[SSC22-WKP2-04]

CubeSat Radiation Hardness Assurance Beyond Total Dose: Evaluating Single Event Effects

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ABSTRACT

Radiation poses known and serious risks to smallsat survivability and mission duration, with effects falling into two categories: long-term total ionizing dose (TID) and instantaneous single event effects (SEE). Although literature exists on the topic of addressing TID in smallsats, few resources exist for addressing SEEs. Many varieties of SEEs exist, such as bit upsets and latch ups, which can occur in any electronic component containing active semiconductors (such as transistors). SEE consequences range from benign to destructive, so mission reliability can be enhanced by implementing fault protection strategies based on predicted SEE rates. Unfortunately, SEE rates are most reliably estimated through experimental testing that is often too costly for smallsat-scale missions. Prior test data published by larger programs exist, but may be sparse or incompatible with the environment of a particular mission. Despite these limitations, a process may be followed to gain insights and make informed design decisions for smallsats in the absence of hardware testing capabilities or similar test data. This process is: (1) Define the radiation environment; (2) identify the most critical and/or susceptible components on a spacecraft; (3) perform a search for compatible prior test data and/or component class data; (4) evaluate mission-specific SEE rates from available data; (5) study the rates alongside the mission requirements to identify high-risk areas of potential mitigation. The methodology developed in this work is based on the multi-institutional, National Science Foundation (NSF) Space Weather Atmospheric Reconfigurable Multiscale Experiment (SWARM-EX) mission. The steps taken during SWARM-EX's radiation analysis alongside the detailed methodology serve as a case study for how these techniques can be applied to increasing the reliability of a university-scale smallsat mission.

1 INTRODUCTION

Radiation poses known and serious risks to smallsat survivability and mission duration, with effects falling into two broad categories: long-term/cumulative total ionizing dose (TID) and displacement damage (DD) effects, and single event effects (SEE), which occur spontaneously at a statistical rate. While the severity of both types of radiation effects are dependent on environment and lifetime, TID is an accruing, long-term effect while SEEs are independent, probabilistic effects. Increased shielding, while a foundational technique, is not a comprehensive one; shielding increases a spacecraft's resiliency to TID, but particles that are energetic enough to induce SEEs often have enough energy to penetrate any reasonable amount of shielding for a small satellite. Hence, mission reliability can be enhanced by implementing fault protection strategies based on predicted SEE rates.

Although detailed prior literature exists on the process of addressing TID in smallsats,[1] few resources exist for addressing SEEs, as a comprehensive SEE analysis typically requires far more resources than a smallsat program has access to (although examples of smallsats designed with SEE hardening in mind do exist[2–4]). The approach outlined in this paper is intended to guide programs with small satellites in low-Earth orbit that have limited finances, time, and/or access to experts. Cognizant of these limitations, this paper outlines a process that can be used to make informed design decisions for smallsats in the absence of the resources necessary to launch a full investigation of SEEs. The techniques outlined in this paper were developed to address radiation concerns for the NSF SWARM-EX mission.

2 BACKGROUND TERMS

SEEs are spontaneous, independent events in which a circuit is affected by charge deposition from energetic particles. SEEs occur in any electronic component containing p-n junctions, which is to say any active semiconductors (such as transistors). Many SEEs are one-time events which require a fundamentally different strategy for addressing than TID, in which shielding is usually used to slow cumulative effects (shielding does very little to reduce SEEs). That said, some minorly destructive SEEs may not be catastrophic at first, but can accumulate to a major effect. Two examples of this are microdose/microdisplacements in transistor substrates,[5] and transistor gate leakage current increasing as the gate accumulates damage from single events.[6] At any rate, various types of SEEs exist, and their impacts range from benign to mission-ending. Definitions of acronyms, terms, and common SEEs are provided below as background to the subject of SEE analysis.

- **MOSFET:** Metal-oxide-semiconductor field-effect transistor. MOSFETs are insulated-gate field-effect transistors that serve as the building block of most modern microelectronics. MOSFETs require the insulation of a conductive gate from the bulk silicon of the device via an oxide layer. Radiation commonly affects the oxide and bulk silicon of MOSFETs, hence susceptibility of a device to radiation effects arises at the level of this silicon architecture/topology.

- **CMOS:** Complementary metal-oxide-semiconductor. A device in which logic gates are built from networks of n- and p-type MOSFETs which are connected to common voltage rails and coexist on the same silicon substrate. The continual scaling down of these structures (as predicted by Moore's law) has enabled the fabrication of increasingly powerful computers; as a result, many modern integrated circuits (ICs) rely on CMOS architecture. Because of their reliance on MOSFETs, CMOS devices are particularly vulnerable to SEEs.

- **Single effect upset (SEU):** Upsets occur when radiation deposits sufficient charge to induce a change of state in a memory bit. A radiation event that triggers multiple bit flips may be referred to as a multiple bit upset (MBU) or block error. Resetting or rewriting the affected bits generally normalizes behavior.

- **Single event latchup (SEL):** Latchups occur when radiation deposits enough charge in a CMOS device to enable a parasitic thyristor to activate inside the silicon of the device. This results in a short circuit between power and ground that self-heats and can burn a hole in the device if left unmitigated. Power cycling the affected device generally normalizes behavior, provided it is done rapidly enough.

- **Single event burnout (SEB):** Burnouts occur when an ion strike triggers parasitic bipolar action, resulting in high current in a power transistor and can result in catastrophic failure of the component.

- **Single event gate rupture (SEGR):** One mechanism for gate rupture is charge deposition from a heavy ion that forms a conducting path in the gate oxide. Another mechanism is the formation of charge tracks which collapse the depletion region of a MOSFET, resulting in excessively high fields suddenly becoming present in the gate oxide. Either mechanism results in a MOSFET being flipped into a permanent-on state. Power MOSFETs are particularly prone to SEGRs, which can induce catastrophic failure of the transistors in a similar mode to SEL.

- **Single event transient (SET):** A transient refers to a disturbed output signal or waveform from a device, such as a momentary voltage spike or dropout from a voltage regulator. SETs tend to resolve on their own, but can give rise to system-level functional interrupts if downstream devices are affected by the disturbance.

- **Single event functional interrupt (SEFI):** A functional interrupt refers to a loss-of-function of a device and may manifest at a system level, such as an avionics system passing a data error initially triggered by a SET or MBU. A power cycle can often restore functionality.

- **Radiation hardness assurance (RHA):** A holistic approach to mitigating radiation effects in which mission and system requirements drive component and mitigation selection. The process begins by establishing mission requirements. Next, radiation hazards are determined by modeling the radiation environment defined by the mission requirements. Part selection can then occur, followed by an evaluation of system robustness to radiation effects (a common step in this evaluation is to perform radiation testing on flight model components). This approach is designed to both acknowledge and analyze specific components while also taking into account system and mission-level functionality.

Smallsat missions with limited resources may not have access to the necessary tools to complete a comprehensive RHA analysis, especially in regards to performing experimental testing on flight model components. This testing is the most reliable way to estimate a component's susceptibility to SEEs, but generally far exceeds the budget requirements for smallsat-scale missions. Prior test data published by larger-budget programs exist but are often sparse or irrelevant to the specific application of the particular smallsat mission. Detailed guidelines for identifying acceptable prior test data are given in section 6.2. The techniques discussed in the remainder of this paper are directed to address the needs of resource-limited teams, such as university smallsat programs, that wish to enhance mission reliability by addressing SEEs in their radiation strategies without the budget or time to support experimental testing.

3 EVALUATING THE RADIATION HAZARD

The first step in evaluating any radiation effect is to evaluate the radiation environment defined by mission requirements. Numerous tools exist to aid in this process including ESA's SPENVIS, TRAD's OMERE, STK's SEET, and NASA's RGENTIC, with previous literature on the topic of smallsat radiation assurance providing instructions for and comparisons between these tools.[1, 7, 8] In general, however, radiation environment software tools are simply front-end interfaces for the same set of underlying particle and magnetic field models, so it is simply the user's preference of front end interface and control detail as to which tool to use. These radiation environment modeling software generate a common set of output graphs/data useful for evaluating TID and SEE. The SWARM-EX team chose to use TRAD's OMERE because of prior experience using the interface and option to select particular particle and radiation models.

The most common set of outputs from environment modeling software include particle flux and linear energy transfer (LET) spectra graphs, examples of which are shown in Figures 1 and 2. Particle flux graphs show the intensity of particular types of particles as a function of energy level and are generally reported as integral or differential flux. These quantities are:

- **Integral Flux:** the flux of particles with energies that exceed a specified energy threshold (e.g. all particles with > 1 MeV of energy).[9]

- **Differential Flux:** the negative energy derivative of the integral flux (i.e. $-dJ/dE$, where J is the function that describes integral flux). The negative derivative is taken so as to produce a positive quantity (as the derivative of integral flux is negative on its own).[10]

Ultimately, both differential and integral flux communicate the same information (and all radiation related quantities can be derived from them[10]), but a particular form may be more useful in a particular context; for instance, differential flux may be the quantity directly measured by a spectrometer while integral flux–being an aggregate particle count–is more useful for assessing space radiation effects. The SWARM-EX mission has a 500km orbit at 52.0 degrees inclination. The predicted particle flux environment for this orbit is shown in Figure 1. When considering electron flux in Figure 1, the authors note that electrons are not typically a contributor to SEEs, but are a significant contributor to TID via ionization and Bremsstrahlung effects.

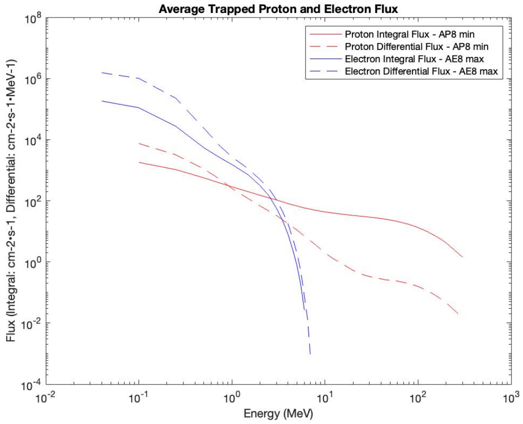

Figure 1: Average integral and differential flux for 500 km orbit at 52.0 degrees. The AP8-MIN (proton worst case) flux is shown in red and the AE8-MAX (electron worst case) flux is shown in blue.

Linear energy transfer (LET) is the amount of energy transferred into a material (through ionization) per unit distance as an ionizing particle travels through a component.[9] As such, LET can be measured in units of energy per distance (e.g. MeV/cm), but normalizing LET by the material density yields the more typical unit of MeV×cm^2/mg.[1] In this calculation the model inputs a specified radiation environment and determines the environment of particles "transported" behind the shielding, accounting for released energy as particles lose energy to shielding materials. The LET spectrum graph describes the radiation environment inside the spacecraft and quantifies what level of ionizing energies the electronic components of the spacecraft will experience. The calculated particle flux environment for the SWARM-EX orbit behind 1 mm of aluminum shielding is shown in Figure 2.

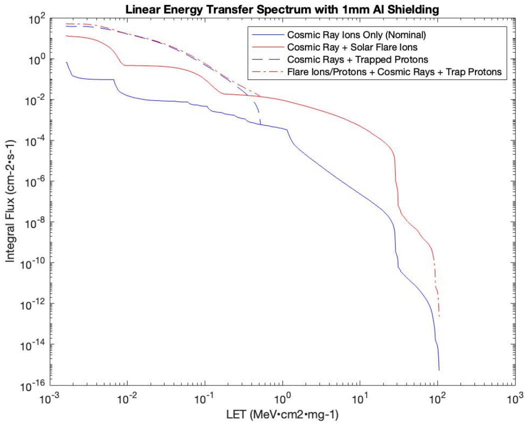

Figure 2: Integral LET spectrum for a 500 km orbit through 1 mm of Al shielding. The various curves show the levels of transported particle flux through a specified shielding for various sets of environment particles.

Because SEEs arise as a result of ionizing energy imparted to a circuit, the LET-flux curve is the information that connects the radiation environment to hardware SEE susceptibility; LET describes charge deposition within a material, independent of ion species and energy. The LET metric allows ground based testing (with known charge deposition) to be representative of the space environment.

The other piece of information necessary to estimating an SEE rate is an experimentally derived probability curve, known as a device's "cross-section," which relates the number of SEEs to the fluence of particles at various LET levels when a component is bombarded by an ion beam. This curve is unique to every component and is described in detail in section 6.1.

4 IDENTIFICATION OF SUSCEPTIBLE COMPONENTS

The first step in analyzing system radiation effects is to identify radiation susceptible components from the mission's component-level avionics parts list. To aid in this analysis, we briefly discuss TID considerations and then present several common associations between families of devices and SEE susceptibility.

- **Total Ionizing Dose:** CMOS devices are typically susceptible to long-term effects as a result of incoming radiation that redistributes or deposits charges on MOSFET oxides. These charges accrue, gradually changing the gate threshold voltage of the transistor. When the gate threshold voltage becomes critically low, electrons begin to flow freely through the transistor. This effectively flips the transistor into a permanent-on state (SEGRs may cause this same effect, though instantaneously). An additional accrued effect of TID is displacement damage (DD), in which radiation physically knocks atoms out of atomic crystal lattices. DD to silicon lattices particularly affects transistors, optocouplers, and other high-precision components that require low voltages and/or currents. Finally, a variety of non-semiconductor components are susceptible to total dose effects.[11, 12] Radiation causes DD to metal crystal lattices and reforms chemical bonds in plastics, resulting in varying material density, plasticity, and ductility. Thermal blankets, for instance, are particularly susceptible to increased brittleness and cracking. Electrical components may be susceptible to charging and experience variations in conductive/insulative properties. Optical components, such as the glass used in camera lenses, are susceptible to fogging in an effect referred to as "radiation darkening." In general, shielding is an effective way to increase the lifetime of components against TID.[1, 7]

- **CMOS Devices:** CMOS devices, including microcontrollers and many integrated circuits, are particularly susceptible to latchup. Most SELs can be mitigated by a power cycle of the affected device (as a thyristor will remain stuck in an on state until power to it is cut), so periodic power cycling may be employed in the absence of the ability to detect a latchup. Setting thresholds for power cycling will depend on the estimated rate of latchups in critical components.

- **Power Electronics:** Discrete power components, such as power MOSFETs or Schottky diodes, are particularly susceptible to SEGR and SEB due to high current loads. In general, SEGR in a power transistor is always destructive. Linear ICs, such as DC-DC converters, most often manifest SETs, such as voltage spikes or dropouts.

- **Memory:** Static random access memory (SRAM) and dynamic random access memory (DRAM) devices are volatile memory devices built upon CMOS/MOSFET architecture and are therefore susceptible to SEU and SEL. Additionally, memory devices are susceptible to "hard errors" in which bits become permanently stuck.[13, 14] FRAM memory devices use ferroelectric capacitors rather than MOSFET components, and are therefore much less susceptible to radiation effects. Nonvolatile flash memory is much less susceptible to radiation effects than DRAM, but are still susceptible to SEU/MBU, which manifest as re-written memory bits, and SEFI, which can manifest as read/write lockups. A particular area of concern with nonvolatile memory are system bootloaders; if a bootloader does not contain a rewriting capability, its corruption could result in mission failure.

Additional notional guidance may be found by using the NASA/Vanderbilt R-GENTIC tool.[15] A summary of notional threat identification is shown in table 1. One additional radiation effect that has not been discussed appears in table 1: Enhanced Low Dose Rate Sensitivity (ELDRS) is a change in device sensitivity parameters on-orbit. For devices susceptible to ELDRS, ground based test results at high dose rates cannot serve to bound the damage that occurs.

For small satellites in low Earth orbit, SEU, SEL, and SET tend to be the most relevant sources of SEEs necessary for engineering considerations: SEU and SEL, because memory and CMOS devices see these effects most commonly; and SET, because it is a recoverable effect that appears most frequently in linear and power devices. SEGR and SEB may also occur (particularly in linear and power devices), but these tend to be permanently destructive effects, so it is difficult to implement mitigations besides redundancy.

On the ground, SEU, SEL, and SET can be measured directly during experimental radiation testing, but it is often difficult to do so directly in space; in practice, many SEU and SEL events will manifest as SEFIs at a higher level of the system (e.g. memory read/write or microcontroller lockups, which may arise from a variable number of SEEs), so mitigation strategies should focus on continued spacecraft operability or autonomous detection and self-mitigation in the event of high-level interrupts to spacecraft components or subsystems.

5 PART REDUCTION FOR ANALYSIS

Reducing the number of parts considered in an SEE study is important because the process of identifying compatible test data requires detailed com-

Table 1: Threat susceptibilities for common classes of spacecraft electronics.

Family	**Examples**	**Radiation Concerns**
Clock/Timing	Circuit or crystal oscillator, DLL, PLL	SEU/MBU, SEL, SET, SEFI, TID
Digital	Comparator, discrete flip-flop or logic gate, multiplexer, PWM, receiver	SEU/MBU, SEL, SET, SEFI, TID
Discrete Power	BJT, HEMT, IGBT, JFET, MOSFET, PIN diode, Schottky diode	SEGR, SEB, TID, DD
Discrete RF/signal	Amplifier, attenuator, demodulator, detector, mixer, modulator, receiver, transmitter	SEU/MBU, SEL, SET, SEFI, SEGR, SEB
Embedded	Digital signal processor, FPGA, microcontroller, microprocessor	SEU/MBU, SEL, SET, SEFI, TID
Imager	Charge coupled device, CMOS imager, focal plane array assembly	SEU/MBU, SEL, SET, SEFI, SEGR, SEB, DD, TID, ELDRS
Linear	Comparator, LDO, op-amp, voltage reference or regulator	SET, SEB, DD, TID, ELDRS
Memory	SRAM, DRAM, EEPROM, FRAM, MRAM, NAND or NOR flash, SDRAM	SEU/MBU, SEL, SET, SEFI, TID
Mixed-Signal	ADC, analog multiplexer/switch, current-mode PWM, DAC, integrated PWM DC-DC converter, voltage-mode PWM	SEU/MBU, SEL, SET, SEFI, SEGR, SEB, DD, TID, ELDRS
Opto-electronics	Discrete LED, optocoupler, photodiode	DD, SEB, SEGR, TID
Power Hybrid	Battery charger, DC-DC converter, load switch, motor drives, multi-voltage regulator IC, peak power tracker, power supply	SEGR, SEB, SET, TID, DD, ELDRS
Sensor	Accelerometer, current, hall effect, pressure, readout IC, resolver to digital converter, temperature	SEU/MBU, SEL, SET, SEFI, SEGR, SEB, DD, TID, ELDRS

ponent information which is often difficult to obtain (hence, analyzing the SEE rate for many components may become debilitatingly time-consuming). The reduction of the full susceptible parts list may be done by considering which components are most critical to the mission being able to achieve the objectives as defined in the mission requirements. This necessitates system-level consideration (as noted by the RHA process), as relatively benign failures in particular components could still result in high level functional interrupts (and conversely, a hard failure in a particular component may not considerably disrupt the system's functionality). Fault tree analysis (FTA) or failure mode, effects, and criticality analysis (FMECA) may serve as tools to aid in identifying the most critical components for analysis. An FTA is conducted from a top-down system approach, while a FMECA is conducted from a bottom-up system approach. FTA takes the form of a tree that breaks a high-level failure into subsequently smaller subsystem failures until reaching the level of individual components. By contrast, a FMECA begins at the level of individual components and faults caused by a particular component are traced upwards through higher levels of the system until a functional interrupt emerges. In theory, an FTA and a FMECA will "meet in the middle" to form a single structure in which paths from mission failure can be traced through various levels of functional interrupts down to individual components. The components which cause the highest probability, number, or most critical functional interrupts are the components which should be investigated.

The SWARM-EX team conducted their part list down-selection with an FTA. The top level of the FTA begins with "failure to meet mission objectives," and the second level specifies critical spacecraft functions per the mission-level requirements. Each successive level indicates successively lower-level faults which could give rise to the higher fault, and each branch of the tree may be labeled with "and" or "or," to specify whether one or all of the lower-level faults must occur to give rise to the higher-level fault. An example fault tree, based on one used by the SWARM-EX team, is shown in Figures 3 and 4. Blue text indicates a link to a lower-level fault tree. Certain component-level failures can be seen in the right-most column of each FTA; it is these failures which drive the importance of a component being analyzed for SEEs.

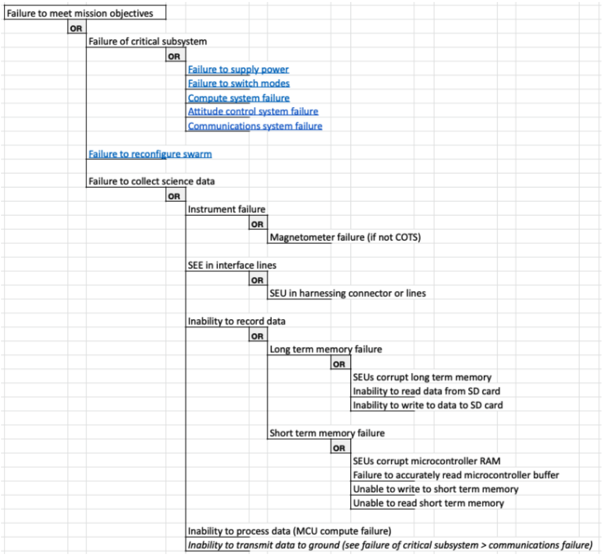

Figure 3: Example high-level FTA for identifying critical components, loosely based on one used by the SWARM-EX mission.

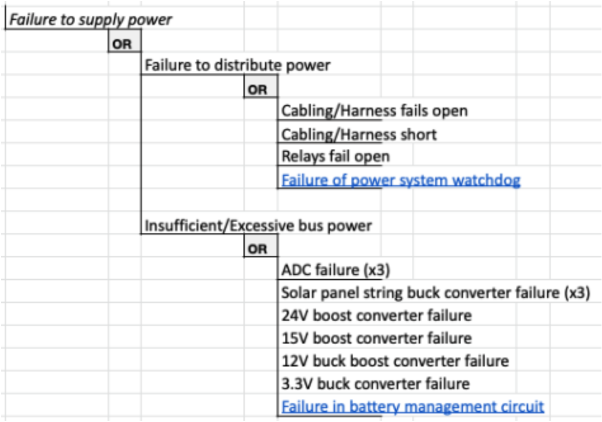

Figure 4: Example of an FTA linked to the higher-level "failure to supply power" fault listed in Figure 3.

The objectives of the SWARM-EX mission are to collect scientific data and demonstrate reconfigurable swarm behavior, so the first level of the FTA was labeled "failure to meet mission objectives" and the second listed failure to complete each of those objectives as high-level functional interrupts, along with a generic "failure of critical subsystem" fault. For SWARM-EX, these critical subsystems included power, mode switching, computation, and communications. For the sake of organization, separate FTAs were built for each of these subsystems. For power, some key modes of failure are failure to distribute power and insufficient or excessive bus power. Ultimately, each of these failure modes can be traced to the failure of a particular component (or components) in the power subsystem, as SWARM-EX utilizes single-string architecture. Ultimately the SWARM-EX team identified 20 components of particular interest and FTA revealed two specific areas of particularly high risk to mission success: a microcontroller unit (MCU) that serves as the spacecraft's main compute element; and a set of DC-DC buck converters used to set power string voltages from the supplied battery voltage. These components were marked as critical to mission success because the three SWARM-EX spacecraft each have a single string design (no redundant components), so disruptions to any spacecraft's MCU or main power line components would seriously threaten a spacecraft's ability to operate. SEE rates for these two components were estimated by identifying prior datasets.

6 COLLECTING PRIOR TEST DATA AND EVALUATING RATES

6.1 Mathematical background for the SEE rate calculation

The final piece of information necessary to evaluate a component's SEE rate is a function which relates the amount of particle energy imparted to a component (the LET) to the probability of that particle inducing an SEE. Once known, the LET-probability function can be combined with the LET-flux curve described in section 3 to relate particle flux to SEE probability and thus estimate an aggregate SEE rate in a given environment. The following information about cross-section data and the rate calculation is provided as background knowledge for the reader, rather than as an instruction set, as the aforementioned software tools are generally capable of performing the curve-fitting and rate calculation.

The LET-probability function must be determined experimentally via component-specific SEE testing. This testing is performed by exposing a device to a beam of particles with known LET for a fixed span of time. The number of anomalies that occur during that time span is measured, as is the particle fluence (the time-integral of flux, representing the total number of particles that passed through the component's area during the test). The probability of an SEE occurring is given by the number of events per unit fluence and is referred to as the component's cross-section, a measurement of probability used in particle physics having units of area.[9] This is represented mathematically as

$$\sigma = \frac{N}{\phi} = \frac{N}{\int \Phi dt} \tag{1}$$

where σ is the component cross-section, N is the number of observed events, and ϕ is the particle fluence, which is mathematically equivalent to $\int \Phi dt$, the time-integral of flux. Flux has units of inverse area and inverse time, so fluence has units of inverse area, giving rise to the cross-section's units of area. Concisely, σ quantifies the probability of a SEE occurring for an interaction with a particle of a given LET and must be measured experimentally.

During experimental testing a component is exposed to particles at a number of discrete LET levels to obtain specific cross-section/LET data points. To obtain a curve, a four-parameter Weibull function is fit to the cross section data.[16] This function takes the form

$$\sigma(L) = \sigma_{\lim}\left(1 - \exp\left(\left[-\frac{(L - L_{th})}{W}\right]^S\right)\right) \tag{2}$$

where W, S, L_{th}, and σ_{lim} are the fit parameters and cross-section is a function of LET level, L. W and S are the Weibull width and shape parameters, L_{th} is the LET threshold, and σ_{lim} is the limit cross-section of the device. The LET threshold is defined as the minimum LET at which an SEE is observed; it is generally assumed that particles below this LET level are incapable of inducing an SEE in that component, and so $\sigma(L) = 0$ for $L < L_{th}$.[9, 10] The limit cross-section is the highest probability of an SEE occurring and manifests as a horizontal asymptote in the test data. This information is given as background to provide intuition for the shape of the resultant curve fit. In general, as long as the reader can obtain a number of test data points (cross-section vs. LET), existing software tools such as OMERE can perform the Weibull fit. WebPlotDigitizer[17] is a free, web-based tool that may aid in extracting data points from a graphical plot.

The CREME96 model is used by most computational tools today (e.g. OMERE, SPENVIS) and calculates SEE rates according to the IRPP (Integrated Rectangular Parallelepiped) model. In this model the differential particle flux-LET spectrum, cross-section Weibull distribution, and chord length distribution of the sensitive volume (assuming a rectangular parallelepiped form factor), are integrated over the LET spectra in the following manner:[18]

$$N = \frac{A_S}{4} \times \left(\int_{L_{th}}^{L_{max}} \frac{d}{dL_W}\sigma(L_W) \int_{L_{th}}^{L_{max}} \Phi_d(L) D\big(\frac{cL_W}{L}\big) dL dL_W\right) \tag{3}$$

where L_{th} and L_{max} are the LET threshold and maximum expected LET, respectively; A_S is the surface area of the sensitive volume; $d/dL_W\sigma(L_W)$ is the differential Weibull distribution; $\Phi_d(L)$ is the differential flux-LET spectrum; and $D(cL_W/L)$ is the integral chord length distribution of the sensitive volume with depth c. Again, equation 3 is provided only as a reference to the reader; software tools that employ CREME96 can perform this calculation automatically given flux-LET spectra data, a cross-section Weibull distribution, and minor information about the geometry of the component.

6.2 Identifying compatible test data

Component cross-section data can only be collected via experimental measurement; costs to rent a particle beam for component irradiation can quickly exceed the budget of a small satellite mission, so it is most ideal to conduct an SEE rate calculation using prior test data. Unless a component of interest has extensive flight heritage, however, it is unlikely that prior test data relevant to both the part and the radiation environment can be found. As a result, it may become necessary to perform rate calculations on test data from similar components. *Because a component's susceptibility to SEEs arises at the silicon-topology level, it is never appropriate to assume that a similar component's test data is representative of the component of interest.* That said, reusing data is often the only option available to small satellite programs. To maximize the chance of a representative rate estimate, a certain set of conditions must be met before moving forward with test data from a similar component. The similar component should:

1. Come from the same manufacturer as the component of interest
2. Share the same technology process (e.g. MOSFET technology/process node)
3. Have a similar internal architecture (e.g. two microcontrollers containing a similar volume of SRAM)

4. Have been tested using the same types of particles likely to be encountered (e.g. heavy ion testing as an indicator of cosmic ray SEEs)
5. Have been tested under the same operating conditions as the component of interest (e.g. at the same supply voltage)

These criteria maximize the chances that a component's manufacturing process gives rise to a similar silicon topology as the component of interest, as well as the chances that a component shares a similar arrangement and distribution of transistor structures within the component of interest (especially if the component is a very-large-scale-integrated (VSLI) or so called system-on-a-chip (SoC) device). Prior test data can be confidently used for a component manufactured with the same semiconductor mask set and at the same process node as the component of interest, but oftentimes this information can only be provided by a manufacturer, if it can be obtained at all. In the absence of this level of specificity, it may reasonably follow that components from the same manufacturer and process node are most likely to have similar system architecture and silicon topology. However, even if this is the case, the application conditions of the test may not be representative of the mission use case (e.g. MOSFET tested passing up to 10V, but the mission requires 30V operation), further impeding the use of historical test data. It is not appropriate to compare prior test data to a similar component from a different manufacturer, however, as variance in design and fabrication processes does not guarantee similar component structure. Similar test data may be appropriately used if it can be determined that the tested component and the component of interest share the same technology process, but this often cannot be determined without contacting manufacturers directly. If this is impossible to do, extensive research may lead an engineer to reasonably infer that a similar component designed by the same manufacturer in the same year employs the same technology process. If not enough similarities between the tested component and the component of interest can be found (e.g. they have different manufacturers or technology processes), it becomes dangerous to assume that the found data is representative of the component of interest.

An additional consideration is that testing is often performed for a particular SEE (such as only SEL or only SEU), so it may become necessary to identify test data for multiple types of SEEs to gain an accurate picture of the net SEE rate for a particular component. An aggregate SEE rate may be estimated by summing together the various rates of SEEs for which datasets are available (e.g. a net SEE rate may be calculated for a microcontroller by summing an SEU rate and an SEL rate each calculated from a separate dataset). This process of seeking separate datasets may also provide insight into the likely failure mode of a particular component. For instance, the SWARM-EX microcontroller's SEE rate is dominated by SEL, rather than SEU. It is important to note, however, that any aggregate SEE rate calculated in this manner establishes only a minimum threshold for the component's SEE rate, and thus should not be taken as a conservative estimate.

A final metric for consideration is the number of events likely to be encountered by a particular component during the mission lifetime. This may be calculated by multiplying a component's SEE rate by the mission duration. The number of events, SEE rate, and severity of consequence to the system together may be used by spacecraft designers to decide whether a particular component carries with it an “acceptable” level of risk, or whether additional radiation mitigation strategies are warranted.

6.3 Component-class sweeping

In the absence of any similarity data for a critical component, one may sweep technologies from the same class of components to identify bounds on the types and ranges of susceptibilities for the class. While this does not provide a firm estimate of SEE rates, it may still provide guidance for system design and effect mitigation. A component-class sweep was used to gain additional insight into the SWARM-EX microcontroller. Test data from a similar component made by the same manufacturer was identified, yielding a rate of 0.3 events/year. This rate was orders of magnitude larger than other components of interest, so the decision was made to search for bounds on the microcontroller susceptibility range. Data was found for a variety of microcontrollers without respect for the manufacturer or technology process, resulting in bounds of 0.0283 to 5179.35 events/year. This wide range of susceptibilities revealed the microcontroller as being a potentially more problematic component than the similarity data alone would suggest. The found datasets also revealed MCUs as a class of components that are particularly susceptible to SEL, and subsequently drove mitigation recommendations to the SWARM-EX systems engineering team.

Table 2: Repositories where test data may be found.

Resource	**Interface Method**
Proceedings of the IEEE Radiation Effects Data Workshop	Journal-specific Google Scholar search (recommended), or IEEE Xplore: `https://ieeexplore.ieee.org/xpl/conhome/1000609/all-proceedings`
NASA GSFC Radiation Database	Searchable online database: `https://radhome.gsfc.nasa.gov/radhome/raddatabase/raddatabase.html`
ESA Radiation Test Database	Searchable online database: `https://esarad.esa.int`
NASA JPL Radiation Effects Database (RAD)	Searchable online database: `https://radcentral.jpl.nasa.gov`

6.4 Searching for test data

Test data may be found in a variety of locations, some of which are summarized in table 2. Test data published in alternate locations may be located via Google Scholar searches that include shortened part numbers as a search term.

The authors note that JPL RAD may not be accessible. Direct correspondence with the JPL RAD team on July 15, 2021 revealed that the database is offline indefinitely pending an internal review, but confirmed that a future relaunch is planned. The database remains offline as of June 6, 2022.

7 MITIGATION STRATEGIES

Mitigation strategies should be employed anywhere where a fault in a component could give rise to SEFIs with sufficient frequency or severity to disrupt a spacecraft's ability to fulfill its mission objectives. A wide variety of mitigation strategies exist, but a thorough description is beyond the scope of this work. Table 3 lists a variety of common mitigation strategies for various classes of SEEs, along with references to outside sources which provide greater detail into examples, use cases, and implementations.

8 CONCLUSION

Evaluating total dose effects is generally a straightforward process enabled by free software tools, but a rigorous SEE study necessitates component testing which typically exceeds the resources available to a small satellite program. Despite this limitation, informed design decisions for smallsats may still be made by performing rate calculations from carefully selected prior test data for similar components. Strategic down-selection of the list of components included in an SEE study is recommended to reduce the time required to search for and verify relevant prior test data. In the absence of these data, general bounds for component susceptibility may be found by sweeping test data for a large number of components of the same class. It is important to note that similarity data cannot ever be assumed to accurately represent a component of interest, but nevertheless may provide insight into the general level of susceptibility and types of effects that may be observed in it. Once a sense of the types and frequency of SEEs is known for each component of interest, mitigation strategies may be employed to prevent faults from propagating in ways that will interfere with fulfillment of mission objectives or cause failure to meet mission reliability requirements, enhancing the reliability, lifetime, and performance of small satellite missions.

Table 3: Table of common SEEs, mitigation strategies, and external references which may provide helpful details on implementation schemes.

Single Event Effect	Common Mitigation Strategies	References
SET	Voltage/current wave filters; improving configuration current and application voltage	[19–21]
SEU	Code checking/error detection and correction (EDAC) algorithms, such as hamming codes; bit or word level instance layer isolation; timing refresh; triple mode redundancy (TMR)	[19,20,22–25]
SEGR/SEB	Component derating (especially power components); single-point monitoring; hardware redundancy; watchdog monitoring	[19,25]
SEFI	Reset and refresh; system watchdogs; power cycling; TMR and voting within embedded systems	[19,23,24]
SEL	Current monitoring; current limiting, such as series resistance; power-cycling schedule/intermittent power supply; system watchdogs	[19,25–27]

ACKNOWLEDGMENTS

The authors thank Gregory Allen, Dr. Raichelle Aniceto, Dr. Randall Milanowski, and Dr. Martin Ratliff for providing guidance throughout the course of this study. This work was supported by the National Science Foundation (award numbers 1936538 and 1936665) and the Massachusetts Space Grant.

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