CRITICAL REVIEW OF SPACECRAFT CHARGING STANDARDS

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ABSTRACT

There is currently work going on through ECSS and ISO frameworks to improve spacecraft charging environment specification and design standards. This paper reviews the existing ECSS spacecraft charging standards and others and describes the background of an ECSS handbook on the assessment of spacecraft worst case charging, which is under development.
The existing ECSS-E-ST-10-04C surface charging worst case environments are limited to the GEO and PEO/auroral regions. They are based on real observations of high charging events. However, the role of radiation induced conductivity is not currently captured in the GEO worst case environment specification which may lead to this effect being ignored, making it excessively severe for many missions.
The ECSS auroral charging environment gives higher fluxes than the GEO fluxes. Its non-Maxwellian environment components are a problem for analysts because they make it difficult to use a fluid approach for electrons. The ambient cold plasma density plays a key role in determining final charging levels but the strong dependencies of ambient plasma density on altitude is not captured in the specification.
Outside of GEO and LEO there are no ECSS worst cases which is becoming a critical issue for electric orbit raising missions. These missions spend a limited time in different parts of the magnetosphere. A long-term worst case may not be appropriate for these missions and a statistical description would be better.
For internal charging, the FLUMIC3 worst case environment model which is specified by ECSS-E-ST-10-04C has dependence on season and solar cycle but these are of little use to engineers. This model ignores the rare CME-driven events which do not follow the same temporal distribution and has been shown to be less good at GNSS altitude than GEO.
Although design validation by simulation is proposed by the ECSS-E-ST-20-06C charging standard, there is a variety of tools and various ways to configure the simulations within the tools. There is an absence of a specification of the performance a charging analysis or even guidelines on this.
The end results of simulations are generally voltage levels and electric fields. The interpretation of these results as hazards is confined to simple critical thresholds within the standard, which do not reflect the physical and geometrical influences of the ESD process.

1. INTRODUCTION

Standards are increasingly important within spacecraft manufacturing and in the management of spacecraft projects. They provide many benefits. For example, they:

- encapsulate best knowledge and practices for design of spacecraft systems
- help ensure that spacecraft designs are routinely safe and reliable
- provide a common set of specifications, across-programmes and across-borders
- help build up design heritage
- help manufacturers cheaply adapt and sell their products to a wide range of customers

To be useful, standards should be clear, practical, not unnecessarily onerous and unchanging. This last attribute is in conflict with the need to encapsulate best knowledge and practices because knowledge and technology is continuously evolving. In practice, standards must evolve, but there is a trade-off to be made on the frequency of updates versus the need to avoid difficult and expensive changes to existing practices.

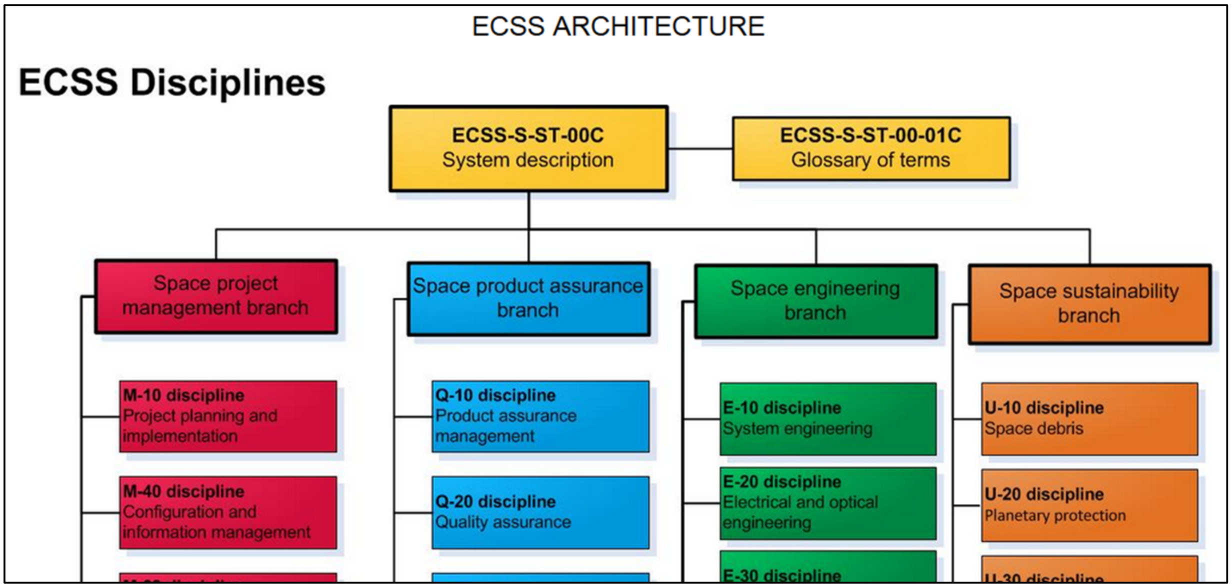

Figure 1 Top-level of ECSS architecture showing its four main branches (intentionally truncated).

2. ECSS SYSTEM

A schematic overview of the ECSS system is shown in Fig.1.

The mission statement of the ECSS programme is reported on its web site (www.ecss.nl) *"The European Cooperation for Space Standardization is an initiative established to develop a coherent, single set of user-friendly standards for use in all European space activities"* . Although this is a European initiative, the space industry has global interconnections and European standards may invoke ISO or other standards.

As part of the ECSS framework, Technical Notes and Handbooks may be produced to explain and supplement the standards themselves.

A new handbook ECSS-E-HB-20-06A 'Assessment of spacecraft worst case charging' is currently in preparation. Its aim is to show how to assess the worst case absolute and differential charging of a space system by definition of worst case environments and defining rules for numerical modelling of spacecraft charging. This handbook will assist in the interpretation of related ECSS standards and it will provide guidance into their implementation. It is possible that a need for changes to the standards themselves will be found in the process of developing the handbook. This activity provides the motivation for this critical review of the existing ECSS (and other) standards related to the assessment of worst case spacecraft charging.

3. EXISTING STANDARDS

ECSS specifications relevant to spacecraft charging are found mainly in ECSS-E-ST-10-04C (Space Environment) and ECSS-E-ST-20-06C (Spacecraft Charging). In addition NASA HDBK 4002A and NASA TP 2361 and other NASA documents have become *de facto* standards within parts of this community.

4. PLANNED DEVELOPMENTS

Within the ECSS framework, ECSS-E-ST-10-04C (Space Environment) is currently undergoing a periodic update. This is, among other things, reviewing the internal charging specification but currently not addressing issues associated with surface charging.

Under the ISO framework there are two important developments being carried out:

- ISO/AWI 19923 "Spacecraft potential estimation in worst case environments" (led by K.Toyoda, KIT, Japan)
- ISO/AWI 20584 "Space environment (natural and artificial) -- Spacecraft charging -- Earth orbit" (led by D.Ferguson, AFRL, USA)

5. SURFACE CHARGING WORST CASE ENVIRONMENTS

The ECSS-E-ST-10-04C worst case (Tab.1) surface charging environment for GEO is a bi-Maxwellian fit to SCATHA observation from 24 April 1979 when charging of -8kV in sunlight was observed [1].

	Electron density (cm^{-3})	Electron temperature (keV)	Ion density (cm^{-3})	Ion temperature (keV)
Population 1	0.2	0.4	0.6	0.2
Population 2	1.2	27.5	1.3	28.0

Table 1 Geostationary worst case charging environment from ECSS-E-ST-10-04C

For comparison, the worst case environment specified by NASA-TP-2361 and NASA-HDBK-4002A is shown in Tab.2.

Electron number density, NE, cm-3	1.12
Electron temperature, TE, eV	$1.2x10^4$
Ion number density, NI, cm-3	0.236
Ion temperature, TI, eV	$2.95x10^4$

Table 2 NASA worst case geostationary charging environment

The NASA environment is described as a 90th percentile single Maxwellian fit (possibly of ATS-6 data).
Some concerns with the existing GEO worst cases:

- For spacecraft charging analysis, we are most often concerned by surfaces with insulators that allow differential potentials to form. Typically these surfaces are thin, such as MLI and paints. For thin materials especially, radiation-induced conductivity can be crucial. Payan et al 2014 [2] showed that, as a result, thin materials can exhibit completely different charging behaviour in the presence of high energy electrons. Since the existing ECSS standards (and NASA handbooks) do not specify the radiation population to accompany the worst case charging plasma, they may lead to this effect being ignored which could result in severely inaccurate results.

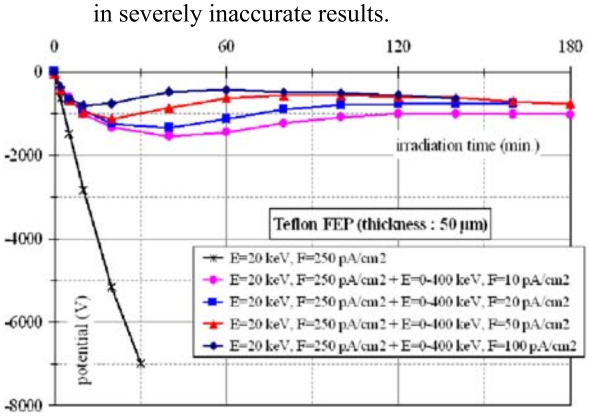

Figure 2 Laboratory measurements of Teflon charging [2] due to a 20keV electron beam with and without high energy electrons.

- Since different spacecraft can vary significantly in geometry and surface composition, they respond differently to a single charging environment and it is possible that one 'worst case' will not be a true worst case for all. This complexity is not captured in the existing ECSS-E-ST-10-04C and it may be better to simulate a selection of environments.
- Currently we apply the geostationary worst case to all missions in the outer magnetosphere. A new generation of electric orbit raising missions is being planned and these satellites will spend a prolonged time in locations intermediate between LEO and GEO during the transfer phase. It is not clear whether the use of the GEO worst case environment is the best policy here.
- For a spacecraft with a mission lasting many years, the application of a true worst case environment is reasonable. For missions that spend only a short time in the geostationary environment (e.g. some interplanetary orbits in an initial GTO phase) this may not be reasonable. Similarly, electric orbit raising missions (EOR) may only spend a few months in a significantly different environment. For such cases it would be better to know the probability of encountering severe environments. Note - an added complication of EOR is that while the thruster ameliorates charging in the steady state, it may dramatically increase differential charging due to the natural plasma at start-up or shut-down.
- Both the ECSS and NASA GEO worst case environments have unequal densities of electrons and ions. Usually, this is not a problem when space charge effects can be ignored but for some applications it may be a problem.

For low altitude polar missions ECSS-E-ST-10-04C specifies a worst case auroral surface charging environment taken from MIL-STD-1809 and ultimately from a statistical study by Yeh and Gussenhoven 1987 [3]. This is expressed as phase space density, i.e.

For E ≤17.44 keV: $f(v) = 3.9 \times 10\text{-}18 \;\; s^3m^{-6}$

For E > 17.44:

$$f(v) = \frac{[N_0(m_e)^{3/2}\exp\{-(E-E_0)/kT_0\}]}{(2\pi kT_0)^{3/2}} \quad s^3m^{-6}$$

where:
$N_0= 1.13x10^6\ m^{-3}$, $kT_0= 3.96$ keV, $E_0=17.44$ keV

An alternative worst case auroral spectrum was proposed in a Phillips Lab (AFRL) handbook PL-TR-9202232, based on work by Fontheim et al 1982 [5].

For charging (>100V) in the auroral zone, Gussenhoven et al 1985 [4] found that there needed to be both:

- A thermal plasma density $<10^4$ cm^{-3}
- A high integral number flux for high energy electrons

Reflecting this finding, ECSS-E-ST-10-04C specifies a cold plasma density of 125 cm^{-3} (from [4]) and a temperature 0.2 eV.

The existing auroral charging specifications appear to have some weaknesses:

- The ECSS-E-ST-10-04C cold plasma density from comes from a single period of severe charging seen on DMSP F7 spacecraft when the spacecraft charged to -317V. Since the cold plasma density is difficult to measure when a spacecraft is charged and yet important., it would be preferable to have more results from similar events and spacecraft.
- DMSP orbited at 830km altitude and we know that there is a general altitude dependence of cold plasma density (see Fig.3 for example). It is unclear if using the 125 cm^{-3} density at all LEO altitudes is really appropriate.

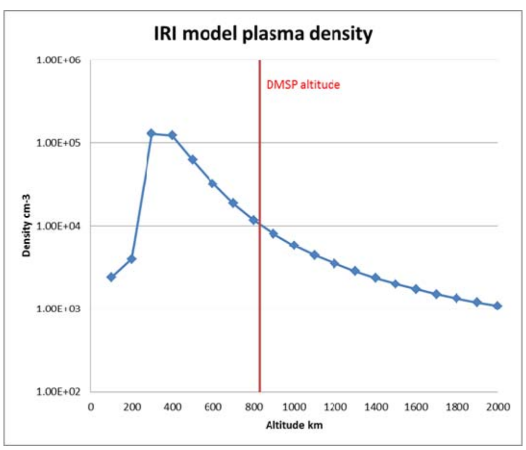

Figure 3 IRI 2007 model plasma density for the same time and position as the DMSP F7 measurement, indicating expected altitude dependence.

- The existing ECSS definition (in terms of phase space density) is not how environments are generally defined in tools. This encourages errors if a user needs to derive flux from it.
- The LEO non-Maxwellian environment specification provides a practical problem for analysts because it prevents using a fluid approach for electrons.

6. INTERNAL CHARGING WORST CASE ENVIRONMENTS

For internal charging ECSS-E-ST-10-04C specifies the FLUMIC V3 model and the worst case environment from NASA HDBK 4002A as an alternative for geostationary orbit. FLUMIC is based on GOES/SEM data which is extended to other L-shells by L-dependent flux profiles from STRV1b/REM data. It corresponds approximately to the 99th percentile of the GOES data. The model includes solar cycle and seasonal variations (see Fig.4 for the solar cycle variation).

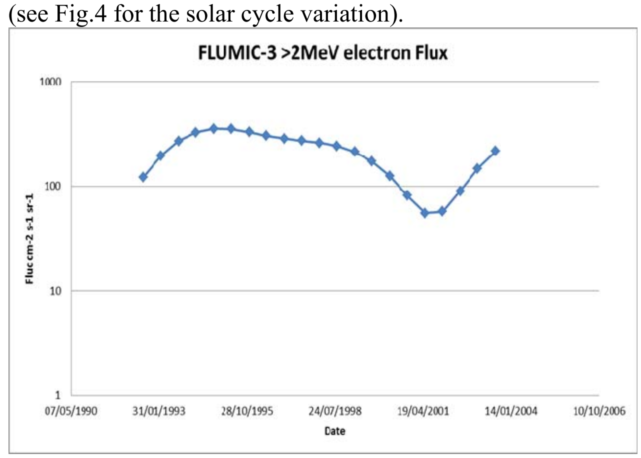

Figure 4 FLUMIC v3 >2MeV electron fluxes for a complete solar cycle

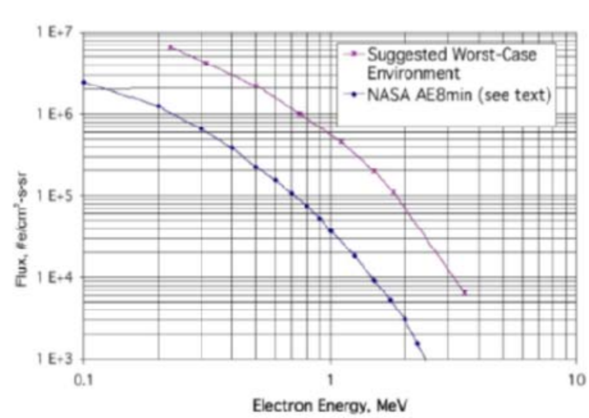

Figure 5 Geostationary worst case from NASA HDBK 4002A.

The spectrum proposed as a geostationary worst case in NASA HDBK 4002A is described as approximately the 99.9th percentile of LANL97A/SOPA data.

The ECSS internal charging worst case specification also has some problems;

- The FLUMIC model has dependence on season and solar cycle but these are of little use to engineers because most missions last a significant fraction of a solar cycle and launch uncertainties mean that one has to design for the worst period of the solar cycle anyway.

- FLUMIC ignores the rare CME-driven events ('Anomalously Large Events') which do not follow the same solar cycle distribution.
- FLUMIC has been shown to be less good at GNSS altitude than GEO – A new model MOBE-DIC [6] based on GioveA/Merlin data addresses this problem. Any new specification will need, like FLUMIC, to provide worst case environments for all positions in the radiation belts, e.g. for increasingly important EOR missions.

7. VALIDATION BY SIMULATION

ECSS-E-ST-20-06C specifies that numerical simulation may form part of the validation process for both surface and internal charging. It is not appropriate for a standard to specify the use of one tool, if there is more than one that could be used. Hence no charging simulation software is specified, although a number of them are briefly described in an annex, including SPIS and the NASCAP family of codes. The standard does list a few of the minimum physical processes that must be simulated.

Similarly, some codes that are available in Europe that could help in an internal charging analysis are also listed, including DICTAT, ESADDC, GEANT-4 and NOVICE.

The NASA handbooks NASA HDBK 2361 and 4002A propose initial simple approximate analysis followed, if necessary by numerical simulation. For this second step NASA HDBK 2361 specifies NASCAP, which was effectively the only tool available. The later NASA HDBK 4002A mentions codes (NASCAP family, MUSCAT, SPIS, Environment Workbench and others) without selecting one. For internal charging, this handbook mentions NUMIT and DICTAT as well as the transport codes Geant-4, ITS, MCNPx, NOVICE.

For charging analysis in LEO, NASA HDBK 4006 has a preference for NASCAP-2k and EWB.

The recommendation in the NASA handbooks to start with a simple analysis is something that could usefully adopted in the ECSS-E-20-06A handbook because it could save time and effort in performing detailed simulations. The absence in the ECSS standard of specification of capabilities of the analysis tools and guidance on how to apply the tools will also be addressed within the handbook.

8. DANGER THRESHOLDS

End results of simulations are generally viewed in terms of voltage levels and electric fields (across dielectrics). For ECSS-E-ST-20-06C these are: -1000V (normal potential gradient), +100V (inverted potential gradient) and 10MV/m (electric field). The +100V inverted gradient threshold is now seen as controversial and disagrees significantly from NASA HDBK 4002 which proposes +1000V, +400V, and 20MV/m respectively. Apart from reviewing the threshold values themselves there may be more guidance that can be given into environmental dependence of these thresholds. Also, not all ESDs are a serious problem. Small discharges in certain locations may be permissible.

9. CONCLUSIONS

Because of work to develop an ECSS handbook on Spacecraft charging assessment, we have reviewed the existing ECSS charging standards and others. Some observations on the ECSS-E-ST-10-04C surface charging worst case environments:

- It is limited to the GEO and PEO/auroral regions.
- It is based on real observations of high charging events
- The role of radiation induced conductivity is not captured in the GEO surface charging environment
- A single worst case may not be enough for all spacecraft
- A statistical description may be required for missions transiting a region
- Auroral charging is non-Maxwellian environment which complicates analysis
- There is no cold plasma dependence of ambient density on altitude

For internal charging

- The FLUMIC model has dependence on season and solar cycle that is of little use to engineers.
- Rare CME-driven events do not follow the same temporal distribution and are currently ignored in the standard
- FLUMIC is less good at GNSS altitude than GEO.

For numerical analysis

- No particular tool is specifically required in ECSS-E-ST-20-06C standard
- There is very little specification of the performance of a charging analysis
- There are no guidelines on how to perform an analysis
- ESD thresholds may require update and are simplistic

This review is helping direct the work to develop the ECSS-E-HB-20-06A handbook. It is expected to be released for public review in June 2017.

10. REFERENCES

1. Gussenhoven, M.S. and E.G. Mullen, “Geosynchronuos environment for severe spacecraft charging”, J. Spacecraft and Rockets 20, p. 26, 1988.
2. D. Payan, A. Sicard-Piet, J.C. Mateo-Velez, D. Lazaro, S. Bourdarie, et al.. Worst case of Geostationary charging environment spectrum based on LANL flight data. Spacecraft Charging Technology Conference 2014 (13th SCTC), Jun 2014, PASADENA, United States.
3. Yeh H.-C. and M.S. Gussenhoven, “The statistical Electron Environment for Defense Meteorological Satellite Program Eclipse Charging”, J. Geophys. Res., pp.7705-7715, 1987.
4. M.S.Gussenhoven, D.A.Hardy, F.Rich, W.J. Burke and H.-C.Yeh, High-Level Spacecraft Charging in the Low-Altitude Polar Auroral Environment, Journal of Geophysical Reseach, VOL. 90, NO. All, PAGES 11,009-11,023, NOVEMBER I, 1985
5. Fontheim, E. G., Stasiewicz, K., Chandler. M. 0., Ong, R. S. B., Gombosi, E., and Hoffman, R. A., "Statistical Study of Precipitating Electrons," Journal of Geophysical Research, Vol 87, No. A5, p. 3469-3480, 1982.
6. A.Hands, K.Ryden, C.Underwood, D.Rodgers, and H. Evans, A New Model of Outer Belt Electrons for Dielectric Internal Charging (MOBE-DIC), IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 62, NO. 6, DECEMBER 2015