Robust Design of Satellite Systems against Spacecraft Charging

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Abstract: Space plasma can build up high differential potentials on satellite surfaces resulting in electrostatic discharges (ESD), sometimes causing anomalous behavior of satellite systems. As these phenomena give rise to possible risks affecting the performance of satellite, the charging is one of major concerns for satellite manufacturers. It has been investigated the influence of charging phenomena on satellite systems and its mitigation techniques. Our activities include not only investigation of influences on power systems but also that of other risks such as electromagnetic compatibility (EMC) or immediate surge to electronic device. In this paper, some of our assessments and the concerned problems are reported. It is obvious that international standardized guidelines for designing satellite systems against ESD will be established in the near future. It would be desirable if the requirements shall be appropriate and practical for satellite systems design, manufacturing and testing.

1. Introduction

It has been investigated how ESD might affect satellite systems. The effects potentially have the various types of risk, such as the defects on power systems, the electromagnetic interference (EMI) with communication systems or direct effect to electronic device. This paper begins with the introduction of related techniques and problems from the viewpoint of systems design, as general remarks. Then, some of our assessments and the concerned problems are introduced.

The mechanisms of charging and discharge on the spacecraft are not detailed in this paper, but reported in Ref.1 *et al.*

2. Our activities

General measures to avoid ESD hazards are firstly outlined and then our studies related to ESD effects on the satellite systems, such as electrical cables, solar array and electric components, are introduced.

2.1 Generalities

Fundamentally, the designs against ESD are carried out according to the guideline documents and the demand specifications applied in each project. There is also the case that extra designs would be specially applied to the parts assumed to be critical. On the other hand, the cost and the productivity to manufacture ought to be considered, while taking account of requirements or other limitations. It is often difficult to find the optimum solution because of this design and manufacture restrictions.

Figure 2.1-1 shows the general mitigation techniques and issues concerning ESD effects on satellite systems. On the other hand, figure 2.1-2 indicates the typical sequence of designing satellite systems.

Regarding design standards, there are some of international and national guidelines in which the countermeasures against ESD are described, *e.g.* Ref.2-4. Most of these documents are established as the designing rules for EMC. While design guidelines for charging and discharging are described as one of contents, specifications are not equivalent to each other.

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2.2 Influences of ESD on satellite systems

Table 2.2-1 summarizes the influences of ESD on satellite systems. Some examples of our designs and problems are also illustrated briefly.

【Antenna feed】
- Aperture cover: Conductive coating → PIM or electromagnetic reflection.

【Reflectors】
- Thermal control material coated with conductive materials → PIM or electromagnetic reflection
- Grounding →Difficulty to be constructed

【Solar array】
- Short circuit between cells: adequate separation or insulation between strings
- Short circuit caused by degradation of insulation underneath cells: Reinforcement of insulation
- Preventing leakage of solar array current [Leakage into surrounding plasma (around LEO, transfer orbit or electric-propulsion plume)]
- Conductive coating over cover glass → Difficulty to be constructed
- Preventing contamination or degradation on cells (degradation of performance of power generation)
- Protection of exposed harness: Wrapping by means of conductive material →Difficulty for movable parts

【Outside of structures】
- Proper skin thickness against high-energy radiation
- Purpose as 'Faraday cage' : Aluminium-skin enclosure
- OSR with conductive coatings: Prevention from charging
  → Costly and hard to be handled
- Applying Black Kapton ® blanket and ITO coating
  → Costly and hard to be handled
- Protection of pyrotechniques and EED cables : Shielded and grounded electrically
- Protection of exposed harness : Coating by means of conductive material →Difficulty to apply movable parts

【Inside of structures】
- Adequate thickness of device case against high-energy radiation
- Grounding : Prevention from noise and charging
- Insertion of diodes and filters into power line : Protection of surge
-Shielding signal lines: Prevention from noise

Figure 2.1-1 General design philosophy and issues against ESD

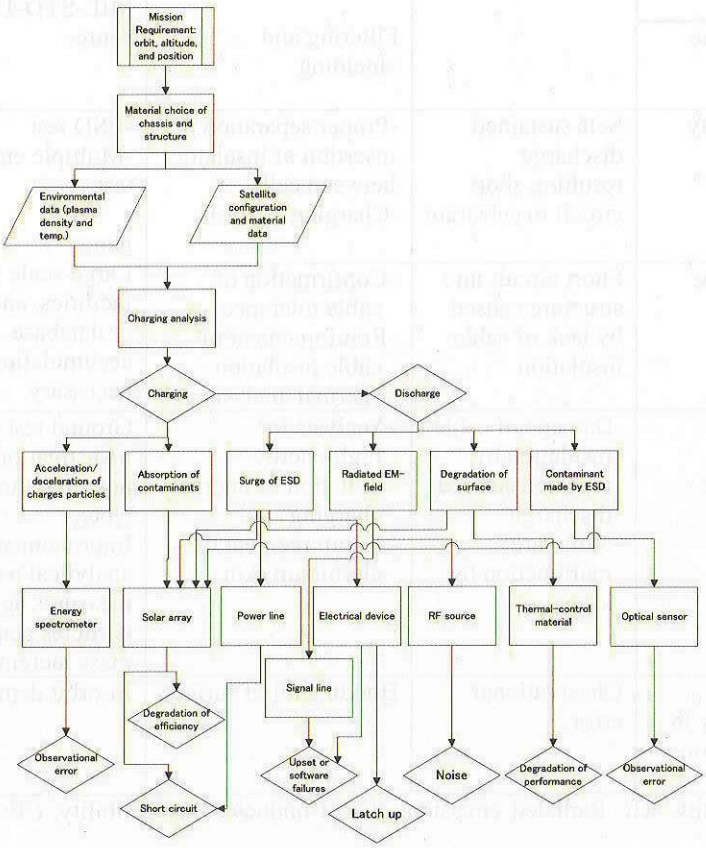

Figure 2.1-2 Typical designing sequences

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Table 2.2-1 Influences of ESD on satellite systems and the countermeasures

Causes	Fail part	Influence on Systems	Guidelines for Design	Design Inspections	Product Inspections
Surge generated by ESD	Power line	-Direct effect: surge injection → circuit destruction -Indirect effect: coupling → software malfunction	-Grounding to avoid charging, in particular, for sensitive devices against ESD -Shielding to avoid coupling by induced field	Qualification test with exposing to MIL-STD-1541 arc source Note. 1) RS and CS with ESD were investigated experimentally in 1982. 2) The effects on device after arcing test at voltage of 10kV and distance of 30cm are evaluated.	EMC or arcing test using engineering model: CS, BR
	Signal line				
	Electrical device (inner circuit, elements, etc.)	-Discharge penetration into device case (or leakage into chassis) - Software fault by coupling			
	Pyrotechnic device	Unexpected ignition			Not Required
Surface degradation or contamination caused by Joule heating of discharge current	Coverglass, OSR (optical solar reflector), aperture cover, etc.	Degradation of performance	Ref.5	Arcing test as described in next section	Not Required
Noise generated by ESD	Electronic device or RF source	Noise	-MIL-STD-461E -MIL-STD-1541 Filtering and shielding	Qualification test with exposing to MIL-STD-1541 arc source	EMC and ESD test using engineering model: RS, RE
	Signal line				
Short circuit in power lines or to structure	Solar array	Self-sustained discharge resulting short circuit to substrate	-Proper separation or insertion of insulator between cells -Charging analysis	-ESD test -Multiple environmental test Note. Large-scale test facilities, analytical tools or database accumulation might be necessary.	Insulation resistance test, Visual inspection
	Power line	Short circuit into structure caused by lack of cable insulation	-Confirmation of cable tolerance -Reinforcement of cable insulation -Thermal analysis		Insulation resistance test, Visual inspection
Internal ESD	In-body cables or electronic device	-Damage of cable insulation by repeated surface discharge - Software malfunction by surge	-Analysis for high-energy radiation or internal charging - Reinforcement of aluminum skin	Ground test or in-orbit investigation (e.g. potential monitor) Note. Improvement of analytical techniques, measures against particles penetration vs. mass increment	Not Required
Effects by charging	Sensors, especially in observation satellite	Observational error	Bonding all of surface	In-orbit demonstration	Not Required

*RS: Radiated susceptibility, RE: Radiated emissions, CS: Conducted susceptibility, CE: Conducted emissions, BR: Bonding requirements

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2.3 Influences on bus line

Since the wires transmitting the electric power and signals use the dielectric substance as an insulator, they have the possibility to cause the charging problem due to the charged particles. Our fundamental rules designing bus lines against ESD are introduced briefly as follows:

(a) Grounding:
- The electrically floating electrode (metal) is avoided.
- The shields of wire should be grounded to satellite structure frame.

(b) Material choice:
In order to avoid the effects of charging, the dielectric is selected in consideration of
- Corona-discharge-proof,
- tolerance to high voltage,
- in addition, low resistance.

(c) Mounting:
As aluminum-skin structure functions as a Faraday cage, cables are mounted inside of satellite body and the outside parts limited to the minimum. Although the configuration as routed directly from outside into inside the body is avoided, even in such a case, connection through the relay connector is used in order to separate between inside and outside dielectrics.

Concerning assembling wires and connector inside of the body, it is based on the design which does not have any exposed electrodes for instance, by adhesive potting, Kapton® attachment and so on.

2.3.1 Influences on power line

Though the surge of ESD has little influence on the power line immediately because of the characteristics of low impedance, a wire mounting design takes prevention of a short circuit into consideration. The damages of cable insulation caused by the repetition of ESD can lead to the short circuit, that is, self-sustained discharge. It is the reason for selecting insulation with high-voltage proof, and keeping insulation distance not to arise self-sustained discharges between HOT and RTN line even if triggering discharge occurs.

As direct influence of surge, current penetrating cable insulation, a latch-up or upset of electronic device is assumed. Accordingly, the concerned lines are made of double insulation covering with both ETFE and a glass-fiber tape, and withstand voltage test is carried out in order to confirm the effectiveness.

2.3.2 Influences on signal line

As influences of the surge on signal line, there might be incorrect behaviors of electronic systems by the induced electric field. The concerned cables are made of shielded jackets, double-shielded if necessary, to prevent its effect by the induced field. Besides, the grounding as close a connector attachment as possible is considered in order that surge current would not directly affect on electronic component.

2.4 Influences on solar array

Regarding the effects on solar array, the electric-short failure caused by sustained discharges between the cell strings has been pointed out. Charges caused by interaction with space environment can induce an ESD between cover glass and cell. The electric power supplied from solar array concentrates at the discharge point and causes short circuit, so-called sustained arc between the cell strings through plasma generated by the ESD. Continuous energy supply through solar array heats and degrades insulation on the substrate surface. This deterioration of insulation can cause solar-array current to flow into substrate. This phenomenon was assumed to be cause of the trouble of TEMPO-2 satellite on the geostationary orbit [6] and has been focused on thereafter.

From these viewpoints, we have intended to make the mechanism clear by investigating discharge characteristics. Figure 2.4-1 shows an example of simulated results on the potential distribution in the neighborhood of the cell gap. From this figure it is evident that both upper edges of the cells have higher electric field because of the dense concentration of the equi-potential lines and that the potential distribution over the cell gap expands to free space and the potential gradient exists on the cover glass. Therefore, the electron emission causing ESD initiates at the triple junctions of the upper edges of the cells.

Experimental investigation indicated that the inverted potential gradient as one of conditions causing discharges was formed on the sample by negatively biasing the sample and by irradiating electron beam to it. Figure 2.4-2 illustrates the test setup. The experiments by measuring transient currents and observing discharge lights induced at the time of the occurrence of ESD were performed. The detailed results were reported in Ref.7.

Based on these analytical and experimental results, the robustness and validation of our solar array design have been verified. Furthermore, we are planning continuous investigation for future high-power satellite.

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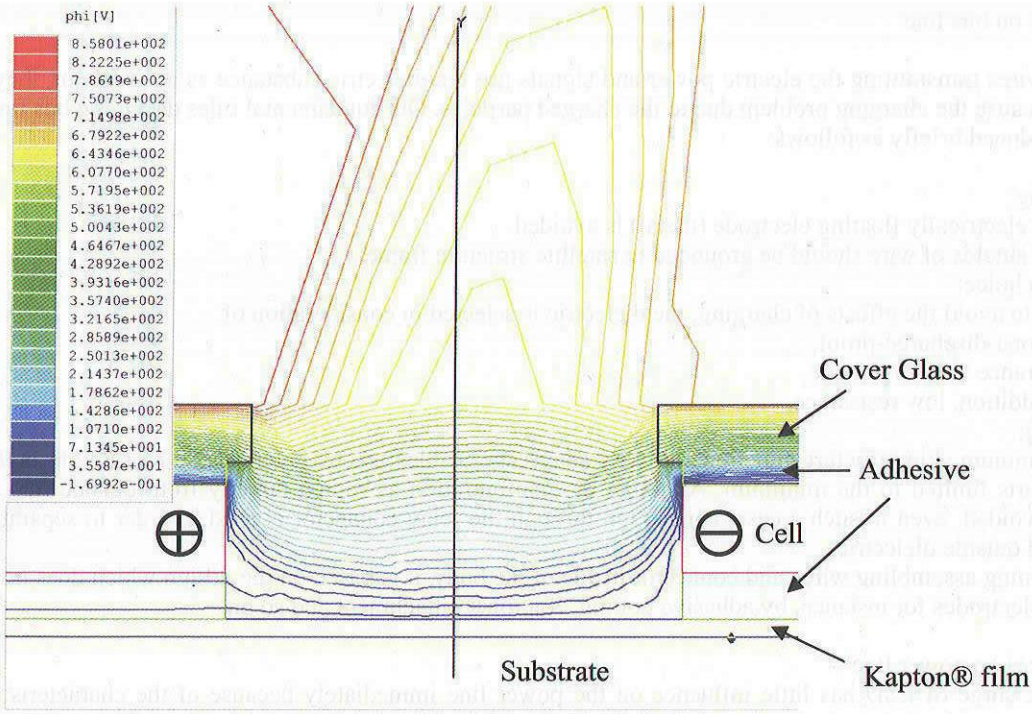

Figure2.4-1 Potential distribution near the cell gap

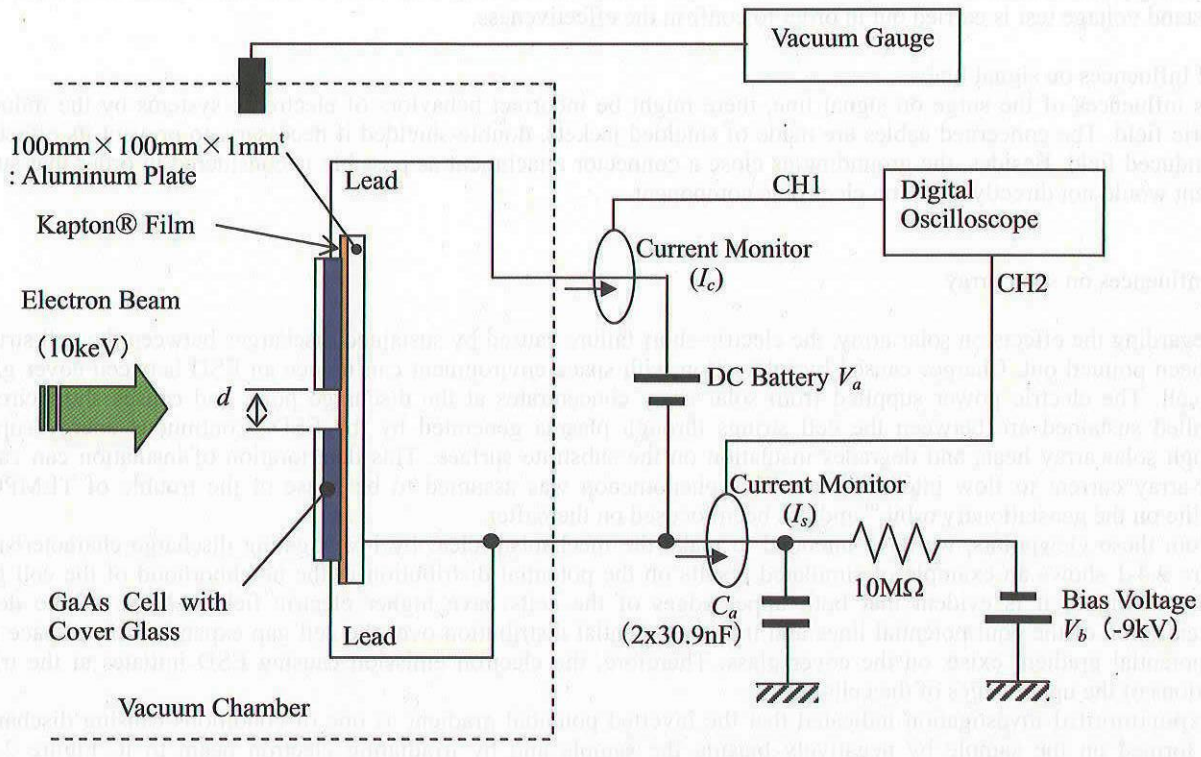

Figure 2.4-2 Experimental setup

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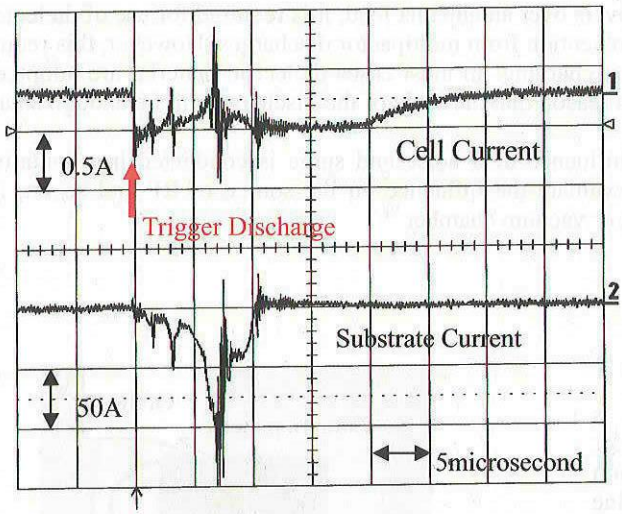
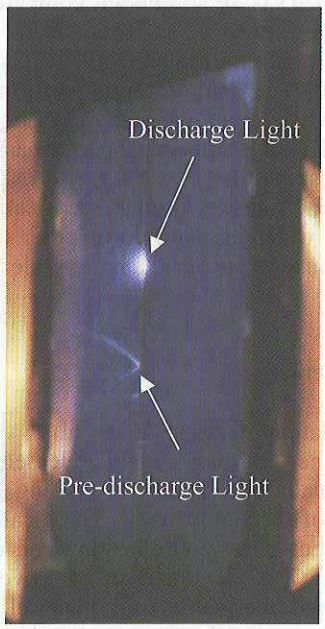


(a) Waveforms of transient currents



(b) Photograph of light

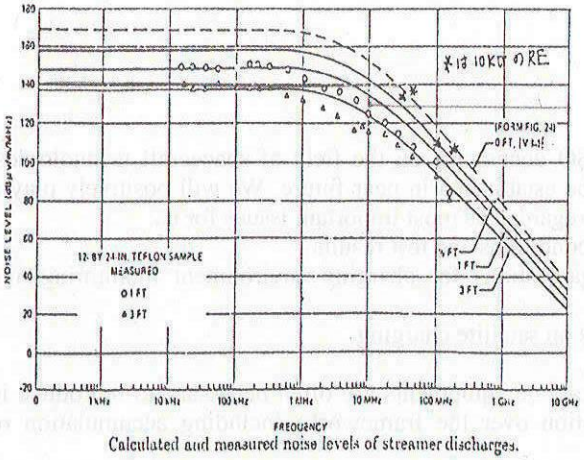
Figure2.4-3: Example of the waveforms of transient currents and the discharge light

2.5 Influences on electronic systems or RF sources

As a mechanism that ESD forms disturbance to an electric systems, the surge to the electric devices is pointed out. This phenomenon can be classified as the type of immediate influence. On the other hand, electromagnetic coupling with electromagnetic(EM)-field generated by ESD is a direct one. Such coupling phenomena are prevented by earthing a metallic case properly to GND potential.

Relative to electromagnetic fields radiation, it is required that there will be no degradation of a function and a performance even if electric devices are exposed to the arc source defined in MIL-STD-1541. The standard has specified discharges at 30cm-isolated point, while closer situation not mentioned.

In closer situation, the influence of RE and CE should be thought. As typical frequency-domain radiation characteristics of electromagnetic field, Figure 2.5-1 are obtained.[8] This radiated EM-field may behave as the source of a noise because it covers broadband of frequency, similar to so-called "white noise". It is also problems that there is few data released for higher Ku- or Ka-band used in the commercial communication satellite. Fig. 2.5-2 is one of the results



Calculated and measured noise levels of streamer discharges.

Figure2.5-1 Experimental results on EM-field radiation induced by ESD [8]

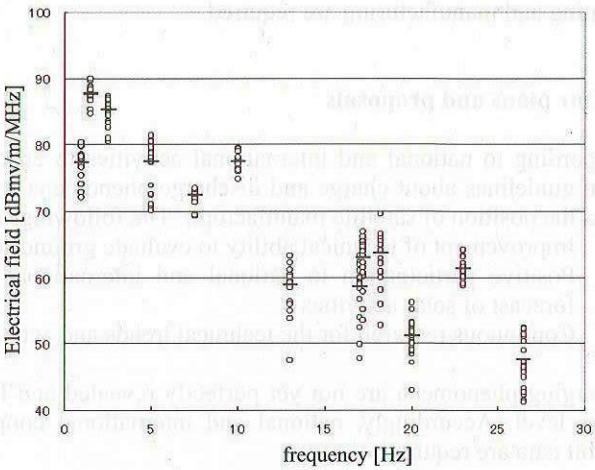


Figure2.5-2 Sample of experimental data on EM-field radiation induced by ESD

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of acquiring in a high-frequency-band EM-field generated by ESD. As these results, it is confirmed that the EM-field induced by ESD is small enough compared to RS specification. Nevertheless, it still be needed that an examination setup should be improved and that reliable data should be acquired and accumulated more.

For the thermal-control material such as aperture covers over an antenna feed, it is required for use of dielectric from the viewpoint of a communication performance and prevention from multipactor discharges. However, this requirement is disagree with the above-mentioned concepts against charging. In most cases dielectric material are adopted as the results of risk evaluation versus performance. It is also reason that the scale of the discharge will be enough small and a noise is almost in pulse.

As mentioned above, product verification of the influence of a noise and surge is conducted in a tentative way. System test, which is required in order to actually evaluate the influence on the source of RF and so on, is much difficult because it may need a large-scale shield room or vacuum chamber.[9)]

2.6 Other interaction

2.6.1 Degradation of surface material

Though the thermal energy released by ESD is extremely small, it is capable of causing sublimation or degradation of surface material. The local concentration of ESD current arises Joule heating and causes decline of material. The degradation of cover glass over solar-array and thermal-control material covered with spacecraft is noticed as one of important issues concerning satellite life. As shown in Fig. 2.6-1, it is examined that evaporation-layer on the surface of OSR (Optical Solar Reflector) was melted when energy of ESD was released. Considering that the discharge was generated on the top of needle electrode, this should be superfluous examination as larger current flowed locally than actual condition. An experiment in the more similar condition to on-orbit, for instance using electron-beam irradiation, is needed. In addition, imitation of the total number of discharge through life cycle is necessary.

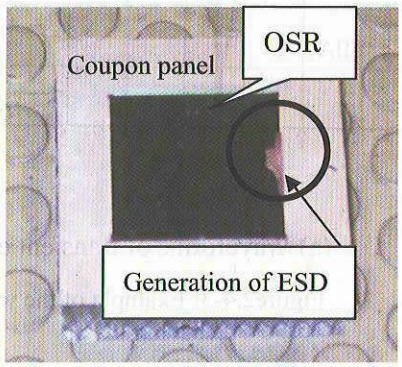

Figure2.6-1 Experimental sample of degradation of OSR surface: It is assumed that evaporation-layer is sublimated and then underlying adhesive is made exposed.

2.6.2 Internal charging [4)]

Internal charging is caused by over-1MeV particles penetrated the structure skin. The harness covers or inner board of component charged by these particles can lead to surface discharge or breakdown on the weak part of insulator. Each result may induce system failure potentially, such as the electric short between harness and structure, or the destruction of electric device. The mechanism hasn't been resolved yet and no obvious guideline is indicated. Although the thickness of both structure and case are optimized to protect from high-energy charged particles, the additional reinforcement would be demanded in order to avoid the internal charging as mentioned above. These change affect significantly both mass and cost. More studies of a physical phenomenon, assessment of risks and then reflection to designing and manufacturing are required.

3. Our plans and proposals

According to national and international activities to enact ISO documents on the field of spacecraft technologies, design guidelines about charge and discharge phenomena will be established in near future. We will positively play a role as the position of satellite manufacturer. The followings are regarded as most important issues for us:

- Improvement of technical ability to evaluate ground-test conditions and test results
- Positive participation to national and international organizations for charging environment monitoring and forecast of solar activities
- Continuous research for the technical trends and activities on satellite charging

Charging phenomena are not yet perfectly revealed and large-scale equipments are often necessary to reproduce in system level. Accordingly, national and international cooperation over the frameworks including accumulation of on-orbit data are required.

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