Standards for Space Radiation Environments and Effects

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Abstract-- **Under the auspices of the European Cooperation on Space Standards (ECSS), a standard is being established to help engineers assess radiation effects on space systems. The standard indicates the most appropriate methods to evaluate the various radiation effects that may be encountered. Effects include total ionising and non-ionising (NIEL) damage, single event effects, radiation interference with payloads, and effects on biological systems. The standard complements existing and planned ECSS standards on the space environment (ECSS-E-10-04) and EEE components (ECSS-Q-60). Relationships with testing and margin issues are discussed.**

I. INTRODUCTION

THE European Cooperation on Space Standards (ECSS) is a joint undertaking 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-10, 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.

A new standard, ECSS-E-10-12, “Methods for Calculation of Radiation Received and its Effects, and a Policy for Design Margins”, is in preparation which defines in more detail the methods to be used for quantitative analysis of radiation effects and this effort is the main focus of the present paper.

In addition to ECSS efforts on standardization in this area, the International Standards Organization (ISO) has established a working group on the space environment under its subcommittee responsible for standardization in the field of space systems and operations (TC20/SC14) [2].

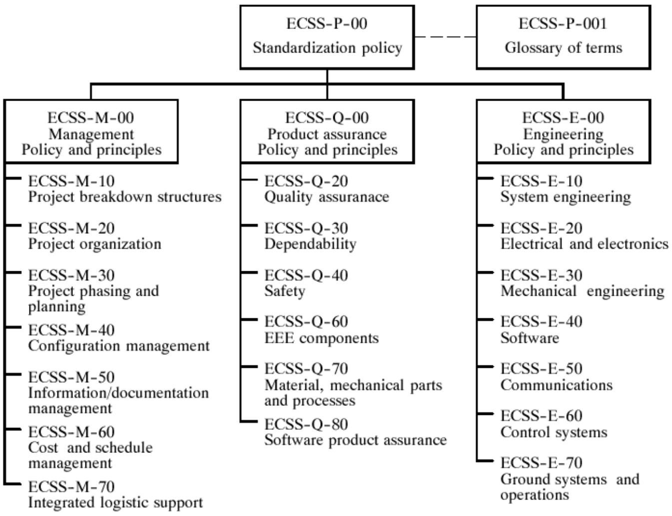

Fig.1. The ECSS documentation architecture showing level 2 documents. Level 3 includes E-10-04 on space environment and E-10-12 on radiation effects calculation methods. Q-60 includes radiation hardness assurance.

II. ECSS-E-10-04 STANDARD ON THE SPACE ENVIRONMENT

The level 3 standard on the space environment was established as part of the engineering branch, system engineering sub-branch (“ECSS-E-10”), and published as ECSS-E-10-04 in January 2000 [3]. Apart from an

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extensive section on the energetic particle radiation, it includes sections on plasma, atmospheric, fields and particulate and gaseous environments. The radiation section includes discussion of models for trapped radiation, solar energetic particle radiation and galactic cosmic rays. It contains details of effects and shielding and has some overlap with the E-10-12 standard described in the next section. The standard will be updated in the next year to ensure harmonization with E-10-12. The current version of the standard has been implemented as an "active" document within the *space environment information system* Spenvis [4]. Links have been established in the document between discussion of models and the actual model execution in Spenvis.

III. SCOPE AND CONTENT OF THE E-10-12 STANDARD

In order to engineer space systems that survive and operate successfully in the space radiation environment, one must consider carefully the effects of radiation. It is the aim of the E-10-12 standard to help the engineer achieve a sound quantitative analysis of effects. The standard seeks to improve the efficiency of European space industry by both educating the unfamiliar engineer with the issues and by ensuring that collaborative development (including customer-contractor and contractor-subcontractor relationships) proceeds smoothly on the basis of common use of well-understood methods.

A comprehensive compendium of radiation effects is provided in order to introduce the issues and also as a navigation aid for the user to find more detailed information related to effects on particular types of spacecraft systems or components. Effects include effects on electronic components and materials (both total ionising and non-ionising (displacement) damage), single event effects, radiation interference with payloads, and effects on biological systems, as shown in Table 1, where parameters and testing issues are also introduced.

The engineering process, including design of units and sub-systems, involves several trade-offs, one of which is radiation susceptibility. Some radiation effects can be mission-limiting where they lead to a prompt or accumulated degradation which results in unit failure or catastrophic system anomalies. Examples include damage of electronic components due to total ionising dose, or damaging interaction of a single heavy ion ("latch-up"). Other effects can be a source of interference, degrading the efficiency of the mission. Examples are radiation "background" in sensors or corruption of electronic memories. Biological effects are also important for manned missions and some other missions where biological samples are flown.

Each of the radiation effects mentioned in Table 1 are addressed in detail in the chapters of the document and often further supported by an "Informative Annex". The

TABLE I
RADIATION EFFECTS AND PARAMETERS USED IN THEIR ASSESSMENT

Effect	Parameter	Typical units	Examples	Particles
Total ionising dose (TID)	Ionising dose in material	grays (Gy) or rads 1 Gy = 100 rads	Threshold voltage shift and leakage currents in CMOS, linear bipolar (note dose-rate sensitivity). Damage to materials. Creation of colour centres in optical media.	Electrons, protons, bremsstrahlung
Displacement damage	Displacement damage dose Equivalent fluence of 10 MeV protons or 1 MeV electrons	kev/g or non-ionising Gy or rads cm^{-2}	All photonics, eg CCD transfer efficiency, optocoupler gain Reduction in solar cell efficiency	Protons, electrons, neutrons, ions
Single event effects From ions	Events per unit fluence from linear energy transfer (LET) spectra & cross-section versus LET	cm^2 versus MeV cm^2/mg	Memories, microprocessors. Soft errors, latch-up, burn-out, gate rupture, transients in op-amps, comparators.	Ions
Single event effects from nuclear reactions	Events per unit fluence from energy spectra & cross-section versus particle energy	cm^2 versus MeV	As above	Protons, neutrons
Payload-specific radiation effects	Energy-loss spectra, charge-deposition spectra	counts s^{-1} MeV^{-1}	False count rates in detectors, false images in CCDs	Protons, electrons, neutrons, ions, induced radioactivity (α, $\beta^{\pm}$, γ)
Biological damage	Dose equivalent = Dose(tissue) x Quality Factor	sieverts (Sv) or rems 1Sv = 100 rem	DNA rupture, mutation, cell death	Ions, neutrons, protons, electrons
Charging	Charge	coulombs (C)	Phantom commands from ESD	Electrons

exception is Charging which is the subject of a separate ECSS document, ECSS-E-20-06, “Standard on spacecraft charging: environment-induced effects on the electrostatic behaviour of space systems”.

Furthermore, the document contains sections on shielding and on design margins since these aspect are relevant to assessments of many different effects.

IV. RELATIONSHIP WITH THE SPACE SYSTEM DESIGN PROCESS

The correct evaluation of radiation effects should occur as early as possible in the design of systems, and be repeated as necessary throughout the development phase [5]. Severe engineering, schedule and cost problems can result from inadequate anticipation of space radiation effects and preparation of the engineering options and solutions. A radiation environment specification is required to be established and maintained as a mandatory element of any procurement actions from the start of a project (e.g. pre-phase A). The specification should be specific to the mission and should take account of timing and duration of the mission, the nominal and transfer trajectories, employing the methods defined in ECSS-E-10-04.

ECSS-Q-60 [6] requires that a “radiation control programme” for electronic components be implemented for a project and that “*the required radiation tolerance, including types and levels of radiation, shall be specified by the organisation responsible for the design of the product into which each component is to be embodied*.” It further requires that “*specific information as to the radiation control programme, including test facility, test method, planning and control, shall be included in the Component Control Plan or issued as a separate document*”.

Structural, optical and thermal control material degradation also have to be assessed though a similar radiation control process. Control of astronaut radiation exposure limits is based on the ALARA (as low as reasonably achievable) principle, defined in the ECSS-E-10-12 document.

In order to make a radiation effects evaluation, test data are needed, both to confirm the compatibility of the component with the environment it will operate in, and to provide data for quantitative analysis of the radiation effects. In general there is one effects parameter for each radiation effect, as indicated in Table 1. In some cases, knowledge about the radiation effects on a particular component type can be found in the published literature or in databases on radiation effects. These data have to be used with extreme caution since verifying that data are relevant to the actual component being employed is often very difficult. For example, in evaluating electronic components, consideration has to be give to:

- variations in sensitivity between manufacturers' "batches";
- variations in sensitivity within a nominally identical manufacturing "batch";
- changes in manufacturing, processes, packaging;
- correlation of measurements made on the ground and in-flight experience is far from complete.

As a consequence, and to account for accumulated uncertainties in testing procedures, component to component variations and environmental uncertainties, *design margins* are usually applied to the radiation effects parameters for the particular mission. The E-10-12 document also seeks to give information on uncertainties and to indicate when and how to apply margins. Application of margins can have important effects on the engineering. Too high a level, implying a severe environment, can require change of components (leading to increased cost or degradation of performance), de-rating, application of additional shielding or even orbit changes. Margins are discussed further in Section VI.

V. SHIELDING

To achieve a radiation tolerant design it must be shown that an adequate radiation design margin exists for all individual components and for the system as a whole. Whilst sensible component selection and adherence to good design practice is invaluable to achieving this aim, it is only half the story. To demonstrate tolerance an assessment must be made of the radiation arriving at each part of the design and thereby show that sufficient margin exists. The assessment of the amount, energy and type of radiation arriving at any particular location requires an accurate knowledge of the external environment and also an understanding of the shielding effect of any material between the location and the external environment. Shielding can be very effective against some environments, such as low energy electrons and protons. But it is not a universal solution and it can be difficult to use shielding to relieve some problems caused by some environments. For example, high-energy ions are not easily shielding and generate significant secondary radiation in thick shields, and bremsstrahlung caused by electron interactions in shields can propagate through significant shielding thicknesses.

Shielding occurs in two ways; built in shielding, that is the fortuitous shielding afforded by materials already included in the design, and add-on shielding, that is the shielding which is added specifically for the purposes of attenuating radiation. A section in E-10-12 on shielding deals briefly with some of the physical processes involved in radiation transport through matter and any subsequent effects. The section also deals with methods for making the best use of shielding material at minimum cost and weight penalty and deals with the computer modelling of shielding. Consideration of shielding materials is important and related to the particular environment encountered. High-Z materials effectively attenuate electrons but generate significant bremsstrahlung. Therefore multi-material shielding is often implemented with low-Z materials attenuating the bulk of the electron flux, followed by a high-Z material to attenuate the resulting secondary photons. Hydrogenated materials (such as water and plastics) are effective at shielding against ions.

Radiation environmental specifications are often given in a way that includes shielding effects. For example "dose-depth curves" provide the ionising dose expected in an environment with given amounts of aluminium shielding, assuming a planar or spherical shield, and SEU rates are given assuming spherical aluminium shielding. These represent the simplest level of "shielding model". A more complex method is "sectoring" which uses ray tracing to establish material thicknesses in directions around a "target" point in a system. The shielding effectiveness in each direction is deduced from a dose-depth curve. This is an approximate approach because materials are usually "reduced" to aluminium and particle scattering and secondary production are only approximately treated. The most complete approach is to treat explicitly the detailed physical interaction processes of the different particles (including all their secondaries) with an accurate representation of the geometry and materials making up the spacecraft or system. The majority of simulation codes that can model radiation physics at this level of detail are of the "Monte Carlo" type. These various approaches are presented and recommendations made for their application.

VI. MARGINS

In the context of radiation effects, a margin is factor or difference between the design environment specification for a device or product and the environment at which unacceptable behaviour occurs. The margin policy in a project normally requires that a minimum factor or difference be retained, to account for uncertainties in the radiation effects evaluation process. The design environment specification is part of the product requirements, which should include qualification margins. The qualification process demonstrates whether an entity is capable of fulfilling the specified requirements, including the margin [7]. A Radiation Design Margin (RDM) is often used in relation to electronic components, defined as:

$$RDM = \frac{\overline{D_f}}{D_D}$$

where $\overline{D_f}$ is the mean dose (for the devices sampled) resulting in the violation of operating conditions or failure of a device resulting in a malfunction of the system, and D_D is the specified environmental dose. This can be similarly applied to solar cell degradation, where the failure is defined as the cell reaching a power generation limit. However, it cannot so simply be applied to effects of a single event nature, since the definition of "failure" or perhaps more preferably, unacceptable performance degradation, is specific to the application of the component. For material degradation, similar arguments apply.

A margin is clearly related to uncertainties concerning the performance of a device or product and this may be due to uncertainties concerning the environment within which it will operate, or concerning the radiation effects on the device or product. Several issues contribute to the margin, and projects often adopt a "lumped" approach to margins in this domain by assuming that a single margin covers all the issues. Traditionally in radiation effects assessment, a margin was adopted across the board based mainly on experience, but with little analysis. The new ECSS-E-10-12 document tries to outline the elements that contribute to the uncertainties leading to margins and provide guidance on deriving a particular margin value. However, the subject is complex, understanding is limited in many areas and research is on going. As a consequence, the advice provided is less solid than it might be. The contributors to the margin are:

- Environmental uncertainty (models or other data)
- Uncertainty in predicting effects parameters (shielding uncertainty, uncertainty in parameter prediction (e.g. dose, SEU rate, etc.)
- Testing: testing is complex and subject to both systematic and statistical uncertainties;
- Procurement processes
- Project management decisions

The application of a margin is ultimately a project management decision, but is based on consideration of a number of uncertainties in the radiation hardness analysis of a particular device or product. Applying a margin may result in problems for spacecraft development:

- a different component class may be necessary;
- COTS components may become unusable,
- additional shielding may be necessary,
- alternative, lower performance components may have to be used,
- additional and costly testing may be necessary;
- and so on.

There is often pressure to reduce the margin and often it is reduced without any risk analysis. On the other hand situations may arise where a mission becomes unfeasible with application of "standard" margins.

The following also have to be considered:

Criticality

A target (component, experiment, astronaut) may be critical to mission success in which case the margin may need to guarantee a high probability of survival/functioning. Less critical functions (experiment mass storage, for example) may be affected in such a way as to represent a "nuisance", and so a less stringent margin can be employed. Missions themselves also have differing levels of "criticality". For example low cost science or technology missions are often willing to accept greater risks.

Immunity

If a target can be shown to be immune to radiation to a degree where the most conservative simplified assessment of the effects parameter(s) is considerably below the expected problem threshold, assuming worst-case margins, little further analysis is warranted.

De-rating is the "*Process of designing a product such that its components operate at a significantly reduced level of stress to increase reliability*" [7]. ECSS-Q-60-11 [8] discusses in detail the de-rating methods for a wide range of components. If it can be demonstrated that de-rating improves the ability of the component to withstand radiation effects, it can usefully be employed. Nevertheless, it does not affect the margin to be used – it rather allows a component to comply with the specification, including the margin. System de-rating can also be useful. For example, in the presence of single event transients (SET), filtering and slowing the response of the circuit or system to analog signals can protect the system against invalid responses to erroneous analogue signals induced by SET.

VII. CONCLUSIONS

We have presented the new ECSS-E-10-12 standard "Methods for Calculation of Radiation Received and its Effects, and a Policy for Design Margins" and discussed some of the issues it seeks to address. The standard has been prepared with the active participation of European industry, national space agencies and ESA, and so it is hoped that it fulfils the ECSS goal to create user-friendly consensus standards. The radiation effects community is invited to contribute to the improvement and maintenance of this and related standards.

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