EVALUATION OF ESD EFFECTS ON SOLAR ARRAY
in Different Space Missions

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Keywords: Electrostatic Discharge, Solar Array, Electrical Power Subsystem.

Abstract: This paper studies the electrostatic discharge effects on solar arrays in different orbits. This paper starts with a statistical overview of solar array failures and their relations with ESD events. Then the space environmental conditions and their impacts on ESD occurrence are discussed for the most commonly used orbits for satellite missions. Spacecraft charging phenomena and different modes of charging are studied further in the paper. Finally the effects of ESD events on the elements and subassemblies of solar arrays are investigated.

1 INTRODUCTION

Increase in energy demand in new high power telecommunication and observation satellites leads to need for higher power generation by their electrical power subsystems (EPS), which requires larger area of solar arrays (SA). Larger SA provide more power, and deliver it to the loads through higher voltage buses, which made them more susceptible to Electrostatic Discharge (ESD).

At the same time increase in power consumption may require a higher level of current drawn from a typical primary regulated bus, that in turn augments the risk of ESD event on SA cables and the whole harness subsystem of the satellite. Therefore more knowledge about ESD and its impacts on the EPS, especially on SA design and operation, is an essential requirement in designing high power satellites.

2 SOLAR ARRAY FAILURES

Immunity against ESD is an essential requirement in subsystem level for designing the EPS of a satellite. Among all the EPS elements and parts, SAs are the most susceptible one to ESD effects. ESD events can take palce on SA and most of its subassemblies like solar cells, coverglasses, metallic frames, cables and connectors, in different conditions which are exist in various space missions.

During ten years of space missions (1996-2006), more than 47% of the numbers of insurance claims for the satellite failures were because of the EPS faults and anomalies. Almost the half of the costs of these failures are related to SA anomalies, and more than 90% of the array anomalies are due to the failures in their elements and subassemblies operation. The majority of these in-orbit failures and anomalies are originated from ESD events on SA. The bar-chart in figure 1 shows the number of SA anomalies in different orbits during 1996-2006 and the pic-chart at top right side of figure 1, displays the percentages of these anomalies (Rodiek, 2008).

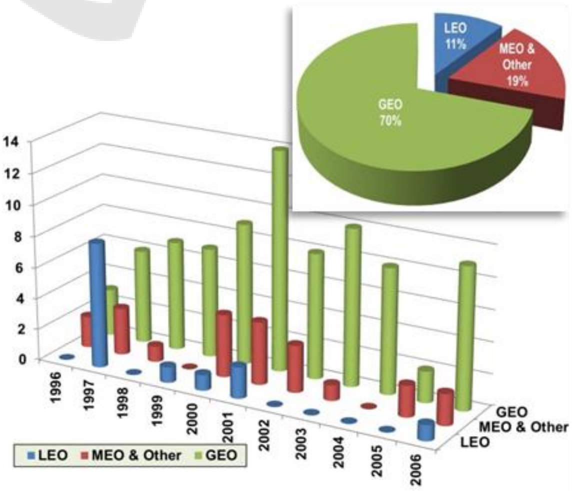

Figure 1. The numbers of solar array anomalies in different orbits during 1996-2006 (bar-chart), and the percentages of these anomalies (pic-chart at top right)

Shekoofa O. and Kondori M.
EVALUATION OF ESD EFFECTS ON SOLAR ARRAYin Different Space Missions.
DOI: 10.5220/0005414500940098

In Proceedings of the First International Conference on Telecommunications and Remote Sensing (ICTRS 2012), pages 94-98
ISBN: 978-989-8565-28-0

In order to avoid such dominant risk in SA operation, it is required to consider the ESD phenomenon, the enviromental conditions for ESD occurrence and its causes in designing SA. It is also needed to apply adequate ESD control and mitigation techniques in the EPS manufacturing and assembly process.

3 ESD & SPACE ENVIRONMENT

The main reasons for ESD occurance on SA is the accumulation of electrical charges on the SA surface. Whenever charge buildup takes place, there will be the risk for ESD event. The existent space environment which surrounds the whole satellite, generates the required conditions for causing the ESD events. Satellites in different orbits encounter different environmental conditions like plasma and Sub-storms. Therefore they experience different levels of internal and external charging which might lead to different levels of risks for ESD occurrence.

In table 1, three different levels are defined for the possibility of spacecraft (SC) charging in different orbits (Mazur, 2003). These levels are in compliance with the illustrated information in figure 1. Table 1 also shows different possibilities for charging on SC surface and internal parts which will be discussed in continue of this paper.

Table 1: Spacecraft charging levels in different orbits

Orbit	Surface	Internal
LEO, Inclination <60	Low	Low
LEO, Inclination >60	Medium	Low
PLEO	High	Medium
MEO	High	High
GPS	High	High
GTO	High	High
GEO	High	High
HEO	High	High
Interplanetary	Low	Low

According the information of table 1 and regarding the importance of GEO and LEO orbits for satellite missions, the environmental conditions in these orbits are considered in more detail in sections 3.1 to 3.3, and summarized in table 3 (ISO 11221:2011).

3.1 GEO Conditions

GEO is characterized by the presence of electrons with energies (E_e) greater than 1keV. In GEO orbit two different conditions may be considered:

- Quiet condition: refers to a condition where in the absence of solar sub-storms the current of the incident electrons (J_e) is less than the photoelectron current (J_{ph})
- Stormy conditions: where J_e is higher than J_{ph}

3.2 LEO Conditions

LEO is characterized by the presence of low energy but dense ionospheric plasma. For an object in this condition, current from electrons of energies 0.1 to 0.2 eV dominates over any other current source to spacecraft.

3.3 Polar LEO Conditions

Polar LEO (PLEO) is characterized by auroral electrons, with energies greater than 1keV, which coexist with the low energy ionospheric plasma.

Table 2: The specifications of different orbits' conditions

	Conditions	Specifications
GEO Quiet	High energy electrons (No magneto-spheric substorms)	E_e> 1keV $J_e < J_{ph}$=10µA.m^{-2}
GEO Stormy	High energy electrons + Emitted secondary electrons (Magneto-spheric substorms)	E_e> 1keV $J_e > J_{ph}$
LEO	Low energy but dense plasma,	Particles density ≈ 10^8 to 10^{12} m^{-3}
	Attracted ions to the negatively charged SC body	J_e is generated by electrons with E_e ≈ 0.1 to 0.2 eV
	SA bus voltage level	$V_{SA\text{-}BUS}$>100 V
PLEO	Auroral electrons + Low energy ionospheric plasma LEO-like dense plasma+ GEO-like high energy plasma	E_e >1keV J_e= 1mA.m^{-2} > J_{ph}

Since the actual space environments are not known precisely, it is common to use a simulated environment for numerical simulations and calculations purposes instead. For example, NASA recommended "worst case" charging environment is presented in table 3. Sensitivity studies have shown that the actual condition for SC charging is much less severe than these conditions (Katz, I., and others, 2000).

Table 3: NASA Simulated Environment Parameters

Parameter		Value	Dimension
Electron number density	n_e	1.12×10^6	m^{-3}
Electron temperature	T_e	12	keV
Ion number density	n_i	2.36×10^5	m^{-3}

Parameter		Value	Dimension
Ion temperature	T_i	29.5	keV

4 SPACECRAFT CHARGING

The essential reason for ESD occurrence is the SC charging. In different missions with various orbit parameters, different charging conditions may exist. For example, a typical ESD event can occur under the following conditions (NASA Report, 2007):

- Vacuum pressure $<10^{-5}$ torr, and either
- Dielectric surface voltage is greater than 500V
- The electric field between a dielectric surface and a conductor is greater than 10^5 volts/cm.

Each of these two electrical characteristics can be generated by a certain environmental condition. This is why the probability of ESD occurrence directly depends on the space condition in the studied orbit. For instance the electrical characteristics, such as electrostatic potentials (V_{ES}) of the various parts of the SC, in a GEO satellite can be totally different than the similar parameters for a LEO satellite due to the different charging levels. Some of these differences are presented in Table 4.

Table 4: Charged parts and the relevant electrical effects in different orbits

	Charged Parts	Electrical Effects
GEO	SC body (between adjacent surfaces)	$V_{ES} = V_{SC} \approx$ several hundred to several thousand volts (particularly during sunlit)
LEO	SC body	Charging rate ≈ -5 V/s.
	Coverglass and underlying cell	$V_{ES} \approx$ several hundred volts $dv/dt \approx 3$ V/s
	The front surface of the SA faces the Sun	J_e (consisted of charges which are constantly bled off via photoemission from cell coverglasses)
	Gaps between the solar cells, (shaded by the edges of the solar cells)	Negatively charged
PLEO	SC body	$V_{SC} < V_{SA\text{-}BUS}$

5 CHARGING MODES

According to table 1 there are two types of charging for spacecrafts: surface charging and internal charging. Surface charging consists in the charging on visible and touchable areas of the external part of the satellite. Internal charging is resulted from the penetration of energetic electrons into the satellite enclosures (like Ebox) and deposit charge very close a victim site. Since ESD on SA mainly occurs because of surface charging, this type of charging will be more discussed.

5.1 Surface Charging

Surface charging may cause ESDs and arcing on solar arrays and their power cables. It is generally caused by electrons of 5-50 keV in GEO, 2-20 keV in PEO, or high voltage arrays in LEO (Cho, M, 2007). Table 5 provides more information on the causes and effects of charging in different orbits (Ley, W., and others, 2009) (Leung, P, 2010). It should be mentioned that there are two types of potential gradients noted in table 4 as follow:

- Normal Potential Gradient (NPG) which is resulted of differential charging where the insulating surface or dielectric reaches a negative potential with respect to the neighboring conducting surface or metal. It is sometimes referred as Negative Dielectric Positive Metal (NDPM) condition.

- Inverted Potential Gradient (IPG), which is also called Positive Dielectric Negative Metal (PDNM) mode, is the result of differential charging where the insulating surface or dielectric reaches a positive potential with respect to the neighboring conducting surface or metal.

Table 5: Charging causes and issues in different orbits

	Charging Causes	Charging Issues
GEO Quiet	$E_e \approx$ 5-50 keV	No serious surface charging issue
GEO Stormy	SC potential: − Dielectric charged: + In sunlit: 10^2 to 10^3 orders of Volts between adjacent surfaces	IPG
LEO	High voltage arrays V_{SC} floats with respect to the ionospheric plasma potential, within $V_{SA\text{-}BUS}$ range	IPG Min (V_{SC})= $V_{SA\text{-}BUS}$ $V_{Discharge} \approx -200$ V

	Charging Causes	Charging Issues
PLEO	$E_e \approx$ 2-20 keV Driving V_{SC} to a potential more negative than $V_{SA\text{-}BUS}$	Min (V_{SC})= $V_{SA\text{-}BUS}$

5.2 Charging Status during In-orbit Operation

When the satellite continuously passes through cyclic sunlit and eclipse phases, the environmental conditions of the satellite change in the same cyclic manner. In table 6 typical values are mentioned for the main parameters which lead to ESD event during sunlit and eclipse phases in GEO orbit (Payan, D. and others, 2012). For example while the V_{SC}<0, an IPG can be formed due to the ion incident at the ram side of the spacecraft. On the other hand, a NPG can exist even if the V_{SC} is near the LEO plasma potential, i.e., nearly zero (ISO 11221: 2011).

Table 6: Typical electrical characteristics in GEO

	At the ram side of SC and/or in Light Phase	At the wake side of SC and/or in Eclipse
GEO Quiet	Ee ≈ 20 KeV Je ≈ 30-80 pA.cm^{-2}	SC: Negative Potential
		IPG: due to the ion incident
		Ee ≈ 20 KeV Je ≈ 30-80 pA.cm^{-2}
GEO Stormy	IPG: because of the secondary emissions due to the auroral electron incident	Conditions are met to prepare an ESD event when the SC will be powered again at eclipse exit
	NPG: due to SA surface potential	
	$V_{Dielectric} < V_{SC}$ $J_{ph} \approx$ 2 nA.cm^{-2}	
	Max $V_{SC} \approx$ the potential barrier stops the Je leading to a new equilibrium voltage	

These charging statuses could be considered from another point of view, as provided in table 7. This table presents the several impacts of ESD on conductive and insulator parts in different ram and dark sides of the solar arrays (ISO 11221: 2011).

Table 7: Impacts on conductive and insulator parts

	Conductive Parts	Insulator Parts
GEO	Solar cell electrode, interconnector, or bus-bar are negatively charged, equal to V_{SC}	Coverglass, adhesive, or facesheet, have negative potentials, but the values can be different from V_{SC} by 1 kV or greater
LEO	Conductive parts have potentials ranging from -$V_{SA\text{-}BUS}$ to +$V_{SA\text{-}BUS}$	Differential charging on the solar array surface appears as the insulator parts have potentials close to the ambient plasma potential
	ESD issues arise only when $V_{SA\text{-}BUS}$ exceeds the primary arc or snap over threshold voltage	
PLEO	Solar array front surface is facing the ram side in PEO, the aurora may drive the spacecraft body potential negative	insulator surface may be charged by ionospheric ions to a potential close to the ambient plasma potential

6 EFFECTS ON SOLAR ARRAYS

Common problems due to ESD on SA can be divided into two categories according to the duration of their influences:

- Transient effects like primary arcs, EMI and its consequent effects
- Permanent damage like secondary arcs, ESDs, and which cause power cabling or solar array failure

These effects, which threaten the reliability and durability of SA operation seriously, could also be divided into the following categories:

6.1 ESD Direct Effects

Discharge arcs are the first and the most important impacts of ESD events. They have insufficient energy or currents to lead to permanent damage of SA. There are two types of arcing with different levels of risks: Primary and Secondary Arcs. Primary arcs are not so hazardous; however analysis showed that these short duration primary charging arcs could trigger long duration secondary discharges, especially between solar cells supported by the solar array current itself, which can be considred as the source of more severe risks (Katz, I. and others, 2000).

6.1.1 Primary Arcs

If the voltage difference reaches a sufficient level, some electric arc discharges will occur which called primary arcs. These discharges carry very little energy and are harmless. However, they can set free plasma which settles in the gaps between the cells. Several hundred discharge events can lead to a plasma concentration establishing a low ohmic connection to the adjacent solar cell. Primary arcs can only be avoided by a conductive coating of SA surface. Unfortunately this solution facilitates the conditions for a more severe disadvantage, i.e. allowing secondary electric arcs. A better solution can be applied by considering appropriate distances between the adjacent solar cells during the solar cell string design. In this technique the voltage difference between adjacent cells as a function of the gap size between the cell edges never reaches the discharge level and that the driving current remains low enough. The latter is achieved by adding a decoupling diode in series to each string and by parallel connection of the strings to an array behind the diode (Ley, W., and others, 2009).

6.1.2 Secondary Arcs

Secondary arcs will occur if the difference between the nominal operating point voltages of the adjacent cells is high enough and if an appropriate photocurrent is generated within the cells. These sustained arcs could carry sufficient energy to cause permanent damage by evaporation of solar cell material and of the underlying insulation (string failures). The trend to higher voltage and higher power solar arrays makes this type of destructive arcing more probable (Ley, W., and others, 2009).

6.2 ESD Indirect Effects

6.2.1 EMI Generation

One of the most important indirect effects of ESD event is the Electromagnetic Interference (EMI). EMI can be generated both in conducted emissions (CS) and radiated emissions (RS) types. CS occurs as a result of the replacement current that originates when charge is blown off the dielectric surface inducing a replacement current to flow from the satellite structure. RS is generated by the ESD current pulse. The rapid surface potential change induces noise in circuits through capacitive coupling. The discharge current can also induce an inductively coupled signal into the victim circuit. Furthermore, RS can cause diverse forms of field-to-circuit coupling (NASA Report, 2007).

6.2.2 Current Leakage

Since satellite structure parts are made of conducting material, the body serves as a grounding point in the spacecraft circuit. Currents to/from conductive parts exposed to space, and the capacitance between the SC body and ambient space determine the body potential with respect to the ambient space plasma. These current leakages can also reduce the efficiency of SA operation as presented in table 8 for a positively charged solar array (Scolese, C.J, 2007).

Table 8: Leakage current influence on solar arrays power

Altitude [km]	Electron density Ne [cm^{-3}]	Leakage Current [$nA.cm^{-2}$]	Power loss [%]
500	6×10^5	824.5	7.72
700	2×10^5	274.8	2.57
1000	7×10^4	96.19	0.90
2000	2×10^4	28.38	0.265
300000	1×10^2	0.29	0

7 CONCLUSIONS

The effects of ESD event on solar arrays were discussed in this paper. The relations between the environmental conditions and ESD events were investigated and compared for different orbits firstly. Then the charging modes were considered especially for surface charging which is more applicable to solar array in-orbit operations. Finally some impacts of ESD events were discussed for the operation of solar arrays in GEO, LEO and polar LEO orbits.

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