EMC Test and Design Guidelines For ESD Protection in Spacecraft

When charges on spacecraft surfaces exceed breakdown voltages, ESD can occur, disrupting the normal operation of electronic systems.

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INTRODUCTION

The near-earth space plasma environment has a strong influence on the performance of a spacecraft. Some environmental plasma interactions can limit the technical potential of many spacecraft systems and can lead to costly malfunctions or even the total loss of components and subsystems. The major contributors to the space plasma environments are high energy electrons and protons, ions, and galactic rays. The space plasma environment, especially in geosynchronous orbit, can cause differential charging of satellite components, leading to electrostatic discharge (ESD) events and single-event phenomena.

When charges on spacecraft surfaces exceed breakdown voltages, ESD can occur, disrupting the normal operation of electronic systems either through induced electric fields or by the injection of large discharge currents. More energetic space radiation can become embedded in dielectric components and produce ESD in cable insulation and PCBs. This bulk charging and eventual discharge can severely damage electronic devices.

Trapped charged particles in radiation belts, solar flare protons, and galactic cosmic rays can cause single event phenomena (SEP) such as single event upsets (SEU) and single event latch-up (SEL) in electronic components. SEP are the result of high energy charged plasma particles impacting the semiconductor material of microelectronic devices and producing nuclear interactions which generate large quantities of electron/hole pairs. This external inducement of charge carriers can cause device malfunctions, such as SEU and SEL, which can degrade electronic devices. SEP can be thought of as analogous in principle (though through a totally different physical mechanism) to the generation of common-mode current in electronic switching systems. While common-mode currents are detected at the system level, SEP are detected at the microelectronic device level. Nevertheless, both introduce an extraneous current into electronic components.

This article will briefly address the space plasma environment, the charging and ESD mechanisms in spacecraft, and some design and test guidelines adopted by NASA for spacecraft design. The subject of SEP will not be treated since it is beyond the scope of this paper.

BRIEF THEORY OF SPACE PLASMA ENVIRONMENT

The earth's magnetic field magnitude is roughly dipolar; that is

$$B(R, L) = \frac{B_o}{R^3} \sqrt{(1 + \text{Sin}^2 L)} \qquad (1)$$

where

B(R,L) is the local magnetic field magnitude,
L is the magnetic latitude,
R is the radial distance measured in earth radii (R_E), and
B_o is the earth magnetic field at the earth's equator ($B_o = B(R_E, L = 0) = 0.30$ gauss).

As shown in Figure 1, the interaction between the solar wind and the earth's magnetic field can cause the magnetic field on the night side of the earth to stretch into a very large structure known as the magnetotail.[1] A thin plasma sheet bifurcates the magnetotail which extends by about 1000 R_E parallel to the velocity vector of the solar wind.

Because of the interaction between the solar wind and the earth's magnetic field, some of the kinetic energy of the solar wind is converted to magnetic energy stored in the magnetotail. This energy, which cannot build up indefinitely, creates magnetic substorms which dissipate over time. These storms produce energized plasma (5-20 KeV) that is thrust upon the earth. This hot plasma can extend into geosynchronous orbits and charge the dielectric surfaces of any spacecraft to very high negative voltages (>10 kV).

INTRODUCTION TO PLASMA CHARGING OF SPACECRAFT

When spacecraft is in a medium containing free electric charges, the possibility exists that it can develop a charge imbalance in its structure, hence generating an electric field in its vicinity. This phenomenon is called spacecraft charging. The imbalance of charge carriers within the structure of the spacecraft results in a charge density ρ.

From Gauss' law

$$\nabla \cdot \vec{E} = 4\pi\rho \qquad (2)$$

the electric field E can be described in terms of an electrical potential V.

$$\vec{E} = -\nabla V \qquad (3)$$

In the space plasma environment the electrical potential of the vehicle interacts with the external plasma through a rearrangement of plasma charge carriers, creating a distribution function $f(x,y,z,v_x,v_y,v_z,t)$, where $v_{x,y,z}$ is the velocity vector of the plasma charge carriers, which satisfies the Vlasov equation

$$\frac{\partial f}{\partial f} + \vec{v} \cdot \nabla f + \frac{q}{m}(\vec{E} + \vec{v} \times \vec{B}) \cdot \frac{\partial f}{\partial \vec{v}} = 0 \qquad (4)$$

where

q is the charge of the carrier in the plasma, and
m is the mass of such carrier.

Notice that because the space plasma is composed of different carriers (e.g., protons, electrons, ions...etc.), Equation 4 must be satisfied for each of the carriers existing in that particular environment. Given initial and boundary conditions, Equations 2 through 4 must be solved iteratively to obtain the charge density in the spacecraft. If f is a Maxwellian distribution, the complex iteration process can be simplified significantly; such pursuits, however, are beyond the scope of this article.

The charge density and the resulting electrical potential distribution in the spacecraft adjusts itself to an equilibrium condition such that the net electrical current flowing to the spacecraft is zero

$$\sum_i I_i = 0 \qquad (5)$$

where I_i represents the electrical current due to all conceivable charge fluxes between the spacecraft and its environment. At low earth orbit, for example, the following current fluxes will reach a balance[2]:

- the incident ion current (J_i) on the spacecraft's surface,
- the incident electron current (J_e) on the spacecraft's surface,

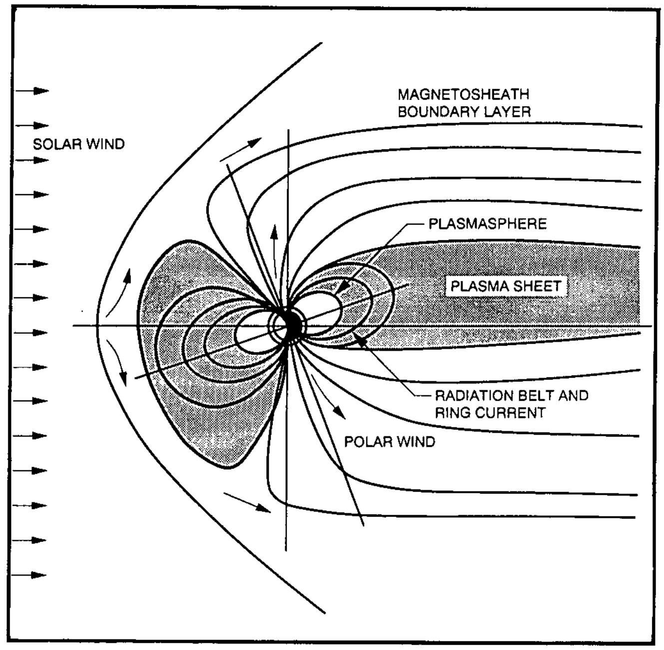

Figure 1. *Interaction Between Solar Wind and Earth's Magnetic Field.*

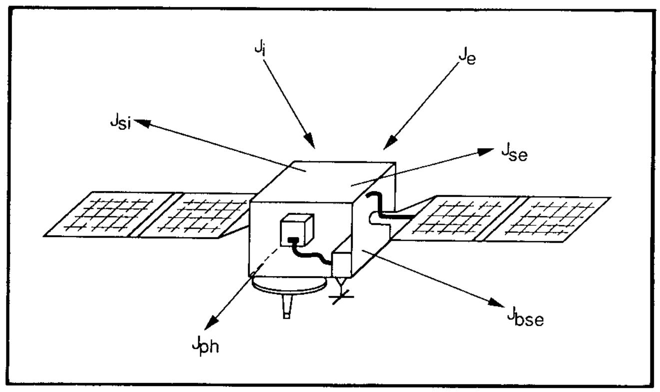

Figure 2. *Current Fluxes in a Spacecraft at Low Earth Orbit.*

- the secondary electron current (J_{se}) due to J_e,
- the secondary ion current (J_{si}) due to J_i, and
- the photoelectron current (J_{ph}) and the backscattered electron current (J_{bse}).

Figure 2 shows the direction of the various currents represented by Equation 5.

An ESD event occurs if the electric field generated by the charged spacecraft exceeds the breakdown potential along the surface of the material or between adjacent materials which are part of the spacecraft dielectric surfaces. Electromagnetic interference (EMI) from ESD events can cause the spacecraft to operate erratically.[3] Figure 3 shows how an ESD event can cause severe perturbation to occur within a spacecraft.

DESIGN GUIDELINES

This section contains some recommendations on design techniques that should be followed in hardening spacecraft systems to spacecraft charging effects. More details of these guidelines can be found in Reference 4. The guidelines are divided into two parts: guidelines which are broadly applicable and guidelines which are more applicable to a particular system.

In general, the following practices are recommended to control satellite charging effects:

- Make the exterior surfaces of the spacecraft conductive and grounded.
- Provide an excellent structural ground system to which all conductive materials, interior and exterior, are bonded.
- Place all electronics inside a well-shielded Faraday cage region.
- Shield exterior cabling and boxes to extend the shielded region over all electronics.
- Filter circuitry which is in locations exposed to ESD.
- Establish assembly procedures to assure that grounding of exterior materials has been implemented per the requirements.

GENERAL GUIDELINES

Grounding. All conductive elements on surfaces and within interiors should be tied to a common electrical ground, either directly or through a charge bleed-off resistor.

- *Structure and mechanical parts*. All structural and mechanical parts, electronic boxes, enclosures, etc. of the spacecraft shall be electrically bonded to each other. All principal structural elements shall be bonded utilizing methods which assure a dc resistance of less than 2.5 mΩ at each joint.
- *Surface materials*. All spacecraft surface (visible, exterior) materials should be conductive in an ESD sense. All such surface materials shall be electrically bonded (grounded) to the spacecraft structure. The dc impedance from surface to structure should be less than $10^9\,\Omega$.
- *Wiring and cable shields*. All wiring and cable exiting the shielded Faraday cage portion of the spacecraft should be shielded.
- *Electrical and electronic grounds*. For ESD purposes, a direct ground reference for all electrical/electronic units to structure is most desirable. If the electronic circuitry can not be isolated from the power ground, the signal ground may be referenced to the structure with a large (> 10 KΩ) resistor.

Exterior Surface Material. For differential charging control all spacecraft exterior surfaces shall be at least partially conductive and grounded.

- *Surface conductivity requirements*. The following guidelines are recommended:
  - Conductive materials (e.g., metals) must be grounded to the structure by $R<10^9/A\ \Omega$, where A is the exposed surface area of the conductor in cm^2.
  - Partially conductive surfaces (such as paints) applied over a conductive substrate must have a resistivity-thickness product $rt < 2 \times 10^9\ \Omega\text{-cm}^2$, where r is the material resistivity in Ω-cm and t is the thickness in cm.
  - Partially conductive surfaces applied over a dielectric and grounded at the edges must have material resistivity $rh^2/t \leq 4 \times 10^9\ \Omega\text{-cm}^2$, where r and t are as above and h is the greatest distance on surface to ground point, in cm.
- *Surface materials*. With the proper choice of available materials, the differential charging of spacecraft surfaces can be minimized. At present, the only proven way that spacecraft potential variations can be eliminated is by making all surfaces conductive and tying them to a common ground. Surface coatings used for this purpose

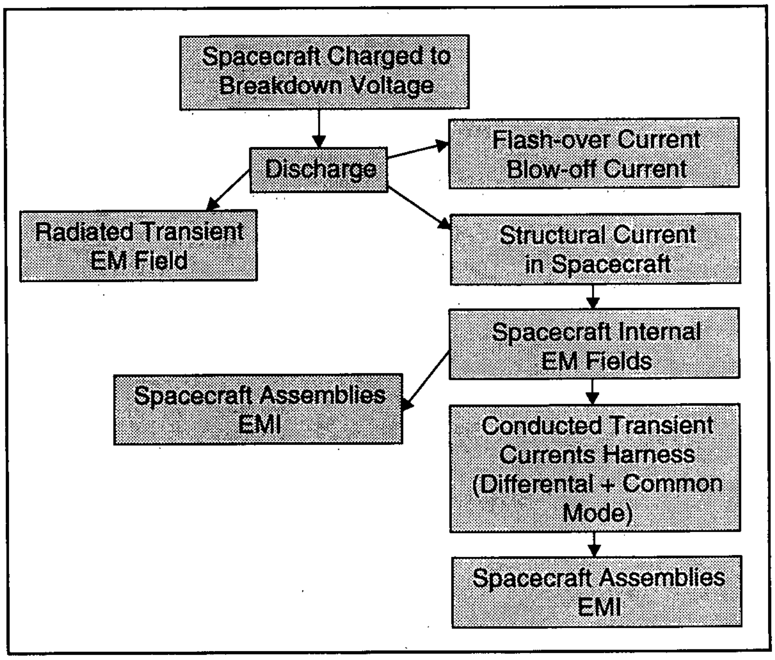

Figure 3. *ESD Perturbations in Spacecraft.*

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ESD PROTECTION . . . (Continued from page 51)

include conductive conversion coatings on metals, conductive paints, and transparent partially metallic vacuum deposited films, such as indium tin oxide (ITO). Table 1 lists and describes some of the more common acceptable surface coatings and materials with successful use history. Table 2 lists and describes other common surface coatings and materials which should be avoided if possible.

- *Nonconductive surfaces.* If the spacecraft surface can not be made 100% conductive, an analysis must performed to show that the design is acceptable from an ESD standpoint.

Shielding. The primary spacecraft structure, electronic component enclosures, and electrical cable shields shall provide a physically and electrically continuous shielded surface around all electronics and wiring (Faraday cage).

Filtering. Electrical filtering should be used to protect circuits from the discharge-induced upsets.

Procedures. Proper handling, assembly, inspection, and test procedures shall be installed to assure the electrical continuity of the spacecraft grounding system.

MATERIAL	COMMENTS
Paint (Carbon Black)	Work with manufacturer to obtain paint that satisfies ESD conductivity requirements and thermal, adhesion, and other needs.
GSFC NS43 Paint (Yellow)	Has been used in some applications where surface potentials are not a problem (apparently will not discharge).
Indium Tin Oxide (250 nm)	Can be used where some degree of transparency is needed; must be properly grounded; for use on solar cells, optical solar reflectors, and Kapton.
Zinc Orthotitanate Paint (White)	Possibly the most conductive white paint; adhesion difficult without careful attention to application procedures.
Alodyne	Conductive conversion coatings of magnesium, aluminum, etc., are acceptable.

Table 1. *Surface Coatings and Materials Acceptable for Spacecraft Use.*

MATERIAL	COMMENTS
Anodyne	Anodizing produces a high-resistivity surface to be avoided. The surface is thin and might be acceptable if analysis shows stored energy is small.
Fiberglass	Resistivity is too high.
Paint (White)	In general, unless a white paint is measured to be acceptable, it is unacceptable.
Mylar (Uncoated)	Resistivity is too high.
Teflon (Uncoated)	Resistivity is too high. Teflon has a demonstrated long-time charge storage ability and causes catastrophic discharges.
Kapton (Uncoated)	Generally unacceptable, due to high resistivity. However, Kapton is sufficiently photoconductive for use in continuous sunlight applications if less than 0.13 mm thick.
Silica Cloth	Has been used as antenna radome. It is dielectric, but because of numerous fibers, or if used with embedded conductive materials, ESD sparks may be individually small.
Quart and Glass Surfaces	It is recognized that solar cell coverslides and second-surface mirrors have no substitutes that are ESD acceptable. Their use must be analyzed and ESD tests performed to determine their effect on neighboring electronics.

Table 2. *Surface Coatings and Materials to be Avoided for Spacecraft Use.*

SUBSYSTEM GUIDELINES

The guidelines in this section are recommended for the following subsystems: electronics, power systems, thermal control, and communication systems.

Electronics. The general guidelines apply.

Power Systems.

- *Solar panel grounding.* Solar array panels and substrates shall be electrically grounded to the structure.
- *Solar panel fabrication.* Solar array panels shall utilize materials and fabrication techniques to minimize electrostatic discharge effects.
- *Power system electrical design.* Power system electrical design shall incorporate features to protect against transients due to ESD.

Thermal Control.

- *Thermal blankets.* All metallized surfaces in multilayer insulation blankets shall be electrically grounded to the structure.
- *Thermal control louvers.* The blades of thermal control louvers shall be grounded.

Communication Systems.

- *Antenna grounding.* Antenna elements shall be electrically grounded to the structure.
- *Antenna apertures.* Spacecraft RF antenna aperture covers shall be ESD conductive and grounded.
- *Antenna reflector surfaces.* Grounded, conductive spacecraft charge-control materials shall be used on antenna reflector rear surfaces.
- *Transmitters and receivers.* Spacecraft transmitters and receivers shall exhibit immunity to transients produced by ESD.

TESTING TECHNIQUES

The philosophy of ESD testing can be categorized as follows:

- The test environment should be more severe than the spacecraft will be subjected to in order to establish some safety margin. The spacecraft will then survive the real environment.
- If an extensive testing sequence is required, test all units of hardware in their more critical operating modes, use long test durations, and apply the ESD test to all surfaces of the unit under test.
- If a modest test program is pursued, delete from test the units which show great design margins, use shorter test durations, test the hardware only in their operating modes, and apply the ESD test to a selected number of surfaces.

Ideally, the spacecraft should be tested in a charging simulation facility. The spacecraft should be electrically isolated from ground and bombarded with high energetic electrons, ions, and extreme ultraviolet radiation to levels corresponding to substorm environment conditions. All spacecraft systems should operate without upset throughout this test. Because it is often difficult to simulate the actual space environment (i.e., space vacuum, plasma species such as ions, heavier ions, electrons, protons, energy spectrum and direction of flow), electrical discharge sources (sparking devices) are used instead. However, care must be exercised because the injected transient source may not be in the same location as the region that may discharge, and a spark in air has a slower rise time than a vacuum arc. The sparking device's location and pulse shape must be analyzed to provide the best possible location of coupling to electronic circuits. For example, to account for the difference in rise time, the peak voltage might be increased to simulate the dV/dt parameter of a vacuum arc.

The following items should be considered in designing ESD tests for spacecraft:

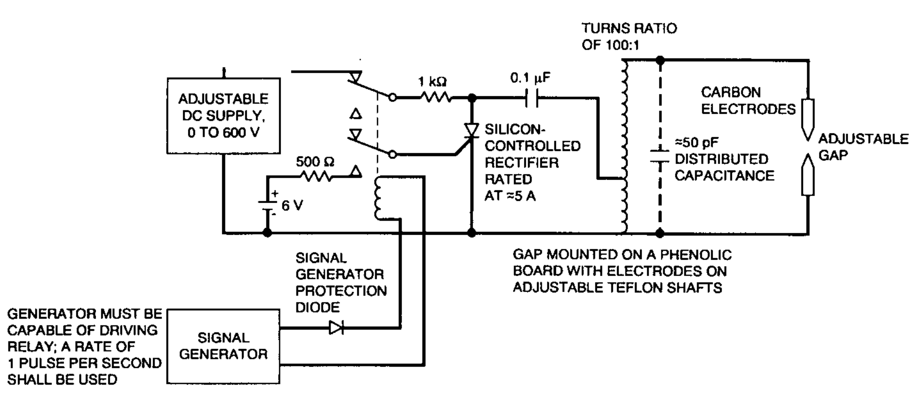
- spark location
- radiated fields or structure current
- area
- thickness and dielectric strength of the material
- total charge involved in the event
- breakdown voltage
- current waveform and voltage waveform (t_r, t_f, t_w, dI/dt, dV/dt).

The most common ESD generating test equipment is the MIL-STD-1541 arc source[5] (Figure 4). Other types of test equipment can be found in Reference 4. Three basic methods are used for ESD testing: radiated field test, single-point discharge test, and structural current test. The radiated energy can range from a few millijoules to 1 joule, depending on the type of space environment expected.

Radiated Field Test. This technique is used to check for RF interference to communication or surveillance receivers as coupled into their antennas or apertures. It can also be used to check the susceptibility of scientific instruments that will measure plasma or natural radio waves. The sparking device will be operated at some distance from the spacecraft assembly under test. Typical RF spectra are shown in Figure 5.

Single-Point Discharge Test. This test involves discharging an arc onto a spacecraft surface (or a temporary protective metallic fitting). The test is more severe than the radiated test, since it is performed immediately adjacent to the spacecraft rather than some distance away.

Structural Current Test. The objective is to simulate a "blow-off" of charges from a spacecraft surface. If a surface charges, and a resultant ESD



TYPICAL GAP-SPACING AND VOLTAGE BREAKDOWN LEVEL

GAP, mm	VOLTAGE BREAKDOWN, kV	APPROXIMATE ENERGY DISSIPATED, Joules
1	1.5	56.5×10^{-6}
2.5	3.5	305
5	6	900
7.5	9	2000

Figure 4. *Schematic Diagram of MIL-STD-1541 Arc Source.*

occurs, the spark may vaporize and mechanically remove material and charges without local charge equalization. In such a case, the remaining charge will redistribute itself and cause structural currents. Defining the actual blow-off currents and the paths they follow is a difficult problem. It is important, nevertheless, to conduct structural current tests to determine the susceptibility of the spacecraft to structural currents by using test currents and test locations supported by analysis.[6-7] Typically, such tests can be accomplished by using one or more of the following current paths (Figure 6): 1) diametrically opposed locations through the spacecraft; 2) protuberance (from landing foot to top and from antenna to body; and from thruster jets to opposite side of body); 3) extension to booms (from end of sensor boom to spacecraft chassis and from end of solar panel to spacecraft chassis); and 4) from launch attachments point to the other side of spacecraft.

The test using current path 1 is of a general nature. Tests using current paths 2 and 3 simulate probable arc locations on at least one end of the current path. These test points include thrusters, whose operation can trigger an incipient discharge, and landing feet and their attachment points, especially if used in a docking maneuver, when they could initiate a spark to the mating spacecraft. Test 3 is very useful because solar panels often have glass (nonconductive) covers, and sensors may have optics (also nonconductive) that can cause an arc discharge. In both cases, any blow-off charge would be replaced by a current in the supporting boom structure that could couple into cabling in the boom (see Reference 7 for analysis). This phenomenon is the worst-case event that could occur in a spacecraft because the common length of the signal or power cable near the arc current is the longest on the spacecraft, and considerable crosstalk coupling could occur.

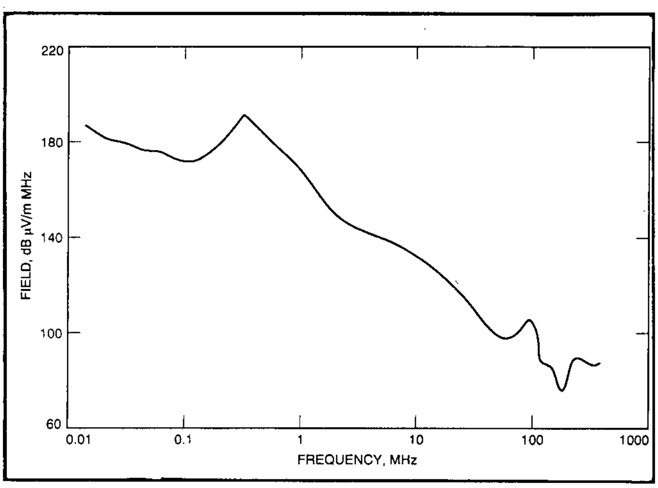


***Figure 5**. Typical RF Radiated Fields from MIL-STD-1541 Arc Source.*

ASSEMBLY vs. SPACECRAFT ESD TESTING

An outline of differences in the priorities of assembly testing versus whole spacecraft testing are identified.

ASSEMBLY ESD TESTING

The purpose is to identify design deficiencies in the early stages when changes can be easily made. However, it is difficult to provide a good determination of the assembly's environment as caused by an ESD event on the spacecraft. Assembly testing could specify a single ESD test for all units or could provide several general categories of test requirements. The following categories are described:

- Internal spacecraft assemblies must survive, without damage or disruption, the MIL-STD-1541 arc source test (discharges to the assembly but no arc currents through the assembly's chassis).
- External assemblies (usually exterior sensors) must survive the MIL-STD-1541 arc source at a 5 kV level with discharge currents passing from one corner to the diagonally opposite corner (four pairs of locations).
- For assemblies located near known ESD sources (e.g., solar array, Kapton thermal blankets, etc.), the spark voltage and other parameters must be tailored to be similar to the spark that is expected from that dielectric surface.

The test configuration for assembly ESD testing is similar to the one for radiated susceptibility testing. The assembly is placed on and electrically bonded to a ground copper-topped bench,and is cabled to its support equipment. The assembly and

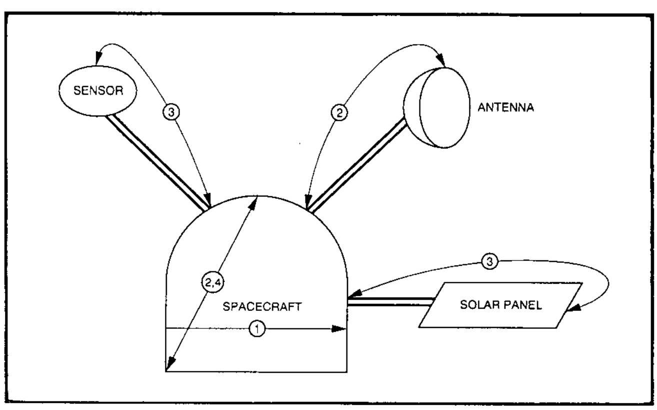


***Figure 6**. Paths for ESD Currents Through Structure.*

associated cabling should be of flight condition. The assembly should be operated in all modes appropriate to the ESD arcing situation. Furthermore, the assembly should be operated in its most sensitive condition to maximize the susceptibility to an ESD event.

WHOLE SPACECRAFT ESD TESTING

System level testing usually provides the most realistic assessment of the expected performance of a spacecraft to an ESD event in the given plasma charging environment. The tests should be conducted on a representative spacecraft before exposing the flight spacecraft to similar tests, in order to insure that there will be no overstressing of flight assemblies.

Detailed test procedures must be developed which define all the parameters to be investigated. The techniques will involve current flow in the spacecraft structure. Shielded rooms are recommended for such tests. MIL-STD-1541 system test requirements and radiated electromagnetic interference tests are to be considered a minimal sequence of tests. Spacecraft should be isolated from ground and both spacecraft and instrumentation should be on battery power. The complete spacecraft telemetry should be monitored. Voltage and current probes, electric and magnetic field monitors, and other sensors should be installed at critical locations. The test levels should be determined from analysis of discharge currents in the given plasma charging environment. It is recommended that full level testing, with test margins, be applied to a representative spacecraft (also known as an engineering or qualification model) with only reduced levels applied to flight units. A typical test plan includes the following steps:

- The MIL-STD-1541 radiated test is applied around the whole spacecraft.
- Spark currents from the MIL-STD-1541 arc source are applied through the spacecraft structure from launch vehicle attachment points to diagonally opposite corners.
- ESD currents are passed down the length of booms with cable routed along them. The noise coupling into the cables is monitored.
- Special tests are recommended for special cases (e.g., ESD from thermal blankets). ESD tests should be applied based on the predicted ESD characteristics obtained from previous analyses.

CONCLUSION

An introduction to the charging phenomena in spacecraft has been presented. While triboelectric charging is the main mechanism for charging of dielectric surfaces here on earth, charging of spacecraft in a space plasma environment occurs through entirely different physical processes which were very briefly described. As a response to the severe threat that ESD poses on spacecraft assemblies, detailed guidelines, analyses, and testing procedures have been developed through the years to minimize ESD phenomena and to contain the damaging consequences. An introduction to such guidelines and testing methodologies has been provided.

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