ECSS-E-20-06 DRAFT STANDARD ON SPACECRAFT CHARGING: ENVIRONMENT-INDUCED EFFECTS ON THE ELECTROSTATIC BEHAVIOUR OF SPACE SYSTEMS

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Abstract

ECSS (European Co-operation on Spacecraft Standardisation) is an initiative to develop a coherent, single set of user-friendly standards for use in all European space activities. One part of this initiative has covered environment-induced effects on the electrostatic behaviour of space systems, including spacecraft charging. This has resulted in a draft standard, ECSS-E-20-06, that describes the performance and verification requirements needed to control these effects.

Contributions to the standard have come from European governmental agencies, the European Space Agency and industry. Before adoption, the standard will be subject to wider circulation and amendment as a result of feed-back.

This draft standard attempts to bring together good practice and de facto standards, from a wide range of sources, into a single reference document. In addition, it provides an explanation of the main physical processes of spacecraft electrical interactions and their effects, covering sheath effects, wakes, tethers, electric propulsion, internal and surface charging, and discharges and transients. Requirements are given for surface materials, solar arrays, internal materials, tethers and electric propulsion systems. Finally, useful information is provided into ways of carrying out the required tests and simulations.

Introduction

The European Cooperation for Space Standardisation (ECSS) is a joint initiative between ESA, European national space agencies and European space industry. It is progressively establishing a system of standards covering all aspects of space system development and operation, including engineering, management and product assurance [1]. The objectives of the ECSS system are to improve the efficiency and quality of the procurement and engineering processes associated with space systems development and operation, and to improve the competitiveness of European space industry. ECSS standards are harmonised to the maximum extent possible with international standards or working practices where these have been adopted by European space industry and the preparation of ECSS standards takes into account information and opinions of all interested parties. ECSS intends to establish a formal status for a part of the ECSS standards as European Standards (EN) through the European Committee for Standardization (CEN), as appropriate.

Figure 1 shows a top-level documentation tree of the ECSS system. The Level 2 standards (e.g. ECSS-Q-60, ECSS E-20, etc.) describe the required objectives and functions for all aspects in the individual domain (electrical engineering, quality assurance, system engineering, etc.). Level 3 documents describe methods, procedures and recommended tools to achieve the requirements of Level 2 documents. In addition they define the constraints and requirements. Level 3 documents are guidelines and are allowed to be adapted to the projects' needs. The subject of this paper, a new standard ECSS-E-20-06 "Charging: Environment-Induced Effects on the Electrostatic Behaviour of Space Systems", is in preparation and defines in more detail the methods to be used for the control of hazards arising from spacecraft charging and spacecraft/plasma interactions.

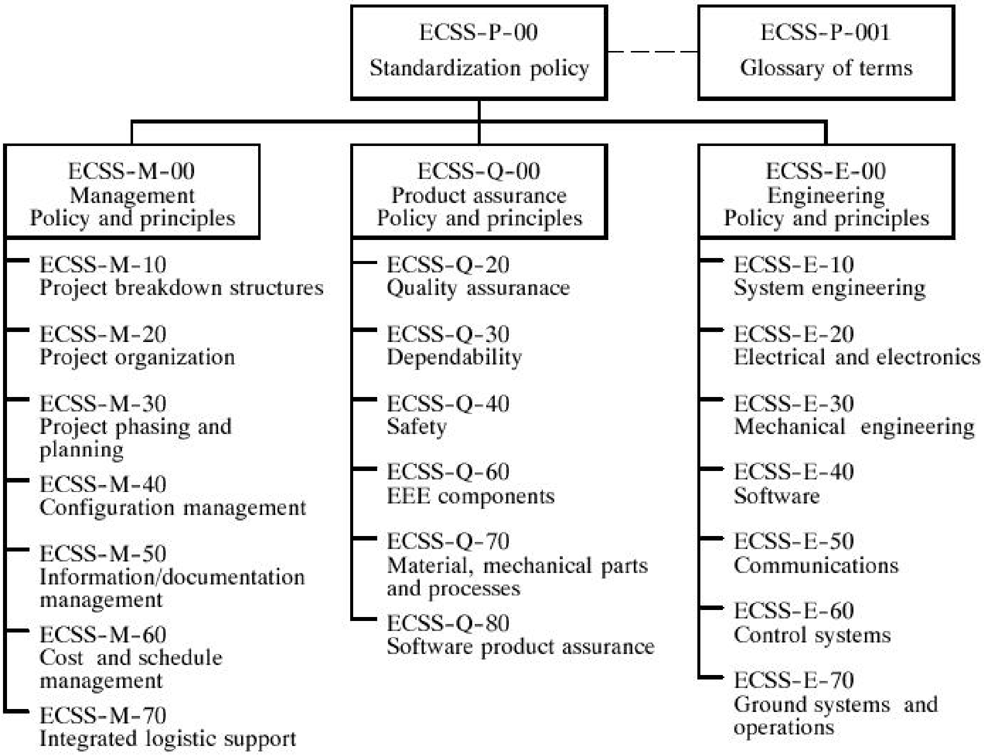

Figure 1. The ECSS documentation architecture showing level 2 documents. Level 3 includes E-10-04 on space environment and E-20-06 on spacecraft charging and environment induced effects on electrostatic behaviour.

Related Standards

A number of existing and planned level 3 standards are related to this standard:

– ECSS-E-10-04 (Space environment) [2], describes the environmental plasma and radiation that influence charging – including the radiation belts and the thermal plasma populations in the ionosphere, plasma sphere and plasma sheet/ ring current. The current version has been implemented as an active document within the 'Space Environment Information System' (www.spenvis.oma.be/spenvis/). ECSS-E-10-04 is planned to be updated next year.

- ECSS-E-10-12 (Radiation dosimetry methodology), in preparation, has relevance to internal charging effects.

- ECSS-E-20-07 (EMC test), is in preparation. Testing of electrostatic behaviour shares many techniques with general electromagnetic cleanliness.

- ECSS-E-20-01 (Multipaction), now in public review, shares a common interest in secondary electron emission with spacecraft charging analysis.

- ECSS-E-20-05 (Control of vacuum-related electric breakdown) has relevance to charging-induced electrostatic discharge.

- ECSS-E-20-08 (Space Voltaic Assemblies), in preparation, describes one of the key spacecraft systems for the charging hazard.

- ECSS-Q-70-71 (Data for selection of space materials), relates to choice of materials. This, is a draft in public review and is an update to ESA's PSS-01-701 [3].

- ECSS-E-10-02 (Verification) and ECSS-E-10-03 (Testing) describe verification and testing strategies and documentation.

In addition to ECSS efforts on standardisation., the International Standards Organisation (ISO) has established a working group on the space environment under its subcommittee responsible for standardisation in the field of space systems and operations (TC20/SC14) [4].

Scope and Content of ECSS-E-20-06

The standard is intended to provide a clear and consistent guide to the application of measures to assess and avoid/minimise hazardous effects arising from spacecraft charging and other environmental effects on a spacecraft's electrical behaviour. It aims to improve the efficiency of European space industry by ensuring that collaborative developments proceed on the basis of a common understanding of the processes and their effects and common requirements for their control. An overview of the types of electrical effects occurring in space is given and there is a detailed description of the physical processes behind them. The requirements, in terms of spacecraft design, testing and analysis that arise from these processes form the core of this standard. Finally, there is a discussion of types of orbits and how to tailor the requirements according to an individual mission.

Although spacecraft systems are clearly subject to electrical interactions while still on Earth (e.g. lightning and static electricity from handling, re-entry plasmas), these aspects are not covered. Many are common to terrestrial systems and covered elsewhere. Instead the standard covers electrical effects occurring in space (i.e. from the ionosphere upwards).

Electrical interactions between the space environment and a spacecraft may arise from a number of external sources including the ambient plasma, radiation, electrical and magnetic fields and sunlight. The nature of these interactions and the environment itself may be modified by emissions from the spacecraft itself, e.g. electric propulsion, plasma contactors, secondary emission and photo-emission. The consequences, in terms of hazards to spacecraft systems depend strongly on the sensitivity of electronic systems and the potential for coupling between sources of electrical transients and fields and electronic components.

Processes and Effects

Sheath effects

Due to the nature of the space plasma, an electrostatic sheath will develop around any object immersed in it. The sheath is a layer of net space charge that will screen the distant plasma from the surface charges. The sheath confines all of the significant electric fields, therefore its geometry relative to the spacecraft dimensions is important for estimating the interaction between the spacecraft and the surrounding plasma.

Ambient charged particle fluxes (ions and electrons), photoelectrons, back-scattered and secondary electrons from the surfaces as well as actively emitted particles from, e.g., thrusters, together with spacecraft geometry and velocity and external magnetic fields contribute to determining the properties of the sheath. The standard includes discussion of the characteristic shielding length, the Debye length and the thin-sheath (space-charge limited) and thick sheath (orbit limited) sheath models. For example, a guide to typical Debye lengths in natural plasma regions is shown in Table 1.

Plasma region	Density (m^3)	Temperature (eV)	Debye length (m)	N_d (m^{-3})
Interstellar	10^6	10^{-1}	1	10^6
Solar corona	10^{13}	$1 - 10^2$	$10^{-2} – 10^{-3}$	$10^4 - 10^7$
Solar wind	$10^3 - 10^9$	$1 - 10^2$	$1 - 10^2$	10^{10}
Magnetosphere	$10^6 - 10^{10}$	$10 - 10^3$	$1 - 10^2$	$10^9 - 10^{13}$
Ionosphere	$10^8 - 10^{12}$	10^{-1}	$10^{-1} - 10^{-3}$	$10^4 - 10^6$

Table 1. Typical Debye lengths and Nd, (the number of particles in a Debye sphere) for different regions of space.

Surface charging

Surfaces in space naturally charge as a result of charged particle collection and emission. Sunlit insulated surfaces tend to charge positively due to photo-electron emission while non-sunlit insulated surfaces tend to charge negatively because of the higher mobility of ambient electrons compared to ambient ions. Grounded surfaces have either positive or negative potential depending on the balance of the various contributing currents to exposed surfaces, possibly involving currents from active devices. High level negative surface charging is widely recognised by designers as a hazard to spacecraft operations especially on geostationary orbit during eclipses. It occurs when primary high energy (typically above a few keV) environmental electrons are collected on spacecraft surfaces, leading to large negative potentials on the spacecraft as a whole and large potential differences between different spacecraft components which can lead to electrostatic discharges. Other consequences include increased sputtering and surface contamination. Electrons from around 1-40keV are needed to produce this effect, which is strongly material-dependent. Electrons of this energy are typical of the trapped plasma of the outer magnetosphere but are generally absent within the plasmasphere and ionosphere, except in auroral regions. In the ionosphere, auroral charging may be facilitated by wake effects. Negative surface charging is countered by a number of processes that cause a positive current to flow onto a surface, e.g. ion currents, secondary electron emission, and photo-emission. A worst-case charging environment was described in ECSS-E-10-04, based on a severe charging event seen on the SCATHA spacecraft.

Even moderate potential (positive or negative) needs to be carefully assessed and possibly controlled for certain types of scientific spacecraft carrying instruments with very sensitive gain or specifically dedicated to low energy particle measurements.

Wakes

The interaction between a moving object and a stationary plasma leads to a disturbance in the local plasma, resulting in rarefaction on the downstream or wake side and, in the case where plasma is back-scattered, plasma compression on the upstream or ram side. These changes have consequences on the currents to surfaces and thus on the charging characteristics of the spacecraft. ECSS-E-20-06 describes the acoustic velocity, the Mach number and the structure of wakes. The wake void region is larger for large spacecraft and those with high Mach numbers. From Table 2 it can be seen that wakes are most important at low altitudes.

Altitude km	Circular velocity km/s	Ion Acoustic velocity km/s	Mach no.	Mach angle degrees
200	7.8	1.4	5.5	10
500	7.6	2.1	3.7	16
1000	7.3	3.6	2.0	29
1500	7.1	4.3	1.6	38
2000	6.9	5.7	1.2	55
GEO	3.0	30 – 500	0 – 0.1	n/a

Table 2. Typical plasma parameters for LEO orbits and GEO (adapted from [5]). A range of electron temperatures from 2eV to 2keV is estimated for GEO.

Tethers

Tethers currently represent a novel technology with prospects for being useful in many ways. Proposed applications include power generation, orbit raising/lowering, aerodrag compensation, inclination changing, atmosphere skimming, as a re-entry mechanism, as an antenna, for towing, to maintain fixed separations between two bodies, to permit improved 3-d pointing stability and for active modification of ambient plasma.

Most proposed uses involve conductive tethers, in which the interaction with the magnetic field is used to generate power or to modify the spacecraft velocity. ECSS-E-20-06 describes how induced potentials are calculated and the forces acting on a current-carrying wire. Problems associated with adequate current collection and tether oscillations, which make the application of tethers difficult in practice, are discussed.

Active plasma sources

Plasma environments may be generated around a spacecraft using active plasma sources - generally electric propulsion thrusters which use a plasma beam to generate a thrust. There is now a wide range of thruster technology available, including field-emission electric propulsion (FEEP), gridded ion engines (e.g. Radio-frequency and Kaufmann), electrodynamic thrusters (e.g. Hall effect) and magneto-plasma dynamic thrusters. Neutralisers form an integral component of many of these systems and may be used separately (e.g. to counter natural charging).

The standard describes the different types of thrusters and their particle emissions (primary, charge exchange and neutral). The effects these produce on the spacecraft potential and on surface properties through sputtering and contamination are discussed.

Internal charging

Internal charging is the build-up of electric charge, due to particles from the external space environment, within the spacecraft structure. In many cases, this occurs inside dielectrics. However, it may also occur on electrically isolated conductors within the spacecraft. ECSS-E-20-06 describes the charging and leakage currents and how they arise. Internal charging is associated with small currents of a high-energy (>0.5MeV) radiation-belt electrons which typically vary on time-scales of hours to days. The time-scale for charging is often days or longer and is typically determined by the capacitative time-constant across the material.

Internal charging becomes a problem when the high electric fields initiate electrostatic breakdown. Immediate effects include the direct injection of large transient currents into electronic circuits or the indirect production of transient currents through electromagnetic coupling. Additionally, a discharge may cause permanent changes in material properties e.g. causing a material to be degraded as an insulator. The main contributors to the charge balance within internally charged components are current deposition from penetrating electrons and current leakage through bulk electrical conductivity which is small but not negligible in insulators. Conductivity is particularly complicated in dielectrics and varies with temperature, electric field and radiation dose-rate.

Discharges and transients

Electrostatic discharge (ESD) is a single, fast, high current transfer of electrostatic charge. It results from direct contact between two objects at different potential or high electrostatic field between two objects in close proximity, as is often the case in space. ESD may occur both on dielectrics and conductors within or outside the spacecraft. It is the main mechanism by which surface and internal charging can cause major disruption to satellite operations.

The standard describes discharge mechanisms for dielectrics including ‘punch-through’, ‘flash-over’ and ‘blow-off’. A charged metal component may discharge slowly through field emission or via adjacent dielectrics through inverted potential gradient discharge.

Design and validation requirements

Surface materials

Requirements for surface materials have the effect of restricting differential surface charging to acceptable levels and thus minimising the probability of electrostatic discharge due to surface potentials. The requirements in this section reflect, to a large extent, good practice as described in NASA’s ‘Design Guidelines for Assessing and Controlling Spacecraft Charging Effects’ [6].

Control of surface potentials is achieved principally by effective grounding throughout the spacecraft e.g.

- where practical all surface materials should be conductive. This implies the use of conductive coatings on insulating materials.

- coatings should be sufficiently thick to survive predicted erosion due to sputtering and atomic oxygen.

- where possible coatings should be selected to have high secondary electron yield, in order to control absolute charging levels.

- grounding of surface materials shall be assured:

  - metals with small resistance to ground

  - partial conductors (e.g. paints) with a low resistivity- thickness product

  - conductive coatings with low resistivity–thickness product and small distance to ground.

In the event that some surfaces are left insulating, an analysis is required to show that the design is acceptable from a surface charging standpoint. The analysis must use the worst-case environment as defined in ECSS-E-10-04.

More stringent requirements are needed for scientific spacecraft, which have the measurement of ambient electric field or of low energy particles as part of their mission. In this event, surface materials must be conductive and conductive coatings must have high secondary electron yield, in order to control overall charging levels. In addition, appropriate modelling must be performed to verify charging levels. In the event that modelling reveals that charging levels are too high, then active neutralisation must be implemented.

Each design requirement requires a validation procedure and for surface materials these include visual inspection of the equipment, testing of continuity and resistance, material characterisation and charging simulation. On solar arrays, ESD can trigger secondary arcing sustained by the power of the photo-voltaic cells. Hence specific test requirements for solar arrays are described.

Internal parts and materials

Internal charging and subsequent discharge effects need to be considered early in the design cycle of spacecraft intended for the outer radiation belt, including geostationary orbit. This is because simple mitigation procedures, like conductive coatings for surface materials, are not effective for internal charging. Instead careful design of dielectric components, choice of materials and sufficient shielding are required. As was seen for surface charging, grounding is a key requirement. Metallic components must be supplied with a grounding path. This requirement includes structural elements, spot shielding, transformer cores, metal packaging of components, unused tracks on PCBs etc. Conductive paths need not be highly conductive however - a resistance of less than 10^{12} Ω will suffice for internal charging but it is practice for lower resistance to be specified for other EMC reasons.

Dielectric structures (e.g. cables) external to the main spacecraft body represent a particular hazard. These components must have the minimum thickness of dielectric insulation consistent with their primary function. This requirement arises because there is a direct relation between dielectric thickness and internal electric fields. In order to minimise the occurrence of discharges due to internal dielectric charging, electric fields within dielectric materials must be kept below 10MV/m. This can be ascertained either by simulation of sensitive dielectric components or laboratory testing in an appropriate environment. In determining the maximum electric field, a suitable worst-case model of outer belt electron fluxes must be used. A time-averaged radiation-belt model, such as AE-8 is not appropriate.

Validation is performed through a combination of inspection, testing and calculation:

- Inspection of the structure, cable harnesses etc. to verify that there are no ungrounded metal components.

- Resistance testing on grounded metal components

- Testing of circuits by the application of appropriate voltage spikes

- Verification that dielectric electric fields are acceptable:

  - Experimental validation is difficult because a worst-case environment must be reproduced in a laboratory chamber.

  - Computer simulation may be used to assess electric fields. For simple structures with 1-d planar or cylindrical symmetry, a 1-d analytical charge deposition and conductivity code can be used. For complicated structures, 3-d Monte Carlo simulations can be used. Both types of calculation requires knowledge of a worst case environment and the electrical properties of the material.

Testing or simulating every dielectric component is onerous and so the standard describes how this may be omitted if one of the following can be established:

- **The material conductivity is very high**, i.e. the material of the part in question has an intrinsic bulk conductivity, at the lowest temperature in which it is to be used, that is too high to permit the creation of high electric fields. (>$2.5 \times 10^{-14} \Omega^{-1} m^{-1}$, or in geostationary orbit only >$2.5 \times 10^{-1}\ \Omega^{-1} m^{-1}$)

- **The part is very well shielded**, i.e. the part is sufficiently shielded that currents under worst-case natural environments will always be too small to cause hazardous levels of charging. (>5.6mm Al equivalent, or on geostationary orbit only >3mm Al)

- **The charging current is very low**, i.e. The part is subject to a very low current density under a worst-case environment when consideration of the amount of shielding and thickness of the part is made. (<1×10^{-10} A m^{-2})

Tethers

Because tethers are still regarded as an experimental technology, the standard does not define quantitative requirements for the electrostatic aspects of their design. Instead, it requires that consideration be given to the key issues:

- Hazards that may arise due to voltages generated by conductive tethers.
- Current collection and resulting problems.
- Hazards arising from high currents flowing through the tether and spacecraft structures, e.g. Ohmic heating and extraneous magnetic fields.
- Continuity of insulation.
- Hazards from undesired conductive paths.
- Hazards from electrodynamic tether oscillations.
- Mechanical hazards to the spacecraft and the debris hazards to other spacecraft associated with a tether that breaks due to electrical burn-out.
- Electrostatic sticking from static electricity or environmentally induced charging.

Electric Propulsion

Electric propulsion (EP) systems employ plasmas and electric fields to provide thrust. Hence the interaction with the plasmas and electric fields of the environment may be complex. The standard makes a distinction between electrostatic processes that concern the thruster's fitness for its purpose (which are not its concern) and processes that disturb the environment and hence other spacecraft systems or environmental effects which affect the thruster (which are both the concern of this standard). Sometimes there is overlap between these areas. Both thrusters and neutralisers (even when no thruster is present) are covered.

The spacecraft charging current arising from the operation of the EP system must be completely neutralised. In general, this means there must be a neutralisation system with capacity to supply more current than the EP beam. This needs to have excess current capacity to cover natural charging currents in a worst case charging environment. For some low thrust systems e.g. FEEPs, in LEO, it may be possible that neutralisation can be achieved through natural ionospheric currents although this expected to be highly unusual and would need to be implemented only after analysis using worst case low density plasma conditions for the appropriate orbit.

Neutralisation of the space charge in the beam itself should be achieved as close to the spacecraft as possible. This is necessary to limit spacecraft contamination from charge exchange ions produced in the beam. Neutralisers should normally be located as close as possible to the EP system however, there may be instances where designers may desire to trade these effects against benefits of a simpler design e.g. where one neutraliser serves two thrusters. Such a strategy must be based on evidence that the beam neutralisation remains acceptable.

To limit contamination, propellant for thrusters and neutralisers shall be selected with this in mind and the atoms emitted from the EP system and their spatial distribution shall be assessed. Acceptable levels of contamination will vary and need to be established on a case by case basis e.g. optical surfaces and thermal control surfaces may have lower acceptable levels than other surfaces.

Except for transient trajectories during switch-on, there should be no ion trajectories from the EP system that impinges on any other surface of the spacecraft. This is necessary to avoid sputtering of surface materials and undesirable thrust torques. Some types of thruster have strong beam dispersion at low energies and if, as a result, it is unavoidable that some ion trajectories do impinge on another part of the spacecraft, it must be established that sputtering and torques are acceptably small.

EP systems may emit substantial quantities of neutral gas. The level of plasma density around the spacecraft due to neutral gas emission must be assessed and consequential discharging through the gas must be considered.

Validation of EP systems is achieved mainly through ground testing and computer modelling. Both of these approaches have limitations and careful consideration needs to be given to using complementary experimental and computer simulations to provide confidence in different aspects of a design. For systems with flight heritage, in-flight performance monitoring may provide further validation.

Informative section

Requirements for validation of a design are termed in ways that exclude references to specific analysis techniques and tools. However, it can be useful for users how they can to meets these requirements with currently available methods. The standard includes an informative section where some of the techniques and tools are described, including measurement sensors, surface and internal charging simulation codes and material characterisation methods.

Conclusions

We have presented some aspects of the ECSS-E-20-06 standard, currently nearing completion. It brings together best practice from a number of areas to form a comprehensive set of requirements governing the control of hazards resulting from spacecraft/plasma interactions. The draft standard is expected to be issued soon for review and the spacecraft charging community is invited to contribute to its improvement before it is, hopefully, formally adopted by ECSS.

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