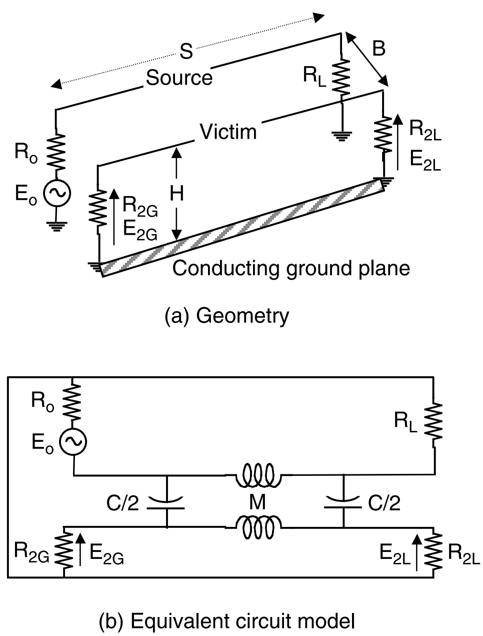


FIGURE 15.4 Capacitive and inductive coupling between two parallel wires over ground plane.

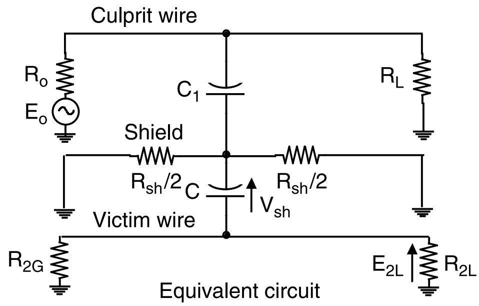


FIGURE 15.5 Capacitive coupling between unshielded culprit and shielded victim wires.

dominant when the termination resistances are high, so that the current flow is low and the magnetic coupling (inductance) is ignored.

At power frequencies up to 100 kHz, the coupling is primarily magnetic. In this frequency range, the following are some practical design guidelines for controlling the cable coupling:

- The coupling increases with the common run length and frequency and decreases with an increase in spacing.
- The noise voltage of the victim's termination load is a function of the load impedance. A capacitive filter connected from the victim line to ground can be used to decrease the load impedance at noise frequency, provided the victim's interface can accommodate such capacitance.
- The cable shield characteristic is defined by the transfer impedance. Lower impedance results in more effective cable shielding. Good impedance values are in the milliohm per meter range.
- The twisted shielded wire pair is effective up to 2 MHz, above which the coaxial cable is required.
- High current power lines and low impedance loads are prime sources of low frequency magnetic coupling. Therefore, the power line leads are always twisted with their returns.
- The twisting effectiveness increases with the number of twist per meter and decreases with the frequency. It is effective only on balanced or single point ground system and up to 100 kHz. Above this frequency, capacitance from the wires to the ground causes ground current to circulate, which generates common mode coupling. Practical twist pitch is 30–50 per meter.
- The capacitive coupling of the electric field is best avoided by shielding the culprit, victim or both cables, and grounding the shield (Figure 15.6).
- Single point ground is used at low frequency where the wavelength of the frequency to be suppressed is longer than 10 times the shield length.

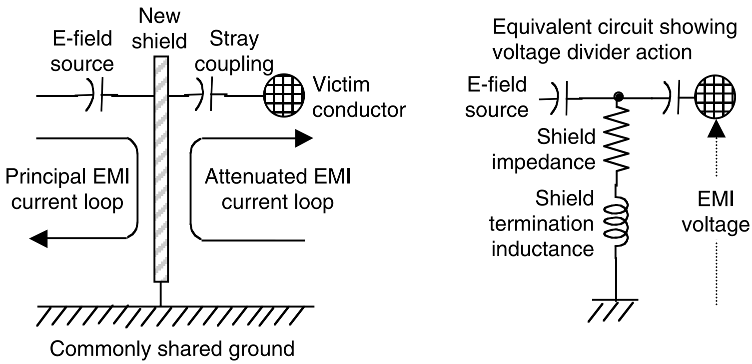


FIGURE 15.6 Shield protection from capacitive coupling.

If the culprit wire is shielded, the ground point is at the exit from the culprit source. If the shield is on the victim wire, the ground point is at the entry to the victim's electronics (Figure 15.7).

- The shield grounding at high frequency should be at both ends of the shield. This directs the return current away from the ground and into the shield, thus decreasing the ground loop currents and common mode radiation pickup (Figure 15.8 and Figure 15.9).
- Single point grounded shield does not reduce the common mode EMI (Figure 15.10).
- A 360° peripheral low-resistance bond should be used via a connector backshell assembly to assure low-impedance shield grounding in high-quality shield cable. This bond resistance limits the shield performance.

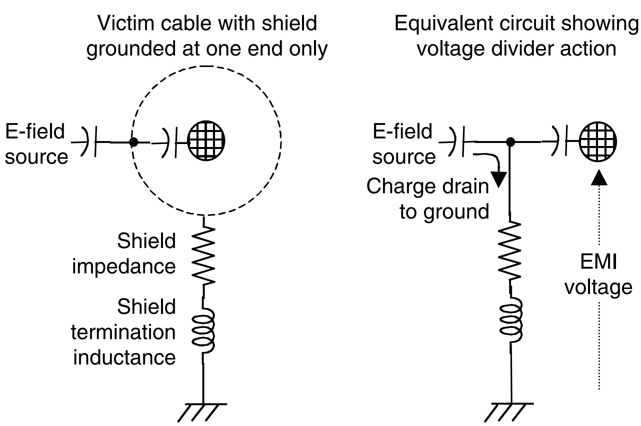


FIGURE 15.7 Victim cable with a shield grounded at one end.

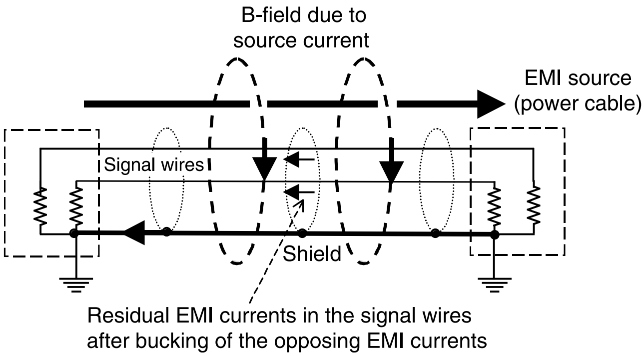


FIGURE 15.8 A shielded cable with both ends grounded.

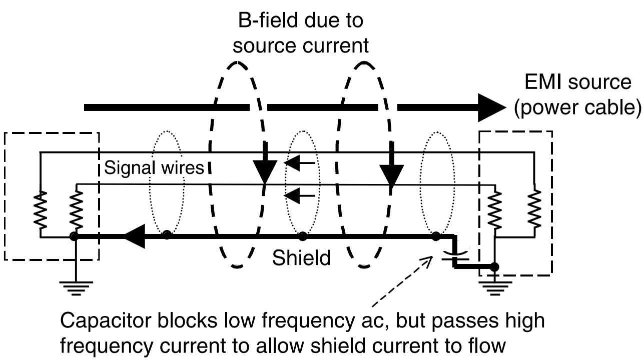


FIGURE 15.9 A cable with shield grounded at one end for low frequency and at both ends for high-frequency signals.

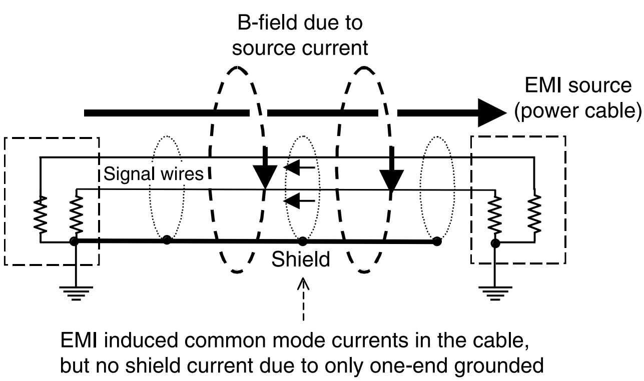


FIGURE 15.10 A shielded cable with only one end grounded.

15.4 EMI/EMC Specifications

The EMI standard establishes the maximum interference an equipment or a system, such as the power system as a whole, can conduct or radiate into the load equipment. The EMC standard, on the other hand, establishes the minimum conducted and radiated interference that an item of equipment connected to the power system must withstand without being susceptible to a functional impairment. Obviously, the susceptible level must be higher than the emission level with comfortable margin, usually tens of dB depending on the criticality of the equipment in the system.

The EMI/EMC levels are specified in dB, which equals 10 $\log_{10}$ (signal power/reference power), or 20 $\log_{10}$ (signal voltage or current/reference voltage orcurrent). Thus, 3 dB doubles the power, or 6 dB doubles the voltage or current.

The EMI/EMC requirement is specified in two parts, the conducted and radiated emission levels of the culprit equipment, and the conducted and radiated susceptivity level of the victim equipment. The general requirements for all spacecraft and launch vehicles come from MIL-STD-461. Those applicable to power equipments are listed in Table 15.1. The spacecraft specific requirements are also specified. Some such representative requirements are shown in Figure 15.11 through Figure 15.17.

The safety margin specified between the emissions levels and the susceptibility levels are generally:

- 20 dB for critical equipment
- 6 dB for all other equipment

In addition, certain self-derived EMI/EMC requirements that have been established in the past on some spacecraft are listed below as examples of what may be required of the power equipment:

- The EMC specification applies at the load points, not at the PRU location.

Table 15.1 MIL-STD-461 requirements applicable to spacecraft and launch vehicle power equipment

Requirement	Conducted (C)	Radiated (R)
Emission (E)	CE01	RE01
	CE03	RE02
	CE07	–
Susceptibility (S)	CS01	RS02
	CS02	–
	CS06	–

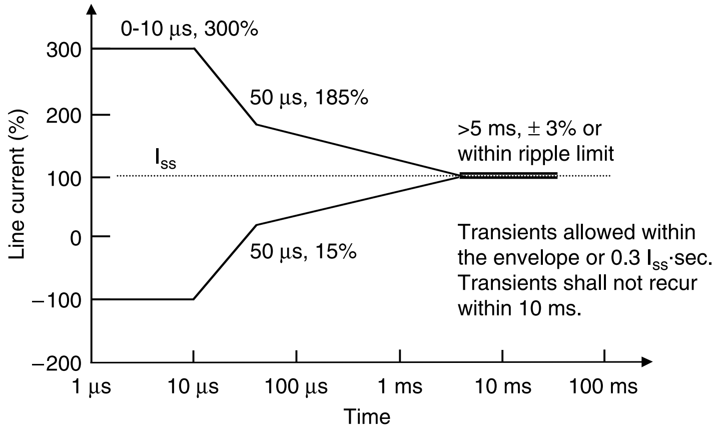


FIGURE 15.11 Repetitive transient current limits for equipment on a typical 10-kW communications satellite.

- The bus output impedance is estimated excluding the bus loads. However, for estimating the bus ripples the effect of major loads on the bus impedance is taken into account.
- The main bus power return, the signal return, and the structure are connected to a single reference ground point. All electrically conductive

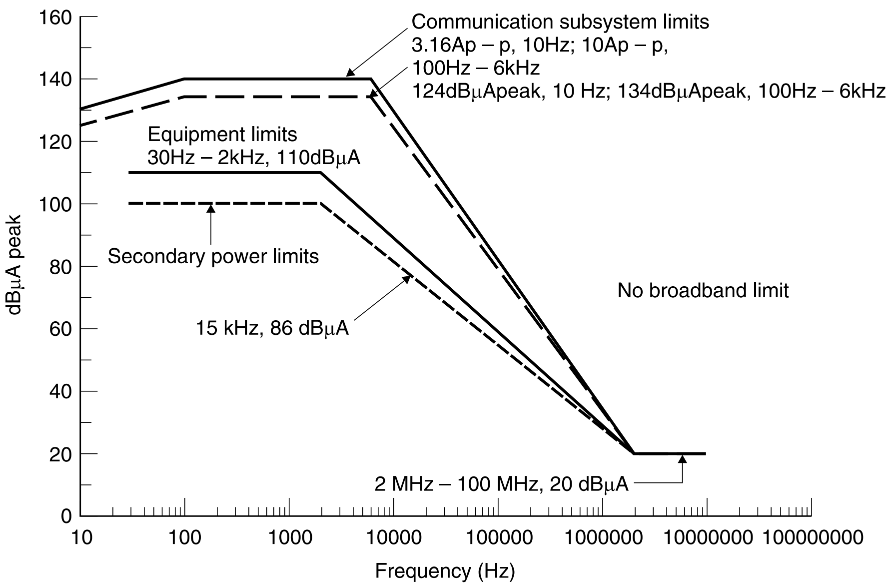


FIGURE 15.12 Conducted emission limits for equipment on a typical 10-kW communications satellite.

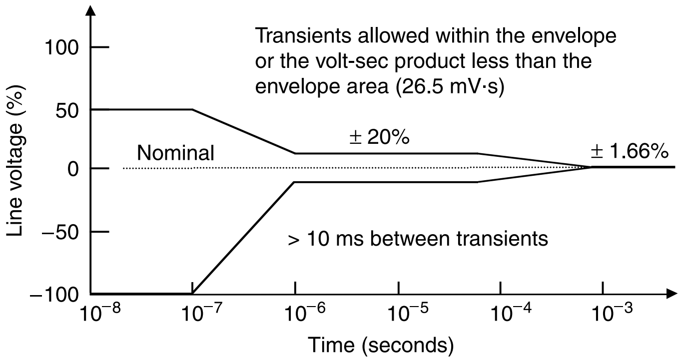


FIGURE 15.13 The CE07 limit for main bus voltage for a 3-kW, 120-V, LEO science satellite.

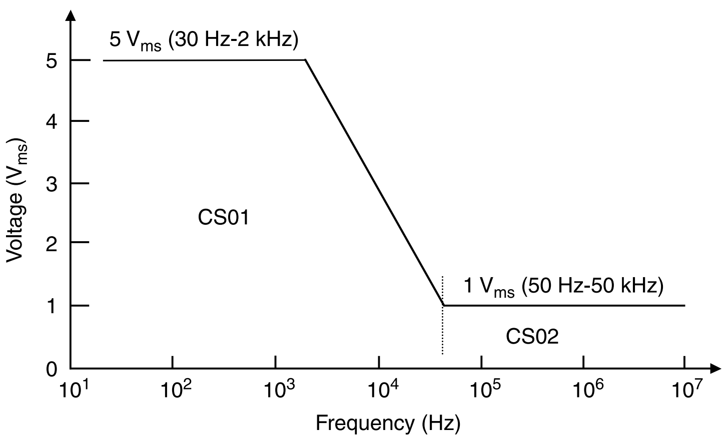


FIGURE 15.14 CS01/CS02 susceptibility requirements.

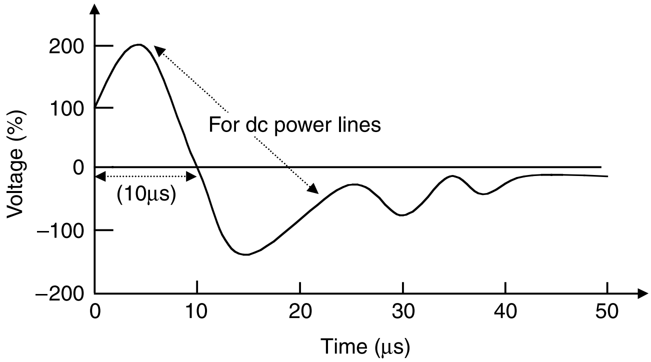


FIGURE 15.15 CS06 transient susceptibility requirements.

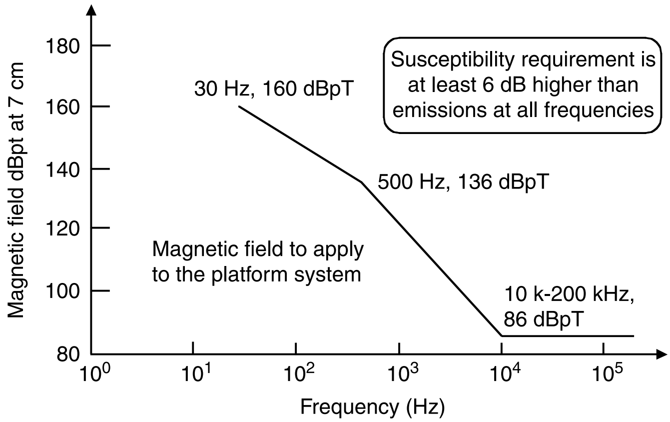


FIGURE 15.16 RS01 B-field susceptibility requirements for a 3-kW, 120-V, LEO science satellite.

surfaces are connected to the bus structure to form a common satellite ground cage.

- The case ground lead for each component is connected to a pin on the respective component multi-pin connector. The connector shell is always conductive and bonded to the case.

Typically, large commercial communications satellites designed for a 5- to 10-kW load and 100-V bus generally have the following self-derived requirements:

- The magnetic dipole moment of each solar array wing is limited to 3 to 5 A·m^2.

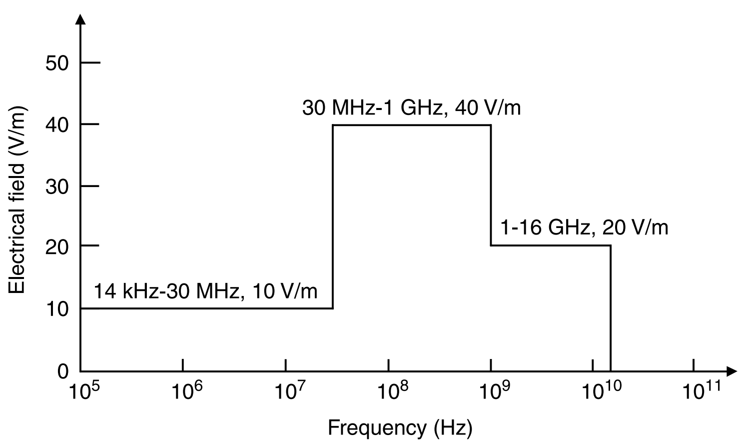


FIGURE 15.17 RS03 E-field susceptibility requirements (14 kHz to 16 GHz) for a 3-kW, 120-V, LEO science satellite.

- The magnetic moment of each battery is limited to 20 A·m^2, which is aligned with the pitch axis of the spacecraft. In two-battery systems, the magnetic dipoles of the two batteries oppose each other to cancel out at a distance.
- The magnetic moment of the whole spacecraft is limited to 5 to 10 A·m^2.
- Any load step is limited to less than 5% of the total load current capability of the bus, and the dI/dt is limited to a few tens of milliamps per microsecond. The undershoot and overshoot voltages are kept below 1% of the bus voltage.
- The load is required to withstand the peak-to-peak ripple voltage of 2 to 4% of the bus voltage, depending on the load equipment sensitivity.
- The dynamic impedance is limited to 250 mΩ in the 50 Hz to 20 kHz range and 500 mΩ for frequencies below 50 Hz.
- The bus voltage ripple at any load point resulting from the load current ripple is kept below 2 V_{p-p} from d.c. up to 50 MHz.

In the class of small satellites, as an example, one 28-V fully regulated defense satellite bus with load less than 1 kW, the ripples were limited to 500 mV_{p-p} at 36 kHz due to the battery discharge regulator. The user turn-on or turn-off dI/dt were kept below 10 A/μs for load current changes exceeding 2 A. Any transients that did not meet this rate had the I–t product limited to 100 μA·s. The bus broadband ripples were required to be 6 dB below that specified in the EMI/EMC specifications for the spacecraft. User equipment dynamic impedance was kept below 8 Ω from 3 to 10 kHz.

For EOS-AM type platform delivering a 3000-W load at 120-V bus, the bus source impedance at the capacitor bank was kept is 0.1 Ω d.c. to 100 kHz, and the ripples were limited to 0.5 V_{p-p}.

15.5 EMI Suppression Methods

Various methods of controlling and/or suppressing the EMI, in the order of their importance, are listed below and some discussed further in the next section:

- Minimize the EMI generation in the first place by
  - Minimizing the current loop area in switching circuits
  - Minimizing the switching transients' dI/dt rate in large current loops
  - Using snubber capacitors to minimize the voltage transients' dV/dt rate
- Minimize the E-field and B-field couplings between the culprit and the victim equipments by

    - Minimizing the inductive coupling by twisting wires or using coaxial cables
    - Minimizing the capacitive coupling by using shields and by reducing area of exposed metal and keeping it far from the ground (since $C = A\varepsilon/d$)
- Divert the energy impinging on the victim equipment to ground by using
    - Proper grounding scheme
    - Faraday shield, single or double
- Protect the equipment from the coupled energy by using
    - L-C filters for conducted EMI
    - Enclosure shield for radiated EMI

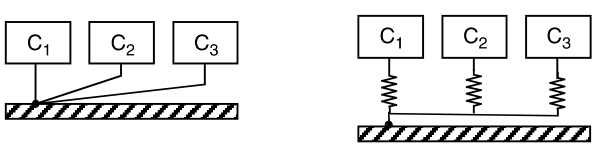
15.5.1 Twisting Wires

The twisting not only reduces the spacing between conductors, it also produces self-contained B-fields of opposite polarities around the adjacent spans. Thus, it results in a much lower B-field at far distance due to the cancellation effect. It does not, however, reduce the local B-field close to the cable.

Note that twisting two wires carrying a common mode current cannot null the B-field. The only effective way to eliminate the common mode EMI is to block the common mode current by breaking the ground loop. An alternative is to use a common mode choke (balun) discussed in Section 15.5.

15.5.2 Grounding

Two configurations of the single point ground (SPG) used for d.c. or a.c. power systems up to 20 kHz are shown in Figure 15.18. Configuration (a) is preferred. Configuration (b) is simple but less effective for high frequency EMI, since the ground wire inductance increases the Z_{ground} between two pieces of equipment. The grounding at a single point in the system effectively minimizes the radiated EMI by avoiding ground current loops.



(a) Parallel grounds (b) Series grounds

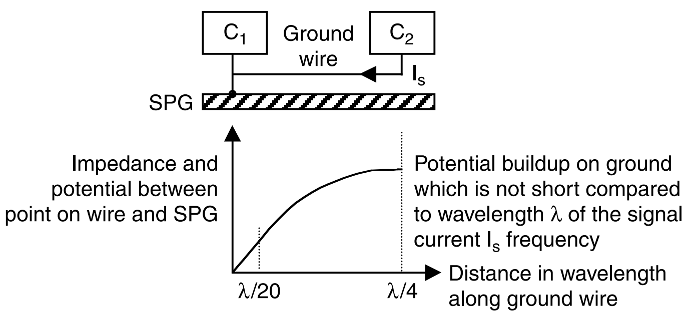
FIGURE 15.18 Single point grounding schemes.

Power return is grounded only at one point. All ground leads are directly connected to one point, which is then solidly connected to the structure. Single-point ground reduces the ground inductance. It is used when the circuit dimensions are less then 3% of the wavelength to be suppressed.

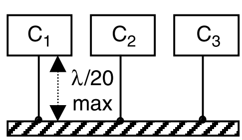
As shown in Figure 15.19(a), a single point ground is used to suppress low frequency EMI. On the other hand, multiple point ground (MPG) shown in Figure 15.19(b) is used for radio and higher frequencies EMI suppression. MPG is used when the circuit dimensions are greater than 15% of the wavelength at the operating frequency. Each ground lead is connected to the closest ground conductor. The ground plane minimizes Z_{ground} between two pieces of equipment. In a box having circuit boards sensitive to different frequencies, a hybrid of the SPG and MPG approaches may be needed.

15.5.3 Cable Shielding

Military and science satellites having stringent EMI requirements cannot tolerate any unshielded segment of the harness, or even an open fuse board. All harness groups — power, signal, and pyro — are kept in separate bundles with separate shielding. Commercial satellites, on the other hand, may have fuse boards or some segments of the harness unshielded. All shields (power and signal) are grounded about every meter to a SPG.



(a) Single point ground for low frequency
λ = Speed of light/frequency



(b) Multiple point ground for high frequency

FIGURE 15.19 Single versus multiple point grounds.

The cable shielding alternatives are the braids versus tape and copper versus aluminum. The braids are used when extreme flexibility is required. The shield mass as compared to the wire conductor is about 40% for flat cables and 20% for round cables. In tapes, 2-mil-thick copper vapor deposited on Mylar or Kapton tapes is widely used. The tape is applied on the cable with insulation touching the cable, followed by another half-lap layer on the top (Figure 15.20). The shield mass with such tapes is roughly 80% of that with braids. The bend diameter must be less than about 10 cm to avoid unwrapping of the tape. Aluminum backed tape can be used, but being brittle, it needs greater bend radius to keep it from cracking at cold space temperatures. It does not create oxidation-related problems, as long it does not come in contact with copper or other dissimilar metals.

15.5.4 Bonding

In fabricating a shielding enclosure or in making ground connections, the conductors are bonded together by various processes. The bond is schematically shown on the circuit diagrams by a heavy dot before the conducting part meets the ground symbol. The solid bond generally requires having impedance less than a few milliohms. Movable parts may be bonded using a strap having resistance less than a few milliohms and inductance less than a few tens of nanohenries. The mechanical and electrochemical stability is required in the bond. Welding is recommended for magnetic enclosures, while brazing and soldering are recommended for conductive enclosures. The corrosion in bonding two dissimilar metals, such as a copper strap to steel box using steel fasteners, is controlled by

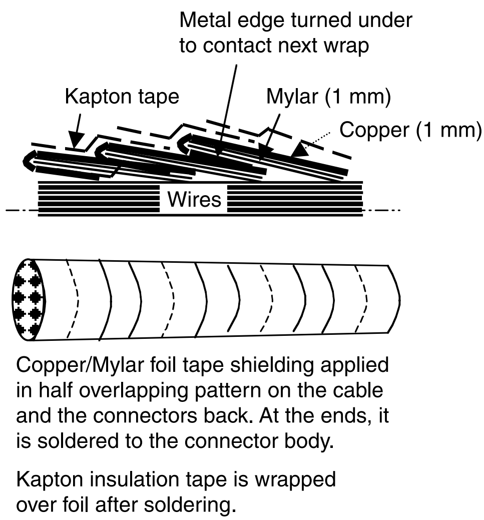


FIGURE 15.20 The cable shielding method using metal backed insulating tape.

selecting two materials in contact with about equal galvanic potentials. This requires the electric potential differences between them to be near zero. Otherwise the condensed humidity between the two acts as an electrolyte, creating a voltaic cell. Copper, silver, platinum, and gold are cathodic, having positive galvanic potential, while many other commonly used metals are anodic, having negative galvanic potential.

15.6 Common Mode EMI

Even a small common mode current can cause trouble. We recall that the induced voltage is given by $e = -L\ \mathrm{d}I/\mathrm{d}t$. A typical value of the wire inductance L is about 80 nH/m. If the rise time of say 100 mA is 1 ns (ESD type discharge), it induces voltage equal to $80 \times 100/(1 \times 10^{-9}) = 80$ V/m length of the cable. This can upset many sensitive electronic and control circuits.

Common mode noise can be detected by a circuit shown in Figure 15.21. The noise can be minimized by using a balun filter as shown in Figure 15.22. A transformer or a coupled inductor inserted between components 1 and 2 reduces the common mode propagation. Its magnetic core provides two large inductances to the common mode current, but provides zero net inductance to the differential mode current. Therefore, the inserted impedance in this mode equals two times the self (mutual) impedance of the transformer plus the self-impedance of the wire with respect to the ground. Bifilar winding or twisting of wires does not reduce the common mode noise. This is in contrast to that in the differential mode noise, where the impedance to the noise signal is equal to the leakage impedance of the transformer plus the wire, which is very small and can be further reduced by using bifilar windings and twisted wires.

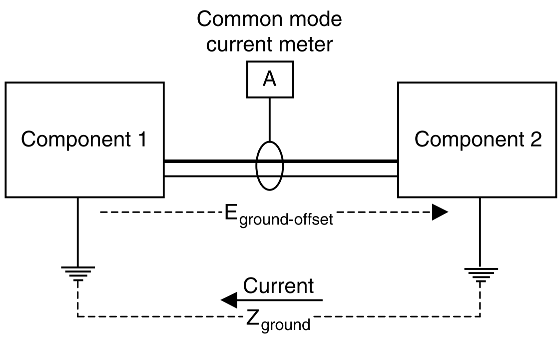


FIGURE 15.21 A common mode noise detection method.

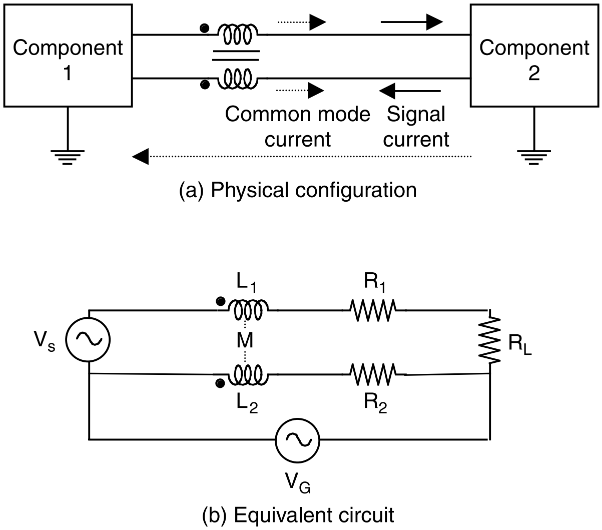


FIGURE 15.22 A common mode noise filter (balun.)

15.7 Broadband EMI

EMI is classified as narrow-band or broadband, depending on the signal's spectral distribution relative to the resolution bandwidth of the receiver used for the measurement. It is essential to know which type of signal is being measured to avoid erroneous test results and the wrong interpretation of data. In this context, the knowledge of the instrument's impulse bandwidth is necessary to correctly determine the absolute amplitude of an emission. Determination of the receiver's impulse bandwidth can be done with a series of measurements, but not simply by multiplication of its 3 dB or 6 dB bandwidth with a constant factor. Only the accurate knowledge of this parameter allows a meaningful comparison of the measured emission levels to a limit line and verification of a product's compliance with an EMI standard.

When measuring impulsive signals, it is necessary to know the impulse bandwidth of the interface filter of the EMI receiver or the spectrum analyzer. Due to the broadband nature of impulsive signals, some of the spectral components are not contained in the interface filter pass-band at any one time. As the filter bandwidth becomes wider, more spectral components are included and the amplitude of the signal at the filter output increases until the filter is wide enough to enclose the entire signal spectrum. Filters implemented in EMI receivers or spectrum analyzers are usually defined by their 3 dB or 6 dB bandwidths, which is suitable for measuring narrow-band signals. However, this specification is insufficient for measuring broadband signal because the filter's amplitude and phase response affect the results.

A comparison of test data taken with different EMI receivers is very difficult (if not impossible) to make. A study conducted in Japan in 1996 showed that the difference in measurement results of up to 6.4 dB is possible when measuring broadband impulsive signals, based on a 3-dB or 6-dB bandwidth specification. This could lead to situations where equipment under test passes or fails a compliance test, depending on the receiver being used in the tests.

15.8 Commercial Off-the-Shelf Equipment

In recent years, NASA and defense agencies have considered using commercial-off-the-shelf (COTS) equipment in space for reducing procurement cost. In Europe, interest in using commercial equipment in space has resulted in the EMC Directive issued within the European Union (EU) and enforced since 1996. The EU undertook a revision of the Directive in 1998, and recently has published its final revised draft for review and discussion among its 25 member countries. The fully and finally revised new Directive was published in mid-2004. It will become effective 30 months after the date of publication, possibly with a 2-year transition period. During transition, products can comply with the old or new Directive as advantageous to the manufacturers.

The EMC Directive requires commercial manufacturers to use EMI test methods similar to those required for aircraft, military, and space equipment. However, this requires acceptable methods to interpret and compare space system EMI test data with commercial test data, and that is difficult.

For example, NASA Specification SSP30237A establishes the electromagnetic emission and susceptibility requirements as well as design requirements for electronic, electrical, and electromagnetic equipment and subsystems designed or procured for use on the International Space Station. The applicability of the emission and susceptibility requirements is wholly dependent on the intended location or installation of the equipment or subsystem within the space station. SSP30237A designates the equipment or subsystem as an internal or external equipment depending on the intended location site. Internal equipment applies to equipment located inside a module or node. On the other hand, external equipment applies to all equipment located outside the modules and nodes. The SSP30237A relies on MIL-STD-461 as its framework document, which has been tailored based upon previous work on known electromagnetic environment for the space station. The MIL-STD-461 limits were adjusted based on power requirements and receiver sensitivity as well as margin for safety and to limit system-level compatibility concerns. The detailed test procedures for SSP30237A are contained in SSP30238A — Space Station Electromagnetic Techniques.

NASA has performed tests as per SSP30237A and has compiled EMI test data on various components. The system designers use this database for locating and co-locating various components within the space vehicle. If SSP30237A data cannot be correlated with data obtained from the corresponding commercial test requirements, then the equipment may either be placed in an environment where it can be susceptible or can cause susceptibility without violating the system level performance requirements. In addition, if correlation is not possible, the system designer may decide to remove the component from a questionable environment to a benign environment. This may cause an extensive redesign and impact on cost and schedule of the entire system.

15.8.1 EMI Requirements in Commercial Equipment

The following are three major EMI test requirements used extensively in the commercial market.

15.8.1.1 Code of Federal Regulations — Part 15 (FCC Part 15)

This Code addresses conducted and radiated emissions in the frequency range of 450 kHz to 1 GHz. The FCC divides the EMC environment into Class A and Class B requirements for office and household environment, respectively.

15.8.1.2 EMC Directive 89/336/EEC

This Directive is for use in the European Community (EC), which specifies both emission and susceptibility (immunity) requirements. The EC documents divide the EMC environment into household and light industrial environment in one class and industrial environment into another class. The European EMC requirements rely on a series of test methods developed by the International Electrotechnical Commission (IEC) and designated as IEC-1000-X-X, the European Union's emission and immunity requirements designated as EN-550XX, and the immunity testing documents designated as EN-610XX.

15.8.1.3 RTCA/DO-160C

This Standard is used in avionics industry for use in commercial airlines. The original version of the document was tailored from MIL-STD-461, but has been updated over the years and contains requirements beyond the MIL-STD-461 test methods, such as lightening and environment tests. Since the space station requires equipment similar to that used in commercial airlines, this standard is important when purchasing navigational and communications equipment.

15.8.1.4 Other requirements

There are areas where the commercial requirements do not fully cover the International Space Station requirements specified in SSP30237A. For example, when comparing CE01 to IEC-1000-3-2, the commercial standard does not fully cover the frequency range. The CE01 requires the measurement of conducted emissions from 30 Hz through 15 kHz, whereas IEC-1000-3-2 requires the measurement of the harmonic current emission only up to the 40th harmonic. Therefore, comparison between IEC-1000-3-2 certified equipment and SSP30237A qualified equipment can only be applicable if the inter-harmonic emissions are not of concern and if the equipment does not have local oscillators less than 10 kHz such as in d.c.-to-a.c. switching mode power supplies. The SSP30237A requires CE01 testing for d.c. power leads only, whereas IEC-1000-3-2 is not applicable to d.c. systems. Since NASA may procure COTS equipment designed for 115 or 220 V, 50 or 60 Hz operation, analyzing a.c. equipment against the CE requirements of SSP30237A to provide a reference point for NASA engineers is necessary. The scope of that work must include identifying differences between various measuring instruments as well as components used in test setups, such as the line impedance stabilizing network (LISN) and feed through capacitors. Measuring instruments are generally similar in related specifications. However, there are some differences that require careful examination. For example, the LISNs called out in the NASA specifications are different from the LISNs in the DO-160-C specifications and the LISNs specified in the majority of IEC-1000-4-X requirements are still of different design.

To narrow the difference, one must include the cable parameters, such as the length of the cable, height above the ground plane, whether the cable is run behind, in front or alongside the equipment under test, and other configuration issues. These all can be addressed by including the cable capacitance, inductance, resistance and ground conductance (C, L, R, and G, respectively) for the type and length of the cable used in the actual laboratory setup. These parameters come from standard high-frequency transmission line theory that covers the entire frequency range from low to high frequencies. The parameters can be lumped for short cables, or can be distributed if necessary for better accuracy in long cables.

15.8.2 NASA Versus Commercial Test Methods

The basic approach must be to analyze corresponding test methods and limits from SSP30237A and the applicable requirements in the FCC regulations, the EC EMC requirements, and/or RTCA/DO-160C. Then it is necessary to develop fitting transfer functions based on the comparison of the two sets of data for translating one of the commercial data into the NASA SSP30237A electromagnetic environment envelope.

We first consider the NASA CE01 and CE03 requirements, and the corresponding commercial requirements, which are listed in Table 15.2. The table shows how each of the SSP30237A requirements are analyzed against the various commercial standards. The analysis must be performed by evaluating various instrumentation, measurement techniques, and applicable limits for each of the test methods. This includes evaluations of different line impedance stabilization networks (LISNs), feed-through capacitors, spectrum analyzers, oscilloscopes, and other test instrumentations that are used in different test methods, which could lead to differences between measured quantities. For example, CE01 and CE03 require the use of a 10-μF capacitor on all power lines and measuring the RF current directly on the power line using an RF current probe and EMI receiver. FCC Part 15 and EN55022 each require an LISN on the power line under test and the measurement of voltage across a resistor in the LISN. Therefore, the two limits are in different units and cannot be simply compared. This requires an analysis to determine the relationship between the measured quantities and thereafter for developing the transfer function between the two.

15.8.3 Testing COTS for Space Compliance

One of the major concerns in comparing different EMI test requirements is the test setup. For instance, the majority of the C-1000-4-X requirements specify that the equipment under test be placed on an insulated surface approximately 80 cm from the ground plane, whereas SSP30237A requires the unit to be placed approximately 5 cm above the ground plane. This would cause a major difference in test results that must be carefully investigated. For the purpose of conducted emission testing, the cable can be modeled as a transmission line having *C*, *L*, *R*, and *G* parameters in an equivalent T network.

Table 15.2 NASA versus commercial EMI requirement

SSP 30237A requirement	FCC requirement	ECLIPSE requirement	DO-160C requirement
CE01	–	IEC-1000-3-2	–
CE03	Part 15	EN55022	Section 21
CS01	–	IEC-1000-4-13	Section 18
CS02	–	IEC-1000-4-6	Sec. 18 & 20
CS06	–	IEC-1000-4-5	Section 17
RE01	–	–	Section 15
RE02	Part 15	EN55022	Section 21
RS02	–	IEC-1000-4-8	Section 19
RS03	–	IEC-1000-4-3	Section 20

The standards being considered use very similar measurement techniques. They use measurement receivers to measure voltages, and current probes to measure currents. They also use current probes to measure current across a known resistor to determine voltage with respect to a given frequency range. Conversion factors are then applied based on calibration of the equipment used to perform the measurement and then a comparison is made to a given emission limit. However, each method has various differences in the approach for maintaining consistency within testing. The IEC-1000-4-X series of documents recommend the use of coupling/decoupling networks to match the typical installation impedance of various cables to the test cable configuration. The idea here is to minimize the distortion between the laboratory measurement and a typical field measurement. The SSP30238A relies on proper calibration of the equipment being used to perform the measurements. The values obtained from the various test specifications require adjustments in order to compare limits and test results. These adjustments need to be handled on a test method basis.

As for the frequency range, the test requirements must be reviewed to determine if they overlap the entire specifications. If not, the differences are taken into account as needed.

The simulations and the laboratory results on the four test setups have shown that the type of cable and its configuration and layout used in the actual setup make significant difference in the results. A parametric study made with PSPICE simulation showed sensitivity of the results to one more parameter, the cable resistance, in determining the peak of the response. This is expected, as low resistance results in a high-Q circuit having high and sharp peak at the resonance frequency.

A seemingly minor variation in the laboratory test setup, in particular the cable length, routing and types such as coaxial, twisted or randomly laid out, and the cable resistance makes significant difference in the correlation between any two test setups. This indicates that for properly comparing similar specifications, a careful and robust analysis of the similarities and differences in the setups is required.

Since the cable length and layout are equipment specific, it is extremely difficulty, and may perhaps be misleading, to correlate one test method to another in space systems, unless the cable length, layout and types are specified in the test standards.

15.9 Electromagnetic Pulse/Nuclear Threat

The electromagnetic pulse (EMP) is a man-made threat that arises from a nuclear detonation around the spacecraft. It can destroy satellites in low and mid Earth orbits. (Figure 15.23). A nuclear burst can upset electronic systems hundreds of miles away. Therefore, it is usually included in the

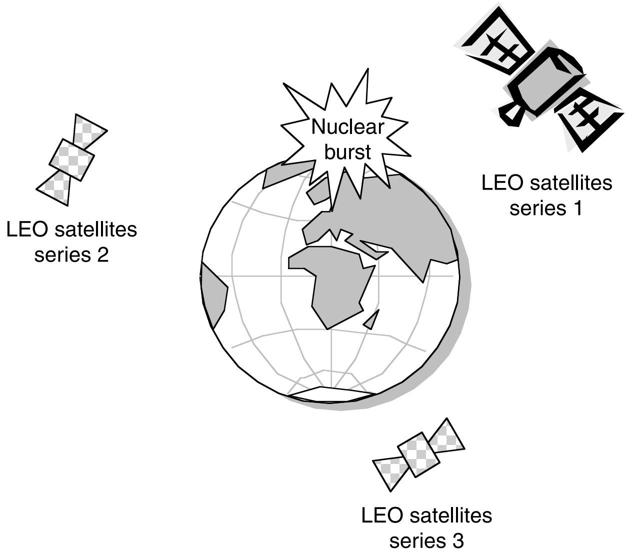


FIGURE 15.23 A nuclear burst in LEO altitude can destroy many satellites.

defense spacecraft power system requirements. The nuclear threat requirement is generally included on defense satellites in any orbit. For example, it was included in the original GPS satellites, which were procured exclusively for defense use of the U.S. Air Force until mid-1990s. It was removed from GPS-IIF and later versions, which were made available for commercial use also.

The EMP is basically the burst of electron flow resulting from the gamma radiation. It is an intense time-varying electromagnetic field of very short time pulse in the nanosecond to microsecond range. The radiation and propagation of the electromagnetic waves in space obey Maxwell's equations. The wave carries little energy to the equipment at far distance, but is deposited in a fraction of a microsecond, making the rate of energy deposition (power) extremely high. As a result, it can cause the following effects in the power system:

- Radiation dose degradation, particularly on solar array
- Common mode noise in power system equipments
- Temporary upset of sensitive electronic parts
- Semi-permanent upset (latch-up), requiring power shut-off and restart
- Permanent damage to sensitive semiconducting devices

The most dominant damage comes from the charged particle radiation dose on solar array and sensitive electronic parts. A high-altitude burst test named STARFISH conducted in 1962 produced a large number of beta electrons, which became trapped in the Earth's magnetic field. Its yield was 1.4 MT at 400 km altitude above Johnson Island in the South Pacific. The intense man-made radiation belt created by this burst ended the functional life of seven satellites within 7 months, primarily by solar cell degradation and command decoder failures. This radiation lingered for 10 years until 1972. Today, since LEO space is crowded with satellites, a severe nuclear detonation can cause the loss of hundreds of satellites resulting in enormous economic loss and national security concerns. It is estimated that a 10-kT burst over Japan at 150 km altitude can shorten the life of many LEO satellites such as *Iridium* and *NOAA* from 5 years to 5 months. The size, magnitude and duration of the nuclear radiation is calculated by the Air Force computer code that models the nuclear burst in space and calculates its effects on satellites. Using this unique code, the Air Force and the Institute to Defense Analysis predict that a 20-kT burst over Iraq would accumulate a radiation dose of 100 krad on *Iridium*-type LEO communications satellites in about 10 months, and the enhanced radiation would persists for several years. In some cases, the electron level would remain over 100 times higher than the natural level even 2 years after the burst. This makes the rapid replacement of destroyed satellites infeasible because they will also fail permanently due to the lingering radiation. For this reason, the replacement must wait and still use a much thicker radiation shield.

The EMP effects can be studied by quantifying the energy deposited on the victim equipment, which is the time integral of power. The power in an electromagnetic wave is given by the Poynting vector, which is the cross-product of E and H fields. The energy is therefore,

$$energy = \int power \cdot \mathrm{d}t = \int (ExH) \cdot \mathrm{d}t \tag{15.8}$$

We then think in terms of energy-coupling to various systems component. Wires exposed to EMP can couple damaging amount of energy into the system. The degree of coupling is a complex function, and is outside the scope of this book. However, it depends on the cable configuration, geometry of the cable run, and its orientation with respect to the electromagnetic field vectors. Once the energy is coupled to the wires, the high frequency transmission line theory applies for propagation along the wires. A part of the coupled energy is absorbed by the load (victim equipment). The remaining energy is reflected, the amount of which depends on how the load resistance matches with the characteristic impedance of the incoming wire. A good conductive paint on the surface can reduce the coupling when the EMP energy impinges directly on the equipment's enclosure surface, rather than entering via cables.

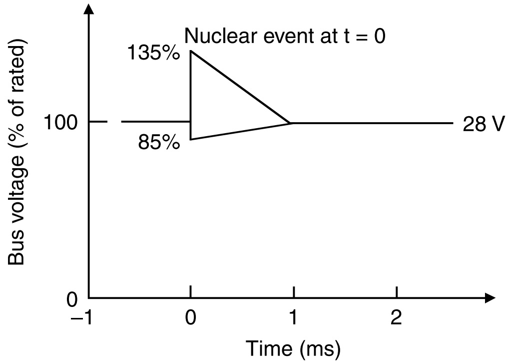


FIGURE 15.24 Main bus voltage transient requirement following nuclear burst on a 28-V fully regulated MEO communications satellite.

As an example of the power system requirement arising from a nuclear threat, the main bus voltage transient following a nuclear burst on a fully regulated 28-V MEO communications satellite was required to be kept within the envelope of Figure 15.24. In another example, the bus voltage of a 28-V fully regulated GEO communications satellite was required to be within the envelope shown in Figure 15.25. All loads must survive and return to the operating state after such abnormal transient is over.

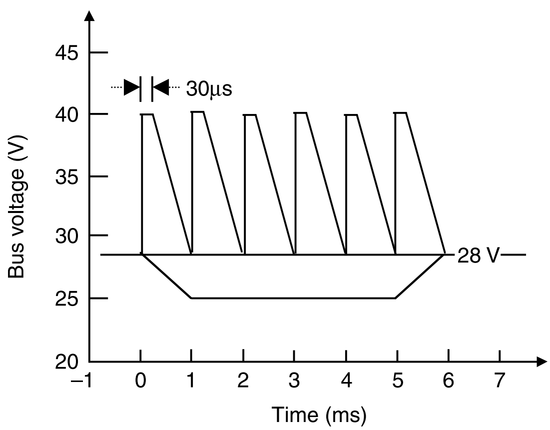


FIGURE 15.25 A main bus voltage transient requirement following a nuclear burst on a 28-V fully regulated GEO defense communications satellite.