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Taking SmallSats to The Next Level - Sensible Radiation Requirements and Qualification That Won't Break The Bank

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ABSTRACT

The natural space radiation environment can be considered harsh for semiconductor electronics that make up SmallSat instruments and systems. Radiation effects impact Electrical, Electronic, and Electromechanical (EEE) device performance in multiple ways: semiconductor material degradation and charge creation within the device. SmallSats usually achieve their goals by utilizing commercial-off-the-shelf (COTS) components, which can be considered more susceptible to radiation effects than high reliability components which have higher piece part costs. The impacts can accrue over the mission life or have instantaneous repercussions, thus, they are highly dependent on the mission environment. Unique mission launch date (period within the solar cycle), duration, and destination (orbit) determine the resultant radiation hazard. SmallSats are seeking a way to plan for operation in environments beyond low inclination, Low Earth Orbit (LEO), and short lifetime. In order to succeed with budget and schedule limitations experienced on the SmallSat paradigm, they will need to adopt practices of radiation hardness assurance (RHA). Radiation requirements and testing need to be tailored such that they do not impose overburden.

INTRODUCTION

System-level radiation requirements can drive test and assurance methodologies for microelectronic and photonic devices that must operate in the natural space environment, engendering trade-offs involving part selection, schedule, cost, and risk. While this is true for many environmental factors (e.g. thermal effects, operation in a vacuum, etc.), radiation threats are largely unique to space environments. The radiation response of each semiconductor is derived from the interaction between the device materials, process, design, and architecture; therefore, radiation testing has played a crucial role in revealing and characterizing vulnerabilities in systems with a family tree's worth of failure modes. For SmallSats, with their reliance on a broad range of COTS devices, low cost, and schedule constraints; testing every part -- or even every critical part -- is not an option.

When SmallSat missions take place in benign environments, undiscovered radiation threats to individual parts may pose acceptable risks, particularly for failure-tolerant missions. However, now that SmallSats are increasingly deployed in harsher environments and for more critical missions, radiation threats need to be taken more seriously, and fault-tolerance design practices are essential. A key step toward this goal is the development of a mission requirements approach that can be tailored to the Mission Environment, Application and Lifetime (MEAL). Increased risk tolerance calls for an approach that considers cost and schedule while providing assurance against radiation threats, which facilitates design innovation.

This paper describes how radiation threats change in different radiation environments, how mission requirements become radiation requirements, and it considers how these changes affect requirements and the tradeoffs faced by system and subsystem designers. Similarity data (and its limitations) are discussed so that caveats and short-comings are understood.

RHA PROCESS OVERVIEW

The RHA process can benefit SmallSat missions that have varied mission profiles and risk postures. It is not the process that needs to be altered, but the activities associated with the process that can be tailored to each mission to defray costs.

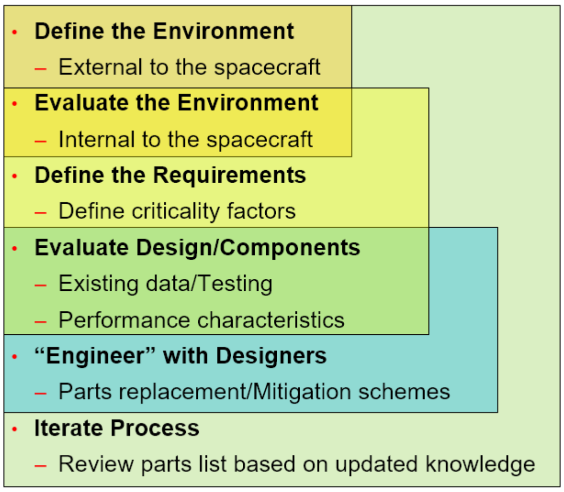

Figure 1: RHA Process, where color coded boxes group interdependent activities [1].

This process is in part necessary because radiation effects come in two distinct manifestations: Single Event Effects (SEE) and Mission Dose (both ionizing and non-ionizing). The environment stipulations and discussion of how RHA deals with emerging technologies and COTS components have been presented by leading agencies and industry partnerships [1-5]. A top-level outline and grouping of activities associated with RHA are shown in Figure 1. The three woven boxes can be succinctly described as:

- *Defining and evaluating the hazard*
- *Making smart radiation requirements*
- *Analyzing the engineering trades*

Each one of these actions can be regarded as an engineering effort or interaction that enables team communication of objectives and how to achieve mission success. The suggested RHA flow can inform and benefit the selection of EEE parts for an intended application while weighing the radiation risks to the system as a whole. The three convolve when considering the impact of the mission requirements. This process is then iterated for the system as a whole when trades are realized, or the environment/design need changes as a result. The time and money spent on working on RHA can increase the likelihood of success by identifying or removing unbound risks to the system.

Clear mission requirements make it easy to identify the hazard and determine what constitutes a device or system failure. Smart mission requirements make it easy to weigh the hazard vs. response and accept risk on the basis of categorization. RHA activities beyond those are focused on buying down the risk with specific data in mind. The true cost savings to SmallSat missions is going to come from requirements that allow the identification and acceptance of risks.

Define and Evaluate the Radiation Hazard

Orbits and environments are tied to mission objectives: astronomy, heliophysics, planetary, Earth science, communications, etc. These objectives also become drivers for the launch date and mission duration, both of which contribute to the dynamic radiation hazard. Typical orbits are referred to as LEO, Sun Synchronous, Polar, Equatorial, High Earth Orbit (HEO), Geostationary Earth Orbit (GEO), Heliocentric, etc. Most are tied to the inclination and altitude of the spacecraft. For the context of this paper, Figure 2 shows radiation contributors in three selected orbits and mission durations for missions with COTS components in mind.

Because each environment is truly unique, there is risk buy down to be gained in defining the environment for which the parts of interest are intended. For instance, short missions may not have a high total dose over the course of the mission life, but will still have SEE contributions that interrupt or threaten the system. Many passes through the Van Allen radiation belts or the South Atlantic Anomaly (SAA) can lead to high doses or temporal SEE threats, while the protection from Earth's magnetic field can attenuate the number of Galactic Cosmic Rays (GCRs) that reach the spacecraft.

Environment

Mission Lifetime	LEO Equatorial	LEO Polar (Sun Sync)	GEO / Interplanetary
> 3 Years	Moderate Dose / Attenuated GCR, Trapped Proton, Some Solar Proton dependence for variation	High Dose / Higher GCR, High Energy Trapped Protons in SAA and Poles, Some Solar Proton dependence for variation	High Dose / High GCR, High Solar Proton Variability
1 - 3 Years	Manageable Dose / Attenuated GCR, Trapped Proton, Some Solar Proton dependence for variation	Moderate Dose / Higher GCR, High Energy Trapped Protons in SAA and Poles, Some Solar Proton dependence for variation	High Dose / High GCR, High Solar Proton Variability
< 1 Year	Manageable Dose / Attenuated GCR, Trapped Proton, Some Solar Proton dependence for variation	Moderate Dose / Higher GCR, High Energy Trapped Protons in SAA and Poles, Some Solar Proton dependence for variation	Moderate Dose / High GCR, High Solar Proton Variability

Figure 2: Radiation contributions for three general groupings of orbits. These are mapped out for different mission lengths leading to notional threat levels, which are relative to one another.

In the figure, manageable dose would seldom cause parameter shifts in most COTS devices, while moderate dose may experience degradation but not functional failures, high dose could pose a threat to COTS operation. Attenuated GCR refers to the flux of particles being reduced by Earth's magnetosphere, and high GCR would be the flux without that protection. It can be seen that an increased mission lifetime changes the hazard from dose (increases the fluence of particles overall), but not the particle fluxes that need to be considered for SEE.

Models of the space environment have been built and are maintained by space agencies/industry, and some are readily available to the public [5, 6]. The on-orbit dose and spectra can be estimated to determine a representative model of what a spacecraft will need to survive. These types of calculation can be used to describe the radiation hazard for mission phases or known operating conditions.

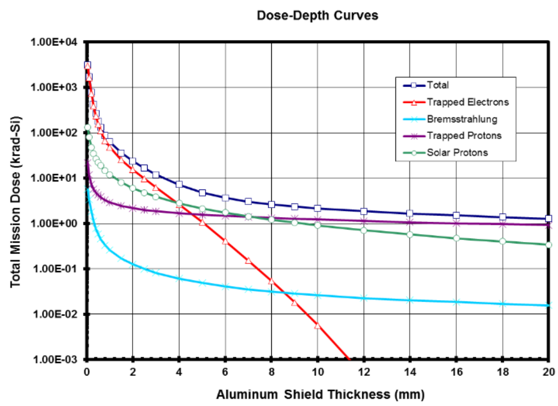

Figure 3: Dose-depth plot; ionizing dose contributions are transported through spherical shielding, the total dose is the summand of all contributions.

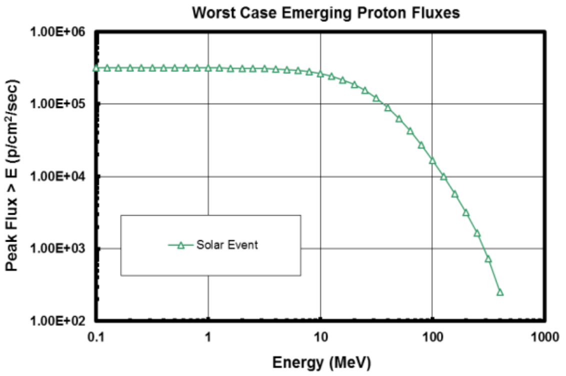

Figure 4: Emerging Protons during a Solar Event; energetic solar protons are transported through shielding materials and resultant integral fluxes are reported. This flux can be used with data on parts to predict a SEE rate during a Solar Event.

Calculated outputs from these environment models that convey two top-level radiation threats in a given environment - the dose-depth curve and the emerging protons - are shown in Figure 3 and Figure 4. It is important to know the species and population of the particles because they ultimately define the hazards. These examples have been chosen to highlight the aforementioned competing threats for EEE parts in a radiation environment: Dose vs. SEE. These two plots are not the whole description, but represent how one can delve into details about the mission environment and its variations. Total Ionizing Dose (TID) is accrued over the entire mission life, this can lead to wear out or aging of certain device parameters causing threshold shifts and leakage that increases over time on orbit. Solar events like flares or Coronal Mass Ejections can eject in the direction of a spacecraft, where inside the emerging protons contribute to the SEE event rate. This would be a worst case prediction, typically used to mimic what particle populations would be seen during a solar storm. Nominal SEE rates would be driven by GCR as a background, with proton contributions from trapped particles as well as solar wind. These spectra are available from environment models as well, though not shown here.

In order to define the hazard:

- Segment the mission into phases where the environment or driving requirements have unique circumstances (transfer orbits, science operation, robotic actions, etc.), this can prove to be useful for conceptually accepting risks.
- Determine the contributing particle populations to the mission radiation environment of trapped charged particles, GCR, solar particles.
- Transport the particle fluence and flux through representative amounts of shielding materials to determine the environment where the electronics will be located, this can done for spherical shells of Al and is often discussed behind 100mils to first order.

Once the hazards have been identified and there is a representative model of what your parts will be exposed to, the design can be evaluated for outlaid risks. SmallSats do not want to plan for a costly parts program with significant margins, so work must be put in to make smart requirements based on how devices will react to their new environment. Indeed, disciplines beyond electrical engineering (i.e., Materials, Spacecraft Charging) will benefit from this type of analysis/activity as well. For "large" missions, a full environment description document serves as a reference and one pointer for many disciplines.

Make Smart Requirements

Acceptance of risk is a part of a validated spacecraft design. SmallSats by and large have systems and subsystems on them that are developed to fit a small form-factor and are readily integrated with other builds. It would be detrimental to the cost and budget of the spacecraft to levy requirements on COTS subsystems that require test and analysis unless absolutely necessary. Mission requirements should flow to subsystems that contain the technologies of interest or that have critical functions where risk needs to be bounded. Maintaining and managing requirements is necessary so that communication and trades happen when beneficial rather than existing as a method of verification after the fact.

Mission requirements feed into how the hazard is determined (what orbit, launch date), but also help to categorize and eliminate risks. Definition of the failure levels, with respect to radiation, are where the mission requirements and radiation requirements overlap heavily. Does mission success rely on one subsystem or even one spacecraft? This is where good communication between a team can glean costs savings on both fronts: analysis resources and the need for testing. Figure 5 explains how the RHA needs can be tailored to different hazards. If the program needs to know the survivability to a moderate dose and whether or not single event effects are going to interrupt the availability of a subsystem, the RHA need would then be high. The higher the need, the more budget should be put in place for radiation support, and the higher the likelihood of requiring specific test data, or needing to test critical parts in their application.

Evaluate RHA System Needs \ Environment Severity/Mission Lifetime	Low	Medium	High
High	Manageable Dose / SEE impact to survivability or availability	Moderate Dose / SEE impact to survivability or availability	High Dose / SEE impact to survivability or availability
Medium	Manageable Dose / SEE needs mitigation	Moderate Dose / SEE needs mitigation	High Dose / SEE needs mitigation
Low	Manageable Dose / SEE do no harm	Moderate Dose / SEE do no harm	High Dose / SEE do no harm

Figure 5: Environment and mission requirements can determine the RHA system needs

Radiation requirements (different than the overarching mission requirements) need to be based on a known hazard, but they also need to take into account the design's functionality and technology. Requiring that all parts survive with large margins ignores the failure mechanisms for different types of parts, and can invoke requirements on materials or subsystems that cannot meet them without analysis or testing that may not benefit the on-orbit mission risk. As such, the mission radiation requirements need to be flowed down to the appropriate technologies. Establishing the radiation requirements by part family will allow quick categorization of risk, and lend itself to a targeted analysis. There are no rules of thumb, only the physics of failure that can be attributed to device process and architecture: Here are the known risks to given technologies [8-11], in a notional order of risk to the part operation. It is up to the mission requirements and design to determine the risk to the intended system operation.

- Destructive single event effects (DSEE): parts can either fail to short or open (family of effects that permanently damage the device and result in it being inoperable).
- Total Ionizing Dose / Displacement Damage Dose (TID/DDD): part shows degradation beyond device specifications, looks like early wear out mechanisms.
- Single Event Transients (SET): Can be rail to rail voltage or current changes that damage peripheral components.
- Single Event Functional Interrupts (SEFI) that require intervention, depending on part type may need a reset signal, or a full power cycle.
- Multi-Bit or Cell Upsets (MBU/MCU) where error detection cannot correct, refresh, rewrite, or power cycle may be needed.
- Single Event Transients (SETs) with error rates so high that information is lost or communications need reset.
- Single Event Upsets (SEU) can change the state of memory cells or switch the state of logic level devices. There are also hard errors where loss of cell use, masking these upsets or the blocks or pages that contain them may keep the remainder of the memory usable.

Key factors that need to be considered are the **criticality** and **availability** of the EEE part in its application. In every available opportunity, ask how a part response will affect the devices that are connected or share failure modes. Ask what impact the typical device response would have at the subsystem or system level. For a discrete transistor, would a gain degradation lead to science loss? Or would the device continue to function as a switch?

Simply stating that if a part failure is a single strain, and if it is critical, can determine the path to mission success.

Analyze the engineering trades

In evaluating the SmallSat design trades, there are significant variables and variation from that of larger mission profiles. If the mission is a secondary payload, with multiple launch opportunities, would the radiation hazard be similar? What would that do to the assumptions of the radiation response? How would that change the mission phases? Where criticality and availability are met with unbound radiation risks, it may be beneficial to test if relevant data does not exist. Figure 6 weighs the EEE part criticality vs. the hazard, with some suggested cases that call for mitigation or testing.

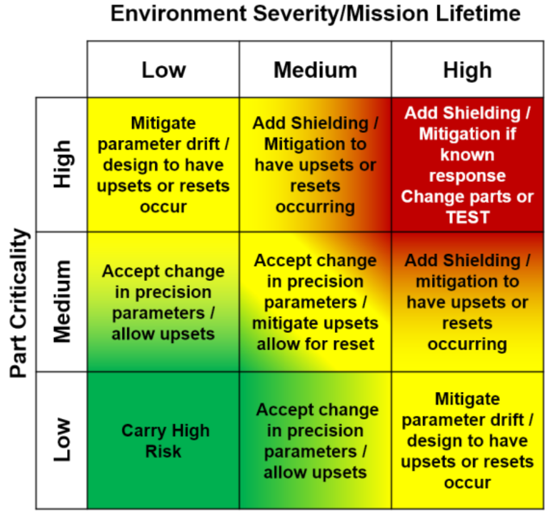

Figure 6: Risk posturing for EEE parts with critical applications can drive the need to test or carry a high risk. If the system impact or upset/degradation is not realized above a subsystem level, it may be cost beneficial to carry the risk.

The margins a program or project put to use are and have been a catchall for uncertainties in many contributing analyses. When testing cannot be done on the flight lot or in a flight-like application, margins need to be applied to account for variability in part responses, as well as uncertainty in the environment models.

Radiation testing to buy down risk can be done sparingly if the requirements on which parts are being examined for flight are specific, rather than blanket statements. Radiation threats are unique to a part's architecture. The process of the device, the mask set used, the semiconductor material, and sometimes even the packaging play a role in the radiation response on-orbit. These dependencies strain the applicability of data on similar parts, but as data accumulates across the community there are intentions and attempts to make statistical use in order approve of a parts use based on previous determinations and findings [13, 14]. Below are some descriptions of radiation responses by device family and notional impacts:

- Power Devices – With high voltage comes stronger internal electric fields, derating no "hard off" states can be the most threatening (where a negative gate voltage is applied for an NMOS, for instance). MOSFETs can experience single event gate rupture (SEGR) or single event burnout (SEB). Thicker oxides will have greater volume capable of trapping charge.

- Analog Components – some bipolar devices will be more susceptible to the dose rate in space vs. the accelerated, ground-based testing dose rates. Filter SETs on the output of the device, if possible.

- Programmable Logic Devices – responses are application-based decisions, don't add triplication and voter complexities if it will disrupt the correct operation of your system

- Complex Digital Components – responses are application-based decisions on frequency and availability

- Memories – consider the feature size and density and expect SEU/MBU. Control logic will have different responses than the memory cells and can result in SEFI or single event latchup (SEL), if not determined.

- RF/Heterojunction devices – faster devices in terms of charge response, therefore, there will be fast transients, but the responsivity to charge will also result in higher SET rates

- Opto-electronics – Displacement Damage and TID can work in concert to degrade performance like charge transfer ratio (CTR). Material degradation will impact efficiency or optical throughput

- Mixed Signal – both analog and digital concerns in one package. Commercial ADCs/DACs exhibit transients and functional interrupts, may have digital single event effects (DSEE) concerns as well

- Hybrid Devices – many types of components packaged together

When it comes to testing, consider system level impacts to determine the cost benefit of conducting a test. Always test in a flight-like application and do not expect results to apply if you are not covering the same state-space the mission will cover. There are relevant tests for each failure mechanism, but they can be considered in the two familiar categories as mentioned previously, TID/DD and SEE. The two types of radiation tests indeed have sub-categories just as the part types and failure modes do. A good synopsis on the types of testing and how to conduct them are the topic of a number of short courses and papers [2-8].

SIMILARITY DATA AND ITS LIMITATIONS

Using available data, rather than conducting a radiation test campaign, can be a cost saver. Radiation facilities are expensive to maintain and the costs show (cyclotron facility costs can be thousands per hour). But caution and information need to be employed when extrapolating previous results to the mission's end-use of an EEE part. Many of the known mechanisms for upsets, failures, or more generally the response from the device are tied to specific biases, frequency, operating temperature, etc. How the testing was conducted needs to envelope or represent the mission application in order to be valid.

Part-to-part variation in response can be attributed to the manufacturing process, as can lot-to-lot variation. If a manufacturer changes foundries or changes the process to increase performance, large changes in the radiation response can be seen. These are the drivers for desiring lot specific test results. SEE testing or data can benefit from the knowledge that a mask set and process have not changed (i.e. the sensitive volumes are similar and the internal transistors are co-located in the same way), whereas TID results are much more process oriented with dependencies on how oxides and interfaces are manufactured and can vary on small deviations in the temperature, doping, or chemical process steps. This is based on trapping locations within the device like imperfections in the oxide or interface. Charge traps are what give rise to parametric shifts in devices and integrated circuits.

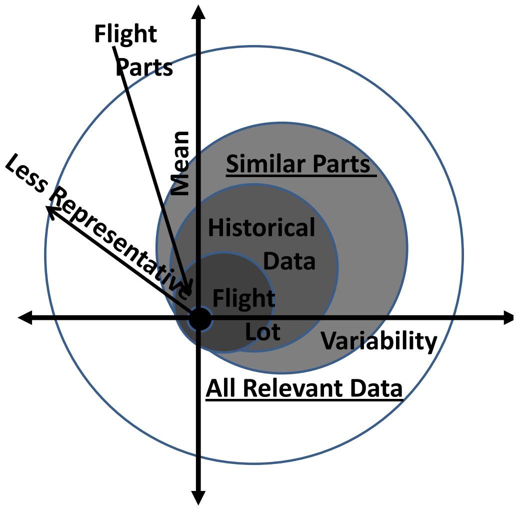

Figure 7: Diagram of relevant data and relation to flight lot representation [13, 14]

The figure above shows how close to representative failure distributions are considered in the realm of relevant data. As you take into account data on the flight lot for a critical mission, you can also accept the risk of part-to-part or lot-to-lot variability on less critical subsystems. If you are able to justify previous data for the mission application, what can be considered useful will inform the decisions of risks to accept. The guidelines and recommendations of the minimum data necessary to quantify a risk to the system can be considered as done in Figure 8. It should be noted that, in some instances, ruling out destructive single event effects alone may provide mission assurance.

Mission Lifetime (With Assumed Risk Acceptance)	Environment: LEO Equatorial	LEO Polar (Sun Sync)	GEO / Interplanetary
> 3 Years	Data on all SEE for critical parts, and have data on dose failure distribution on similar parts	Consider mission consequences of all SEE (Data for critical parts), have Dose failure distribution on lot	Have Data on all SEE, Have Data Dose failure distribution on lot
1- 3 Years	Have Data on DSEE for critical parts	Consider mission consequences of all SEE (Data for critical parts), have data Dose failure distribution on similar parts	Have Data on all SEE for critical parts, Have Data on Dose failure distribution on similar parts
< 1 Year	Look for data on DSEE for critical parts	Consider mission consequences of all SEE, and look for data on dose failure distribution on similar parts	Consider mission consequences of all SEE, and have data on dose failure distribution on similar parts

Figure 8: Radiation Data needs for quantifying risk in the represented missions over varied duration.

SUMMARY

Reliability quantification may not always be possible, but identifying and classifying the radiation risks will inform radiation requirements and trades that are most likely to lead to mission success. Taking the mission environment, device criticality, and technology into account when establishing radiation requirements needed to meet mission objectives will reduce the workload necessary to verify the system design. Risk identification and traceability to system responses can alleviate the need to conduct costly radiation testing. Where unknown risks pose a threat to mission success, there is no substitute for radiation testing in the devices' intended application, identifying the physics of failure, and avoiding that mechanism where possible in similar devices or architectures. Keeping that in mind, when adopting previous results on commercial electronics and designing with fault-tolerance in mind, it will lead to mission success without breaking the bank.

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