PLASMA ENVIRONMENT AND EFFECTS SPECIFICATIONS: ESA'S PERSPECTIVE OF THE FUTURE

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Abstract

The Problems with spacecraft charging in the 70's and 80's led to development of facilities for assessing the environment and its effects for improving spacecraft development. *NASCAP* was the tool of choice for charging calculations and the environment was usually described in terms of "worst-case" Maxwellian or bi-Maxwellian distributions. These distributions are still quoted in standards and specifications. Although they are useful, if we look at contemporary problems and future requirements we can identify some problems. Worst-case specifications do not necessarily lead to the worst-case effect. In spacecraft differential surface charging, charging levels are material and geometry dependent and large differentials can often be generated by moderate environments and not by extreme ones. So in future, the ability to make calculations for a range of environments or time-dependent environments will be important. Improvements in the calculations clearly also depend on improvements in the modelling of the interaction itself and improved understanding of materials and their modifications. These improvements could reduce over-design and costs. The dynamics of the hazardous plasma environment are part of the "space weather". An ability to predict the space weather would lead to many benefits. With a reliable prediction that charging was likely and that there was a discharge risk, operations of a spacecraft, either manual or automatic, could be optimised. So in future we should look towards specification of time-dependent models and data resources rather than highly abstracted worst-case specifications. ESA is working on many aspects of these problems including investigating future space weather programmes, developing modern standards, developing computational tools, and undertaking materials characterisation.

Introduction

The main function of the Space Environments and Effects Analysis Section of ESA's Directorate of Technical and Operational Support is to support the development of ESA projects. Its activities include the specification of environments and performing analyses of environments and effects in all project phases. It also defines and implements research and development activities to underpin these efforts, looking at near-term and far-term issues.

In the area of spacecraft-plasma interactions, there is a need to improve the modelling capabilities available. This is because of shortcomings in existing modelling but also because of new spacecraft-plasma interaction issues such as electric propulsion, scientific instrument interactions. Improvements in modelling will result from improvements in the fidelity of modelling the interaction and responses of the plasma itself, as well as better understanding of the responses of materials including their modifications in the space environment. Efforts to improve modelling are justified by the potential to reduce over-design with respect to the hazard and consequent reductions in cost.

Performing all these tasks in a European context naturally involves a great deal of collaboration with the wider European space community (industry, national agencies, research centres). An important underpinning activity is the preparation of engineering standards. Developing space programmes requires the clear establishment of the requirements for a system and the ability of the partners to review each other's work. It is in this area that standards play an important role. They ensure that all partners understand what is required, and what is being undertaken by the other partners. In this paper we review the current approaches to specifications and standards and look to the future in an ESA and broader European context.

Spacecraft Plasma Environment Specification: The Past

Problems with spacecraft charging in the 70's and 80's led to rapid development of facilities for assessing the environment and its effects for improving spacecraft development [1,2,3,4,5]. *NASCAP* was one of the elements developed at that time and became the tool of choice for charging calculations [6]. *NASCAP* performs a simulation of the surface charging of bodies in a "low density" plasma regime typical of geostationary orbits where the Debye length is long. A long Debye length implies that a simplified model for collection of currents by a body can be applied and trajectories of the charged particles near the body are unaffected by plasma screening ("sheath") effects. *NASCAP* treats a simplified three-dimensional model of the spacecraft where each of a limited number of surface elements is assigned a particular material and electrical connection to the rest of the spacecraft. The simulation proceeds by calculating all the currents to the various surface elements, including those due to the plasma environment, the currents from the surface to space due to solar UV, ambient electron and ambient ion impact, and the currents within the spacecraft electrical "circuit" connecting the surface elements. Therefore, apart from the geometry, the simulation requires as input specification of charging-related material properties, and the environment *NASCAP* remains a popular tool today, in spite of its age and the environment specifications widely used are those compatible with *NASCAP*.

The environment is usually described in terms of "worst-case" Maxwellian or bi-Maxwellian distributions. The Maxwellian plasma distribution functions in terms of scalar velocity, v, is given by:

$$f(v) = 4pn\left(\frac{m}{2pkT}\right)^{3/2} v^2 \exp(-v^2 m / 2kT)$$

where:
n is the density
k is Boltzmann's constant
T is temperature

The double or bi-Maxwellian distribution is simply a superposition of two distributions characterised by different temperatures and densities. These distributions are still quoted in standards and specifications but it is worth establishing whether they are they sufficient for the future? The ECSS Space Environment Standard (E-10-04 [7]) contains the recommended single-Maxwelian environments for quiet and disturbed times shown in Table 1.

	Density (cm^{-3})	Ion Temperature	Electron Temperature
Quiet	10	1eV-1keV	1eV-1keV
Substorm	1	10keV	10keV

Table 1: ECSS recommended Maxwellian parameters for quiet and disturbed conditions

For use in worst-case charging analyses, the double-Maxwellian environment shown in Table 2 is imposed, based on measurements made by the Scatha spacecraft [8]. Note that this is not the same environment as described in the NASA charging guidelines [9], which was felt by the Working Group preparing the ECSS standard to be unrealistically extreme.

	Density (cm^{-3})	Temperature (keV)
Population 1		
Electrons	0.2	0.4
Ions	0.6	0.2
Population 2		
Electrons	1.2	27.5
Ions	1.3	28.0

Table 2: ECSS Standard Double Maxwellian environment for severe charging calculation

Two important points about specifications and the way in which they should develop can be made:

1. Specifications are not usually accompanied by information on the likelihood of the environment. This is needed of the environment is to be used to predict and effect and a "risk analysis" is to be performed related to mission problems resulting from effects. In the future, it would be preferable to have a fuller statistical representation of the environment to enable this.
2. For a particular phenomenon the severity of the effect of a particular environment may not be associated with the worst case (large value) of a particular parameter. Indeed, worst-case surface charging generally occurs when plasma density is low, not high. Surface charging potential depends on the approach to equilibrium of ambient and secondary current sources. Because the secondary electron emission varies with incident electron energy and material type, the highest levels of differential charging are not necessarily seen in "severe" environments. Figure 1 shows material charging behaviour as a function of electron temperature. These results are for single-material charging of spheres in a fixed ion density and temperature and a fixed electron density, as functions of the electron temperature. While the calculation includes no spacecraft geometry, electric field or inter-material effects, it illustrates that the differences in potentials between two materials is not necessarily higher in a more severe environment. This can be seen for example by comparing the curved for "black paint" with "ITO". These differences result from the differences in the secondary electron emission and electron backscatter properties.

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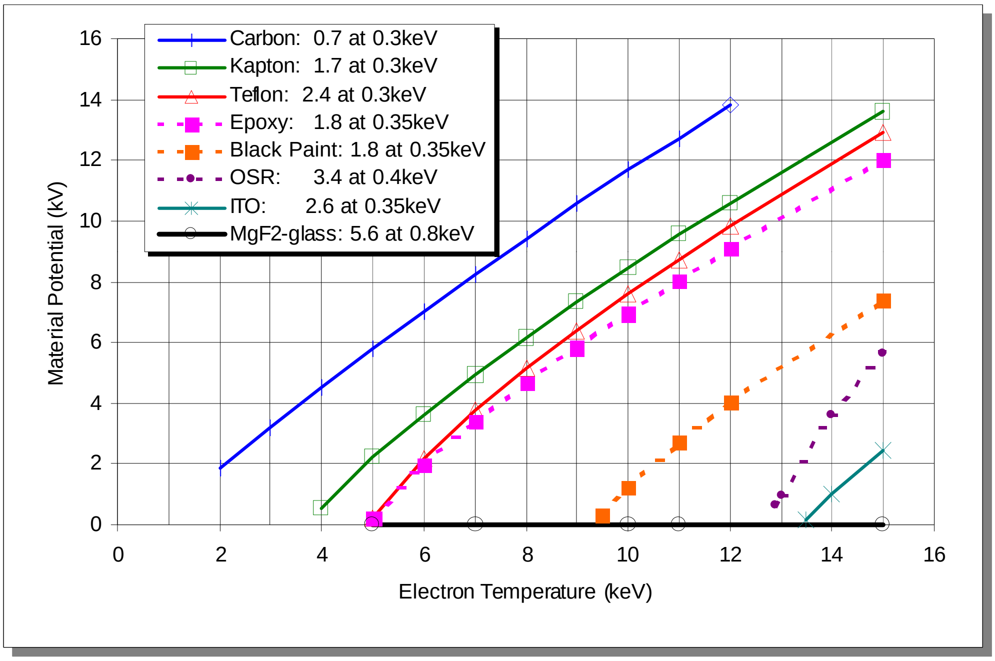

Figure 1 Charging of different materials as a function of electron temperature, showing that charging differences do not necessarily increase with Te

Alternative Specification Methods

A more fundamental approach to space environmental hazards is to ask what is the risk to the system or component of the system due to particular conditions. While this is a more general approach, the question is rarely possible to answer easily. In space radiation analysis, for example, models have been established where the risk of a particular solar proton radiation level is given. To adopt such a strategy for plasma environments requires two steps illustrated in Figure 2: (i) the data has to be kept in the form of a data resource that can be interrogated for statistical information on environments and (ii) the statistical analysis must also be applicable to the resulting effect of the environment. While the first seems feasible, if the second requires fully three-dimensional simulations of spacecraft charging for each environmental condition, it may not. Moves in this direction worthy of note include ESA's *SEDAT* project [10] where data can be interrogated using tools for specific effects (such as charging levels), and the GRID project [11] where large-scale computing resources could become available for statistical assessment of complex calculations.

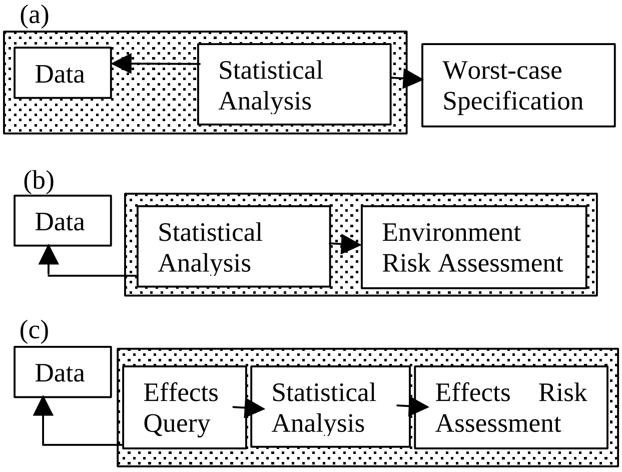

Figure 2Models for specification. (a) illustrates the present situation; (b) illustrates a situation where a risk analysis is performed on the environment; (c) is what a project really needs: a statistical analysis of the risk of a particular severity of the effect

Material Properties and Charging/Interaction Prediction

As mentioned above, material properties play a very important role in the charging of a material and ultimately a spacecraft. Important material properties such as secondary electron emission and material resistivity are sensitive to material contamination, oxidation, ageing, temperature, etc. so that one has to be cautious in assuming that the results of simulation based on a particular set of material parameters will correspond to in-flight conditions. As a result, complete specifications for charging need complete details of materials and their changes in orbit. This latter is simply not available in most relevant cases. Even the relatively simple effect of temperature on resistivity of dielectric materials has proven difficult to characterise to the extent where eclipse to sunlight transitions of spacecraft can be modelled [4]. We conclude that modern charging specifications need complete material characterisation and appropriate standard methods for measuring the relevant properties.

User Needs

Project teams often prefer simple specifications such as "worst-case", "composite worst-case" and the use of "qualified" materials. This can lead to costly over-design. The smarter specifications described above must be constructed so they are easy to apply and are verifiable, otherwise they will not be useable.

Space Weather

The dynamics of the hazardous plasma environment are part of the "space weather". So the data resources implied by smarter specification methods mentioned above would be a natural output of space weather efforts. A space weather system might measure in detail the near-earth plasma environment as well as having the ability to predict or interpolate between measured values using improved models of the magnetospheric environment and its responses to solar and interplanetary disturbances. One may then consider whether any reliable prediction that charging was likely to occur and that there was a discharge risk, would lead to optimised operations of a spacecraft, either manual or automatic, at lowered cost.

As part of the space weather effort, work must be done to "transition" the results from scientific and other research into engineering practice. In the future, the ability to make calculations for a range of environments or time-dependent environments will be important and so time-dependent models and data resources are required rather than worst-cases

ESA Activities

ESA is working on many of the above issues. Within its technology R&D programme it has initiated the *SEDAT* project, being executed by Rutherford Appleton Laboratory, to investigate the use of databases for engineering analysis [10]. It also has plans a project for develop a toolkit for spacecraft-plasma interaction simulation in association with new materials properties investigations and development of a handbook. This follows a pilot investigation of PIC code development undertaken at IRF, Sweden [12] and is associated with the collaboration network SPINE [13].

The related space weather issue is being actively examined. ESA is investigating the needs for a space weather programme and what such a programme might contain. Activities have provided detailed analysis of space weather effects, programme benefits, requirements and implementation scenarios [14]. This will lead to a pilot project in 2002 where prototype services are established including the kind of data and prediction services mentioned above.

Other relevant research and development activities include [15,16] models of the Martian environment, development of tools for energetic particle interactions with matter, development of space environment monitors, various database and tools project , models of the micrometeoroid and debris environments, radiation,…)

Standards

ESA is collaborating with national agencies and European space industry to develop a standards system to help make the spacecraft development process more efficient. This is the European Co-operation for Space Standardization (ECSS). Clearly both plasma environmental and spacecraft effects specifications will feature within such a system.

Standards fulfil a number of important functions. They are a way to ensure experience is passed on. Often one sees a "re-discovery" of a problem which had been identified some years earlier because of a lack of knowledge continuity. Standards are established by consensus. They ensure that all parties to a development understand the methods being employed by partners and are able to evaluate the work. Clearly any standard tools or model has to be available to all.

Apart from ECSS, the International Standards Organisation, ISO is developing space standards. Within the Technical Committee 20, Sub-Committee 14 (TC20/SC14) which is responsible for space standards, a working group (WG4) is preparing space environment standards [17]. These also include standards relating to environmental effects and testing. As far as areas related to spacecraft-plasma interactions are concerned, the ISO working group is working on a standard for the plasmaspheric and ionospheric environments.

ECSS is developing a number of relevant standards, including the already issued ECSS-E-10-04 standard "Space Environment" [7]. A standard on spacecraft-plasma interactions: "Standard on Environment-Induced Effects on the Electrostatic Behaviour of Space Systems", ECSS-E-20-06 is under preparation by an expert working group [18] and an electrical engineering standard has been issued (ECSS-E-20).

The Space Environment Information System, *Spenvis*, is used by ESA as a channel for making available to the European and wider space community the results of its activities for exploitation in space programme development. It aims to give the engineer useful, helpful, authoritative information and tools and includes many space environment models and models and tools for effects evaluation. It was extended in 1999 to include an “active” version of the ECSS Space Environment standard. Development is actively continuing [19].

Conclusions

Improved means of specification are needed beyond simple worst-case types. But to achieve this requires investment in development of better models and data-driven tools and consequently in in-space measurements. Better material properties analyses are also needed.
Standards for environments and effects are a useful asset for an organisation such as ESA. The standards need to be carefully established by consensus and imply open access to data and models.

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