V. Radiation Hardness Assurance: Evolving for *NewSpace*

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***Abstract* -** During the past decade, government agencies, private companies and academic institutions, have launched hundreds of small satellites into space, with dramatically expanded dependence on advanced commercial-off-the-shelf (COTS) technologies and systems required for mission success. While the radiation effects vulnerabilities of components within small satellites are the same as those of their larger, traditional relatives, revised approaches are needed for risk management because of differences in technical requirements and programmatic resources. While moving to COTS components and systems may reduce direct costs and procurement lead times, it undermines many cost-reduction strategies used for conventional radiation hardness assurance (RHA). Limited resources are accompanied by a lack of radiation testing and analysis, which can pose significant risks. Small satellites have benefited from short mission durations in low Earth orbits with respect to their radiation response, but as mission objectives grow and become reliant on advanced technologies operating for longer and in harsher environments, requirements need to reflect the changing scope without hindering developers that provide new capabilities. In this course we suggest RHA strategies that engineers and scientists can apply to a wide range of aerospace systems, including constellations, with a focus on how to manage aggressive system scaling for smaller platforms.

1. Introduction

This course aims to provide guidance to designers and engineers with respect to radiation effects in active semiconductor devices with considerations for *NewSpace,* leveraging on radiation hardness assurance (RHA) practices that benefit mission success, incurring relatively low costs. The path forward for *NewSpace* builds on the successes of SmallSat missions at large: faster schedule, reduced mass/cost, and new mission architectures to achieve science goals. With that comes the risk driver of using new technologies in order to fit this platform. SmallSats usually achieve their goals by utilizing commercial-off-the-shelf (COTS) components; which are often more susceptible to radiation effects than high reliability components which have higher piece-part costs. The emerging technologies that had been identified in the past as challenges for RHA (testability, traceability) are now the integral components to mission builds, and will remain prevalent as missions extend their scope. We consider RHA strategies that engineers and scientists can apply to a wide range of aerospace systems, with a focus on how to manage aggressive system scaling for smaller platforms and new mission architectures. In summary, this course seeks to describe how radiation threats change in different radiation environments, how mission requirements become radiation requirements, and it considers how these changes affect tradeoffs faced by system and subsystem designers.

2. *NewSpace* and SmallSat considerations

NewSpace refers to the anticipation of new solutions, partnerships, and strategies to achieve mission success, with a reduction in cost of implementation. Largely driven by commercial entities at smaller scale and budget than predecessors orchestrated by governments and large, corporate collaborations, *NewSpace* will continue to open doors by reducing the capital necessary to build and launch a spacecraft [1]. The inception of “commercial” space, and the inclusion of secondary payloads on commercial launch platforms, has had a dramatic impact on the way we think of cost per launch, where the idea of a primary payload of only one satellite is archaic for many. Thus far, there are already noticeable outcomes in positing that missions can be achieved in this way:

Size, Weight, and Power (SWaP) are all changing based on commercially available components which have not had the screening and testing mil-spec devices have been through before being offered on the market. Space-grade packaging, space-grade components, radiation ratings or parts that are radiation hardened by design at the semiconductor level suggests that materials and reliability have been screened for before the components are available on the market. This plays a role into the cost of components, and the lead-times necessary to procure them. Manufacturers are attempting to meet their customer needs by blending COTS offerings with older mil-spec parts as they have done in the past, but are able to provide more capable components when things like plastic packaging are not forbidden by reliability requirements from the mission [2]. As a result component grades are merging – into modified Hi-Rel offerings.

The twin benefits of improved capabilities and lower cost are driving the practice of mission RHA from one of risk avoidance to one of risk acceptance. Adoption of new technologies means that the risks identified by teams of radiation experts are here to stay. These new technologies are often the risk driver in the builds that we aim to reliably deliver, not only for radiation, but the system as a whole. System-level radiation requirements call for test and assurance methodologies on 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 competing failure modes. For *NewSpace,* reliance on a broad range of COTS devices, low mission cost, and schedule constraints mean testing every part -- or even solely critical parts -- is not an option.

A. The SmallSat paradigm

SmallSats have changed the way we think about achieving a science goal for space bound systems. Lower costs driven by mass reduction, COTS parts, and reduced non-recurring engineering (NRE) thanks to economies of scale allow for the possibilities of large satellite constellations. Dramatically reducing the size of a spacecraft for an intended mission does not guarantee a more affordable rate and ride to orbit, but having an entire industry move towards that goal does. The obvious benefit of not needing to launch as much mass, or sharing the launch costs, is one realm of spaceflight optimization, but reduction in size also plays a role for manufacturers of assemblies all the way down to components intended for these missions. To meet the new volume constraints, the already optimized Mil/Aero has to take advantage of commercial design archetypes [1]. There are increasingly more sub-assembly companies, and a lot of new customers as the financial hurdles are being lowered.

Another cost savings is standardization at the board or module level; a large part of the SmallSat boom can be attributed to the CubeSat platform, and companies that are building spacecraft in an assembly line fashion for intended constellations, both of which have an impact on RHA.

a. CubeSats/SmallSats

The CubeSat standardized form-factors (1U, 3U, 6U, etc.) have allowed many new entities to put a spacecraft in orbit with relative ease [3]. Successful mission operations don’t come as easily. Fig. 1 shows two outputs from the CubeSat database housed at Saint Louis University, where mission status for individual CubeSats are shown from 2000-to-present, as well as categorical entities who are building more than one CubeSat and their frequency in doing so. What we learn from looking at these metrics is that it is difficult to pull off a successful mission, and that very few iterate on their designs to improve or learn from their mistakes, i.e. minimal mission assurance follow on efforts. Noticeable trends of builders who repeat builds doing better work, achieving mission success criteria, can be due to improved workmanship or mission assurance activities [4][5][6]. The roughly ~68 universities/schools now flying CubeSats (or variations built under the same principles) are also forming the new crop of engineers to come.

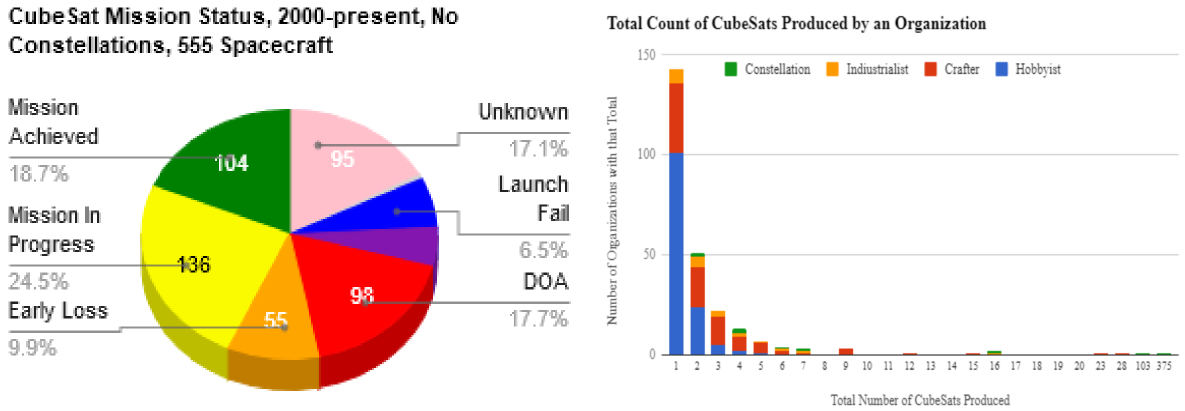


Fig. 1. CubeSat metrics on mission success on the left, and count of CubeSats with follow on builds by organization. Both plots were generated from data collected by SLU [7].

SmallSats however are not constrained to the CubeSat standardization; they come in many sizes. As can be seen in Fig. 2, the relatively new contribution of SmallSats to overall launch activity is not necessarily replacing the need for larger instruments and spacecraft, but augmenting it. The fast pace of SmallSat launches has rapidly changed the demographics of what is on orbit in the last 5-10 years.

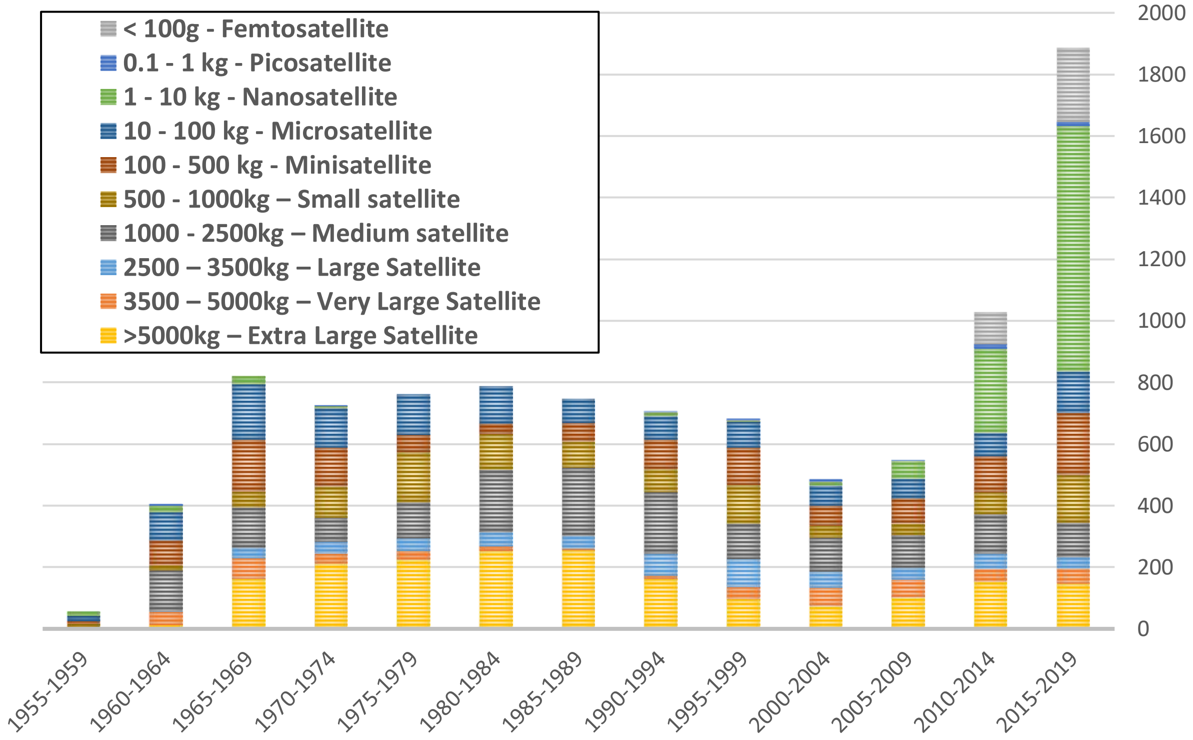


Fig. 2. The number of spacecraft launched categorized by a given mass category in five year increments [8].

Impact to RHA: Not all SmallSats are university-led efforts, and some need to achieve a higher reliability goal, but may be too cost constrained to follow current RHA methodologies. In most instances first time builders of CubeSats will be destined for a benign radiation environment; they may have a compressed schedule or lack expertise and therefore do not perform any radiation analysis or testing. If the mission is largely successful, follow on efforts may still lack the expertise or value added capability to identify failure modes that will show up in a harsher environment. Others could have radiation-related failures but lack traceability to the root cause. Though not currently attributable to radiation, many early losses or unknown states of CubeSats may serve as an example.

b. Constellations

The widespread CubeSat adoption also gave legitimacy to the option of making many satellites intended for a single launch if warranted. A constellation of satellites can consist of many forms and vary in number widely depending on the application [9][10][11][12][13][14]. These constellations span mission class from national assets (GOES) to technology demonstrations. Large numbers of spacecraft launched on a regular replenishment schedule can reduce mission life and reliability (of an individual spacecraft) required to achieve success. Some instances of multi-craft missions will have variations of the satellite designs that have a central unit with more downlink capability, while others are made of ChipSats where the form factor is on the order of an IC [14]. The architecture is regarded as a system, and plans going forward for missions with smaller and smaller form factor are increasing. Fig. 3 is a survey of NanoSats intended for constellations on a public-facing nanosats repository. The number of companies/corporations planning these missions is on the order of ~50 and growing [15].

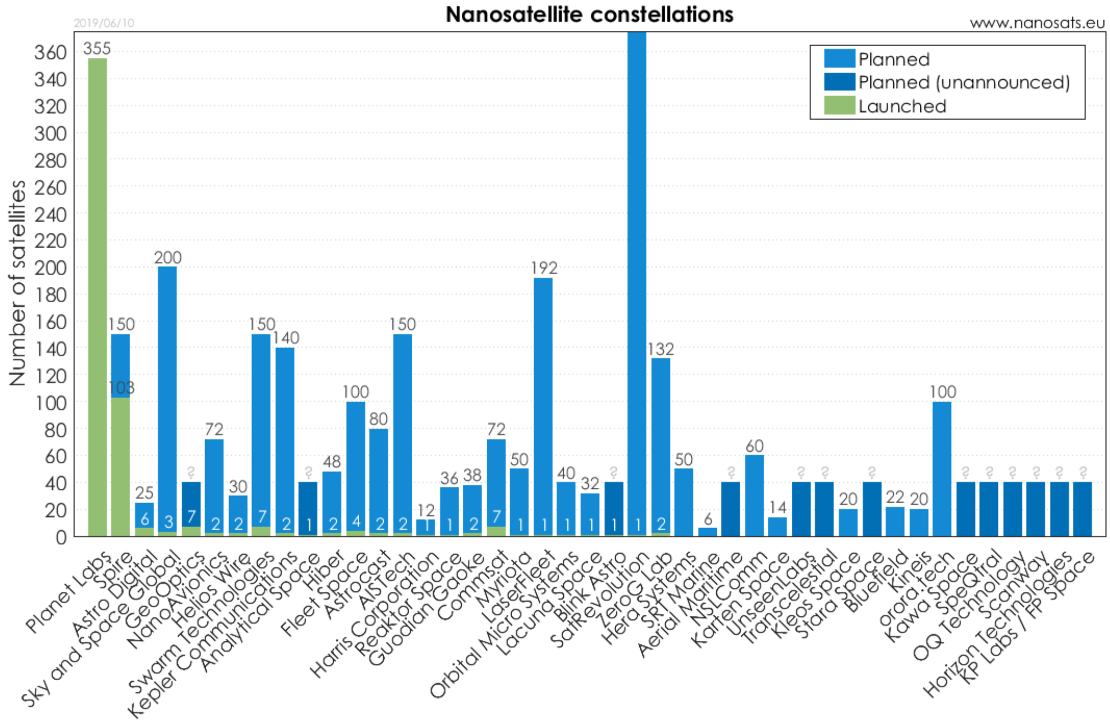


Fig. 3. Many spaceflight mission objectives are opening up with the use of numerous satellites. In some cases total of number of spacecraft in the constellation can be seen as in the hundreds to thousands depending on mission objectives [15].

It is important to note that in the case of missions with numerous satellites there may be a certain number of allowable losses of entire spacecraft without impacting mission success criteria, no doubt a new practice for legacy radiation engineers. The disposability or replenishment to orbit means that low-likelihood, mission-threatening radiation effects we try to identify and prevent altogether may now be accounted-for or ignored altogether during the system design process. While constellations take on many forms, they may have identical spacecraft produced in high volume. This provides opportunity for economies of scale, and allows for systematic change by utilizing industrial processes for satellite manufacturing to increase reliability. Constellation missions are on the rise with the prospect of orbital internet and direct communications links, and Fig. 4 shows projections of the size of those constellations growing in the future, primarily using SmallSats to achieve that. It also shows that mission objectives are embracing longer mission lives than that of typical missions in that same form-factor. These launch data are notional and could change at any time.

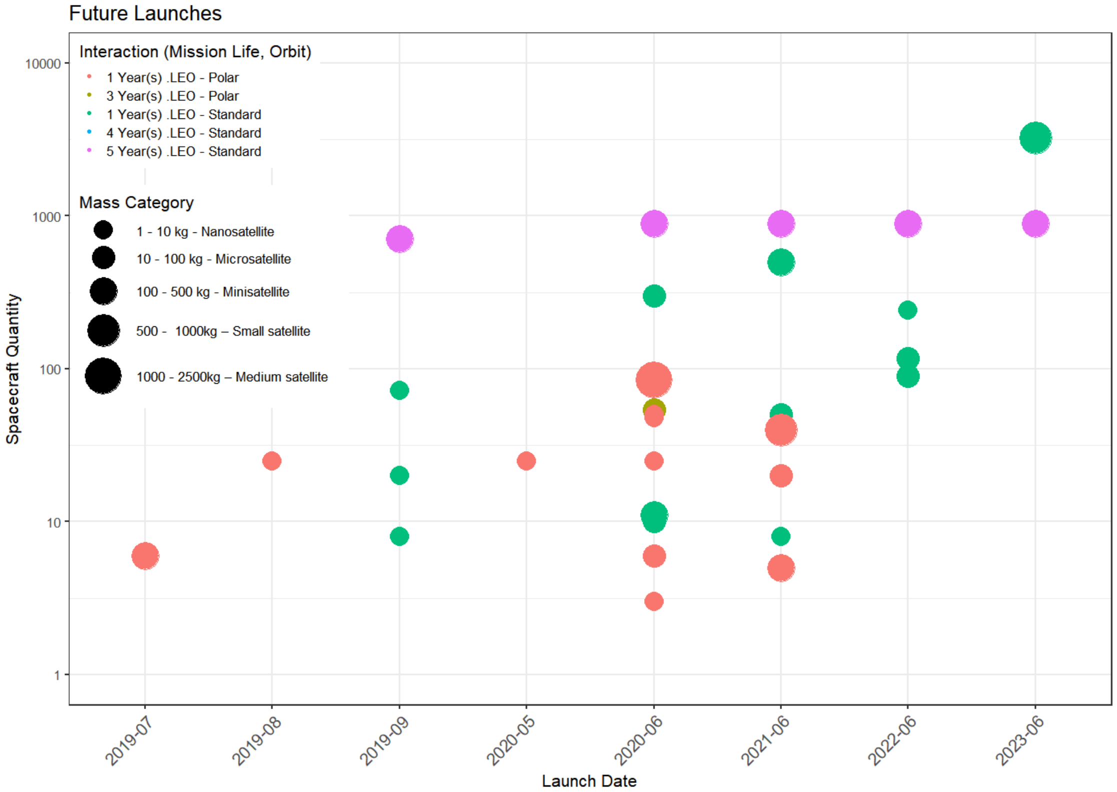


Fig. 4. Launches planned for constellation missions in the near future. Grouped by mission life expectancy, intended orbit, as well as the mass, the plot shows an upward trend of number of satellites in a constellation within the next few years [8].

Impact to RHA: In some instances designers of large systems may want to ignore radiation concerns due to the fact that they no longer need every craft to survive. Common (shared) failure modes, however have the potential to manifest and cause systemic failures in spacecraft thought to have allowable losses. The inherent redundancy within a constellation may reduce some radiation threats, but needs to be addressed early in the project lifecycle to identify possible shared failures within the redundant architecture.

B. The need for RHA on future missions

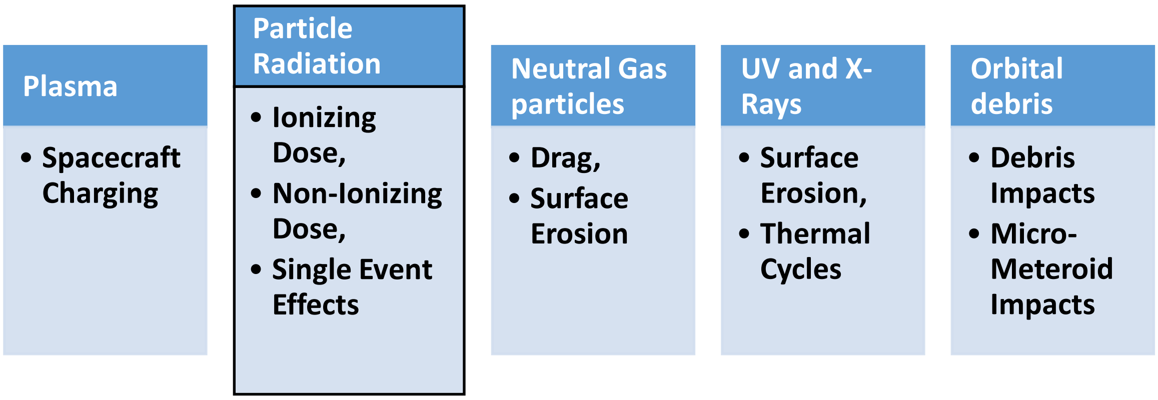
Who needs this type of guidance? The practices of RHA are useful to missions from universities making their first CubeSat, to government agencies looking to benefit from cost savings or proving new capabilities at a specified reliability level. Device manufacturers could use informative decisions basing what they offer on standards that have not yet been made. Programs or projects that are secondary payloads need to know how to "worst case" their design for multiple launch opportunities, and the resultant radiation environment. Or designers may be looking to implement fault-tolerant designs. RHA flow doesn't change when you want to accept a risk. The space radiation environment is and will remain a dynamic system posing a hazard to technologies old and new.

There are no indications the rise of commercial parts on spaceflight missions will slow, as rapid development of commercial semiconductors continues here on Earth. The capabilities of manufacturers' chipsets are accountable to their mass market customers, of which aerospace designs represent a shrinking piece. What that means, ultimately, is that we will be using new technologies with failure modes that are not fully understood. Those cases going forward will present us with unbound radiation risks that we are not able to quantify in terms of likelihood.

When missions take place in benign environments, undiscovered radiation threats to individual parts may pose acceptable risks, particularly for failure-tolerant missions such as constellations or cheap spacecraft on a short-duration replaceable path. However, now that follow on missions are increasingly deployed in harsher environments and with more critical objectives, radiation threats need to be taken more seriously, and fault-tolerant 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) [16].This type holistic view, as taken into account with Single-Event Effects Criticality Analyses (SEECA) enable risk tolerance [17]. Increased risk tolerance calls for a RHA approach that considers cost and schedule while providing assurance against the hazards, which facilitates design innovation.

3. The natural space radiation environment hazard

The natural space radiation environment is harsh for semiconductor electronics that make up instruments and systems. Radiation effects impact Electrical, Electronic, and Electromechanical (EEE) device performance in multiple ways, but primarily through semiconductor material degradation and charge deposition within the device. These effects 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. *NewSpace* missions 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, while maintaining reliability, they will need to adopt practices of RHA. Throughout this course typical destinations are utilized to convey the message of what the hazard is that missions (typically in Earth orbit) will encounter. The natural space environment poses many diverse threats to spacecraft. They include many outcomes, but not all are specific to active semiconductors:



While all of these threats need to be taken into account for the purposes of reliability of a space-bound mission, it is the particle radiation that we refer to when we talk about the radiation effects hazard on EEE parts and components. Protons, electrons, and heavy ions all contribute to the radiation seen by a spacecraft, and their presence for a mission is determined and defined starting with the sources of these particles. The interaction of these particles with spacecraft materials will create the resultant hazard. In order to get there, the radiation environment must be understood and accurately modeled to build and use new space technologies without excessive risk, degraded system performance, or loss of mission life.

A. Particle radiation contributors

The energetic particles that have adverse effects on space flight electronics can be categorized by their sources and locale. The three dominant contributors in the Earth orbital environment are Galactic Cosmic Rays (GCR), Solar Particles (dynamically tied to solar activity), and planetary radiation belts (e.g. the Van Allen belts).

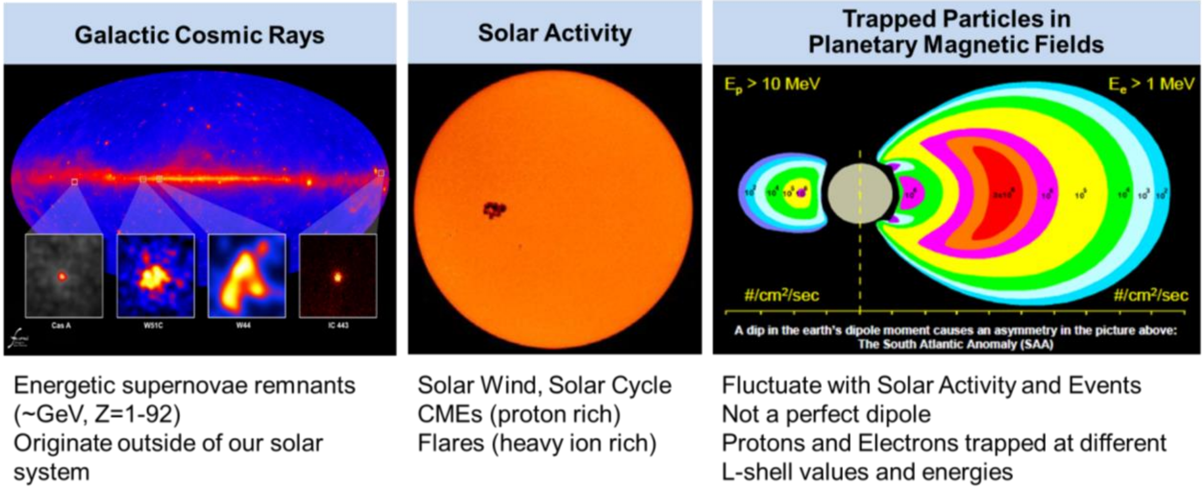


Fig 5. Particle radiation contributors pictured from NASA sources, left to right come from galactic cosmic rays, solar activity, and the charged particles that get trapped in planetary magnetic fields [18][19][20].

The energy ranges of these particles span from GeV to keV per nucleon, and have effects that are dependent on that wide range. For a background on the natural space radiation environment, the story of how these particles end up where they do, and details about the physical phenomena please see past Radiation and Its Effects on Components and Systems (RADECS)/Nuclear and Space Radiation Effects Conference (NSREC) short courses available from IEEE [21][22][23].

B. The environmental hazard to micro-electronics

The impact of these charged particles on active micro-electronics includes both wearout-like mechanisms and instantaneous random failures. While not covered extensively in this manuscript, IEEE is a repository for many studies on detailed structures to understand the physics of failure on semiconductor devices and ICs. Particles interact with semiconductors in a number of ways, and again this threat is twofold: cumulative vs. instantaneous effects. Fig 6 shows how three physical phenomena of particle and device interaction manifest as radiation effects in a simplified device diagram.

1. Recombination – electron hole pairs (ehp)
2. Nuclear Displacement – lattice disruption, vacancies
3. Oxide Charge trapping – imperfections in interfaces/oxides dangling bonds

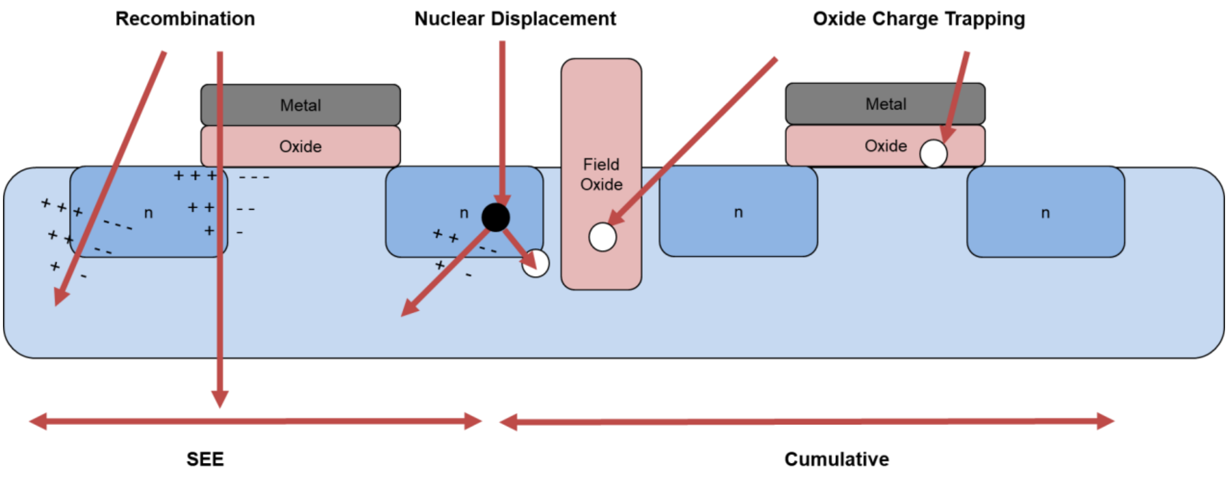


Fig 6. Compound image of particle device interactions on the left recombination of electron-hole pairs that are created by the passage of charged particles and their track, on the right the trapping of charge within the oxides within the device structure [24].

The outcomes of those interactions, the radiation effects, and how they manifest is what we engineer our designs to [25]. We either avoid or manage through screening, testing, observation, mitigation, etc. The next two sub-sections describe environment model outputs that are important to the cumulative/instantaneous hazard, and quick examples of these effects manifest on selected devices.

a. Degradation effects, wear-out

Radiation effects that manifest in degradation of part performance or parameters are cumulative and therefore accrue over the mission life. These effects depend on which contributors are present for a given environment. For total ionizing dose (TID) [26], the contributors include that of protons and electrons, the latter also producing x-rays called Bremsstrahlung ("braking radiation") as they decelerate in spacecraft materials. Displacement damage is a result of total non-ionizing dose (TNID) [27] occurring from neutrons and protons (as primary knock on atoms). The typical terminology of cumulative effects are TID, TNID, and these have units of krad (in material) and equivalent fluence for a particular particle with a given energy, which are not the same as exposure or dose equivalent that are sometimes used for medical or biological dose.

Environment Model Output Examples:

The dose for a given environment can be modeled by tools readily available such as **Spenvis, OMERE,** etc. [28][29][30].Typical practices are to calculate the dose through shielding equivalents of solid sphere, and then plot the dose or fluence vs. the depth of shielding material. Fig 7 shows the output of this environment modeling that is very useful to approximate the dose for different parts of a spacecraft with varied shielding. More detailed analysis can be conducted using tools for ray-tracing, if need be this is done by utilizing mechanical design computer aided drafting (CAD) inputs.

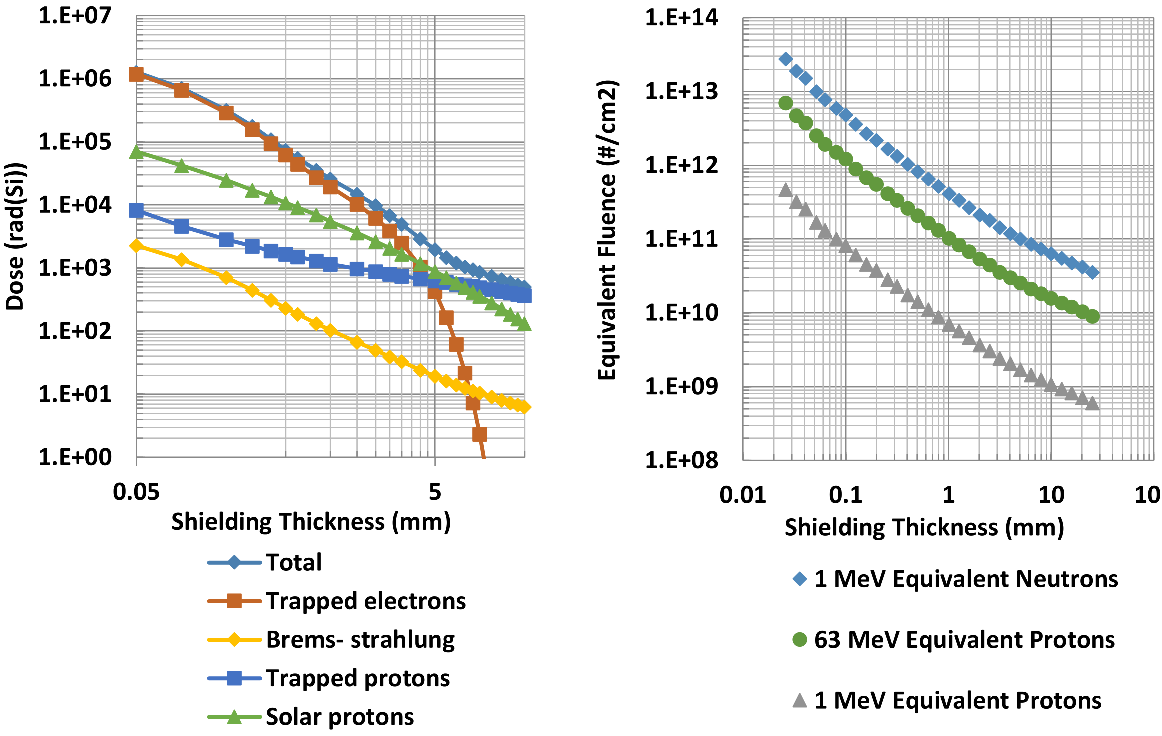


Fig 7. Total ionizing dose depth plot (left), and displacement damage equivalent fluence (right) for a mission are calculated using environment models to help predict impact and effects that are cumulative over the entire mission life.

These curves are often used to later establish dose requirements imposed on EEE part selections. Every mission has characteristics that make it unique, and the contributors can significantly impact the dose a part will see behind shielding materials. That said, if one were to look at total dose expected behind an arbitrary shielding thickness, one can compare for different altitudes and inclinations and see some differences of time spent in one location vs. the other.

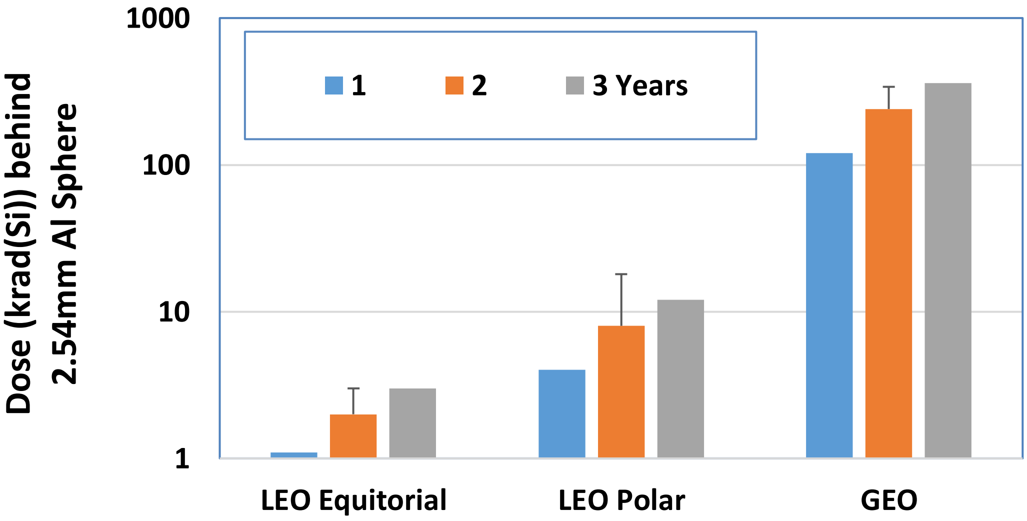


Fig 8. Total Ionizing Dose behind 2.54mm Aluminum Spheres for 3 mission orbits. The mission duration, launch, and altitudes were varied to get notional error bars.

Fig 8 is not an exhaustive look at all possible doses, but a few runs in each orbit with variations on altitude for 1, 2, and 3 years behind 2.54mm Al. This is useful in bounding what type of hazard is to be dealt with at first glance. It also provides a spot check of the order of magnitude that you would expect your dose to be through a typical amount of shielding. It may help you choose a parts rating that you'd like to default, or acknowledge that you are going to have to add shielding for softer parts.

Component Response Examples:

An example of TID effects is gain degradation on bipolar junction transistors (BJTs). Trapped charge within the device diminishes the efficiency of the part resulting in reduced gain, and potentially results in failed operation depending on the application of the device.

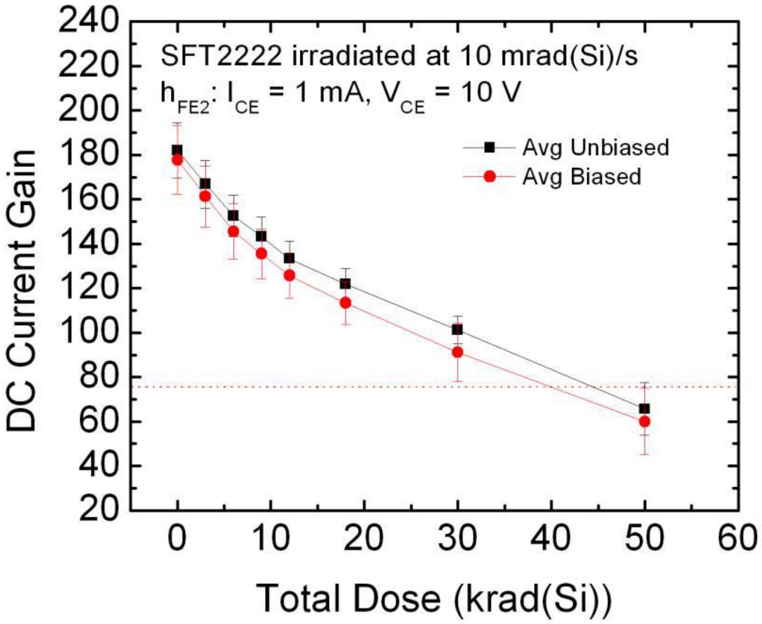


Fig 9. Total Dose response of the SFT2222 BJT. Parameter measurements for hfe2 on the part datasheet show device operation out of tolerance as dose increases beyond 30 krad(Si) [31].

Another example of degradation comes from Displacement Damage Dose (DDD) accumulated over a mission, after which the expected device operation no longer can be considered functional. Here an opto-isolator is no longer able to switch for short pulse lengths in Fig. 10 below. Notably, the devices that are biased during irradiation performed worse than parts that were unbiased on their output voltage.

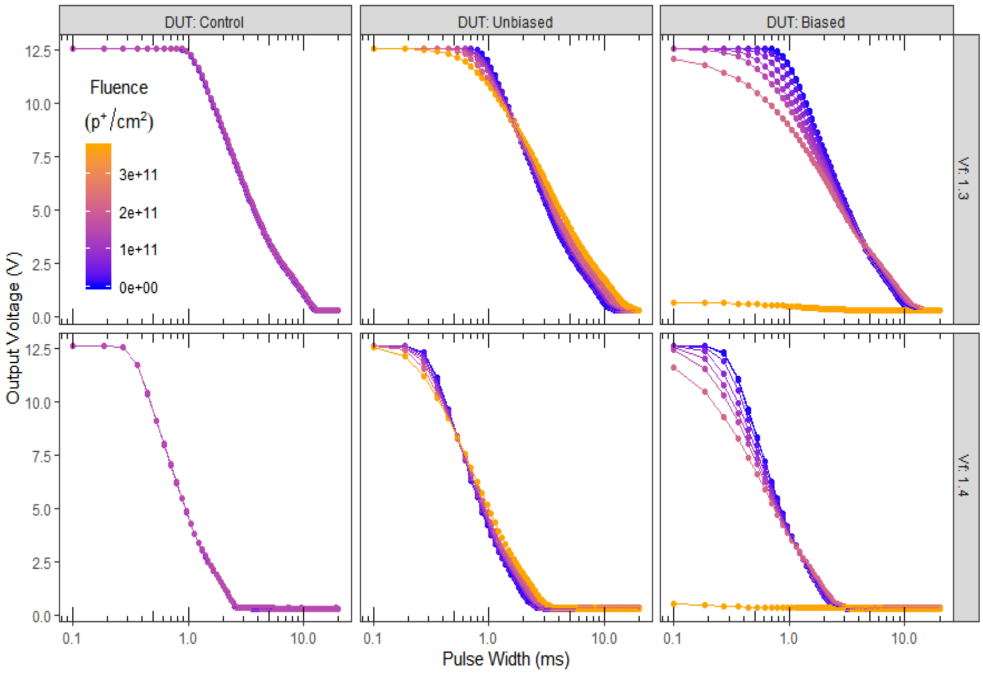


Fig. 10. HSSR-7111 opto-isolator showing degradation from 63MeV proton exposure at two different forward voltages. A dependence on bias during irradiation is shown with pulsed measurements, where the output voltage is no longer able to be switched [32].

These types of responses can be seen as representative, but not limiting responses of semiconductors to dose. In dealing with parameters that are design drivers or have tight tolerance, it is useful to investigate whether degradation of a given parameter be a problem at end-of-life in the application.

b. Single event effects, instantaneous

Radiation effects that manifest from one particle causing the effect are considered single-event effects. The particle contributors to SEE are protons, heavy ions, and seldom lighter charged particles like electrons or muons. Higher than anticipated frequency of upsets can happen on devices susceptible to upset from protons [33]. As radiation engineers, we use models to predict the environment in which our mission intends to go. These environment models typically output the flux of the particles (and their species) such that we can use device data (sensitive cross-sections) to calculate an SEE rate. At a top level, SEE can be divided into two categories, destructive and non-destructive [34][35].

Environment Model Output Examples:

Fig 11 shows the GCR spectra for a mission, and as you can see there is a dependence on solar cycle (the helio-magnetosphere plays a role in the environment as well). Fig 12 shows some of the many solar particle event model output of flux, which can be selected to get a conservative estimate of what will be seen on orbit during a solar event. A typical bound selected is from the October 1989 solar event. The x-axis is the linear energy transfer of a particle (LET), in units of MeVcm^2/mg or pC/micron, analogous to stopping power but normalized to the target material density. We often talk about upset rates per bit or device and per time interval. Output from models like CRÈME give mission spectra to derive these rates [33].

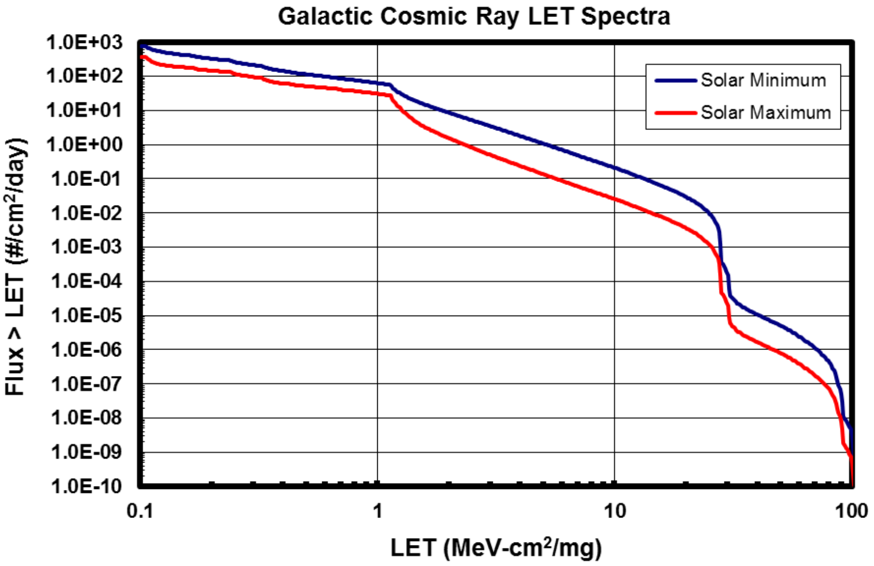


Fig 11. Integral LET spectra for galactic cosmic ray ions hydrogen through uranium assuming 100 mils of aluminum shielding.

While GCR flux are consistent in the background, the orbit and geomagnetic attenuation will have an impact on the spectra for one's intended environment. Solar energetic particles are more dynamic and can be delivered via solar activity such as flares or coronal mass ejections directly as well as the trapping of those particles. The radiation belts can see surges where the particle populations are "pumped up" after a solar storm. Models of major events can be used to bound the worst case compositions for a given orbit, and a typical choice for comparison has been the October 1989 event.

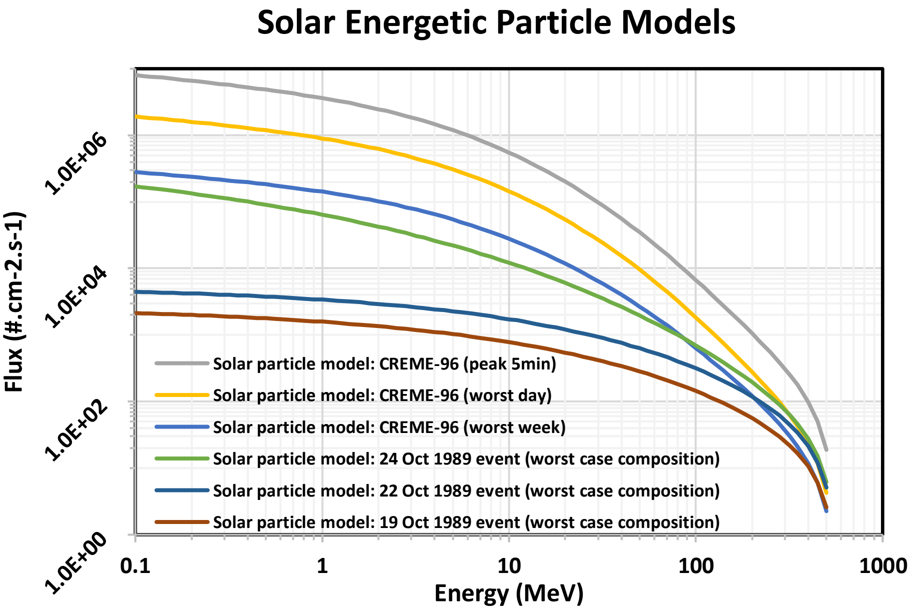


Fig 12. Solar particle event models of flux, outputs from Spenvis, CREME96 and Xapsos2000 selections [29]

Just as cumulative effects depend on where on orbit you are, so too do SEE. Altitude, launch date, orbital inclination all play a role on the SEE rate. Missions with availability constraints will need to focus requirements on what operations lead to demands on the components in terms of utilization and application.

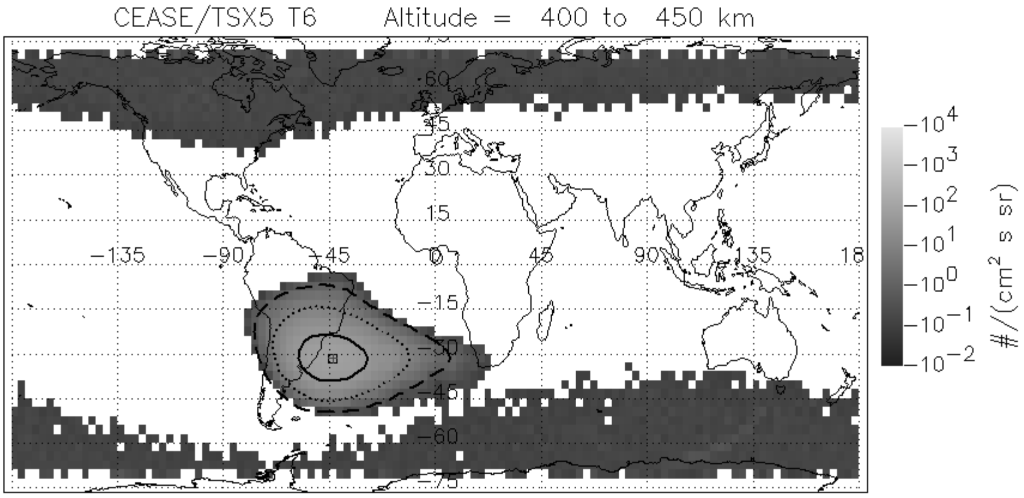


Fig. 13. Energies of particles can vary from one altitude to the next, and location plays a role in the flux dependence as well (e.g. SAA) [37]

Fig. 13 above shows some of the dependence of particle energy based on the latitude and longitude; in particular instances non-uniformity of the natural environment is pronounced. One such example is the South Atlantic Anomaly (SAA), a result of the Earth's magnetic dipole shift, where particle concentrations can be much higher than in other regions of similar altitudes. Changing the altitude of the mission would then result in a different density shape of the SAA. Missions flying through such environments often need to take this into account for single event effect rates during critical mission operations.

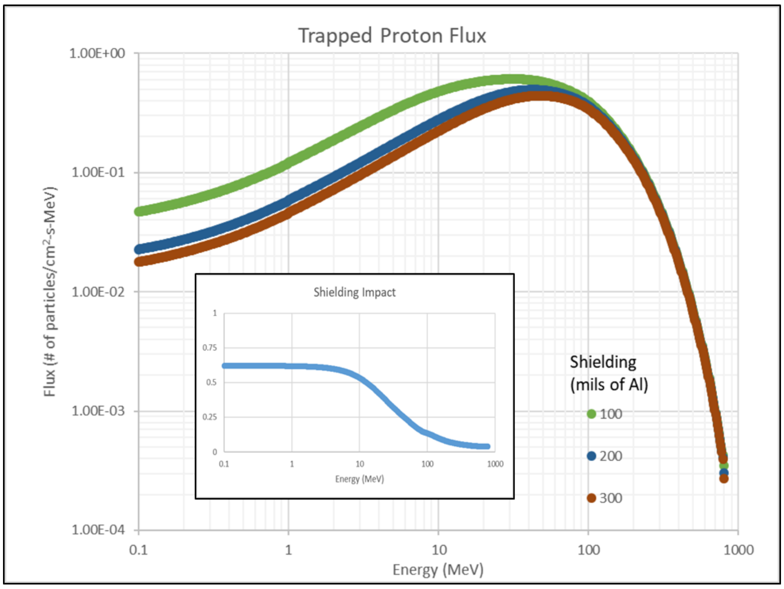


Fig. 14. Trapped proton flux with an inset graph of shielding impact.

Shielding can play a role in the single event effect rate if you are susceptible to low energy particles, but predominantly the higher energy particles are not well shielded and will still penetrate to the part's sensitive volume. Fig. 14 shows the effectiveness of shielding over three thicknesses; most of the reduction in flux only occurs at energy levels less than 10 MeV, where secondaries that have higher

LET are not produced or lack sufficient range to traverse a sensitive volume. As shown, even substantial mass addition for shielding does not attenuate or prevent SEE.

Component Response Examples:

An example of non-destructive single event effect can be transient in nature, or can be upsets that are bit-flips to an unexpected state. In some device technologies that transition from a 0 to a 1 or vice versa maybe be more susceptible in one direction:

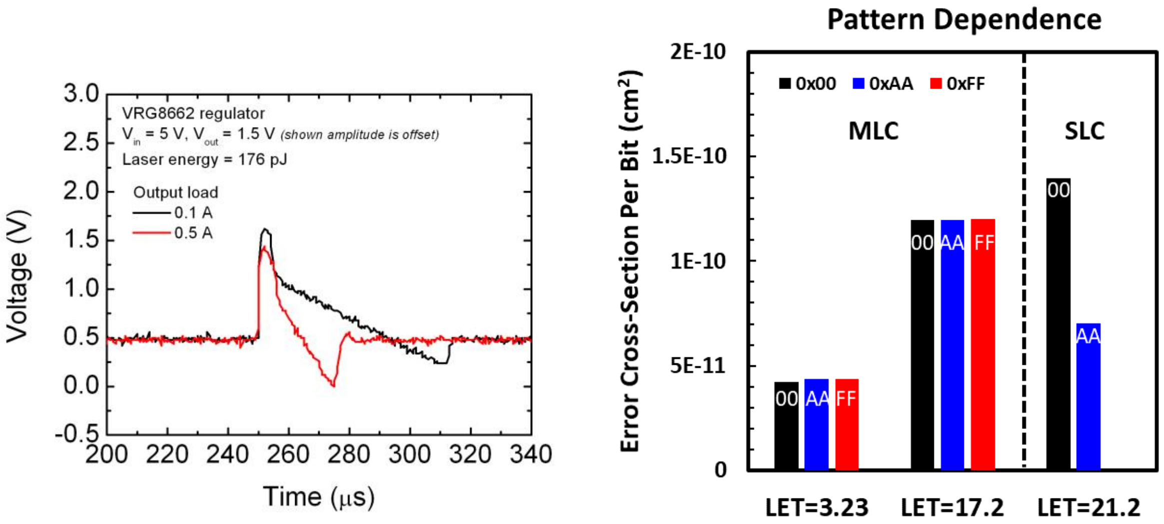


Fig. 15. Examples of non-destructive SEE, analog Single Event transients where the output voltage is unexpectedly drawn down, and digital bit upsets or SEU are present within a memory and have a measured cross section that is dependent on pattern [38][39].

As mentioned, some single event effects can be destructive in nature. Shown in Fig. 16 are two examples of destructive events that end with inoperability of the parts by either failing to open or short circuit conditions. The charge track can create such high electric field within the device such that breakdowns are surpassed, and high current events will occur, resulting in thermal failures.

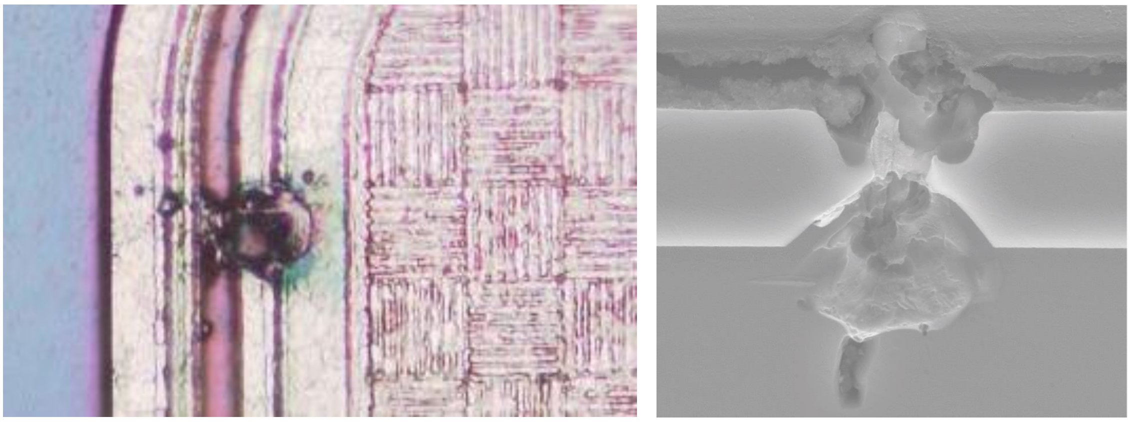


Fig. 16. Example of destructive SEE. Photo after part experienced a catastrophic failure during ground based heavy ion testing. [40][41].

In order to avoid mission loss or operational impact from effects like these, it is important to address the problem early in the mission lifecycle, and have a process to identify the risks.

4. RHA building blocks

RHA consists of all activities undertaken to ensure that the electronics and materials of a space system perform to their *required* specifications throughout exposure to the mission space environment [20][22][25][34]. The RHA process can benefit *NewSpace* 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 and reduce the risk. This process is in part necessary because radiation effects can be both cumulative and instantaneous as described earlier in Section B, on the hazard to micro-electronics. The environment stipulations and discussion of how RHA deals with emerging technologies and COTS components have been presented by leading agencies and industry partnerships [42][43][44][45][46].

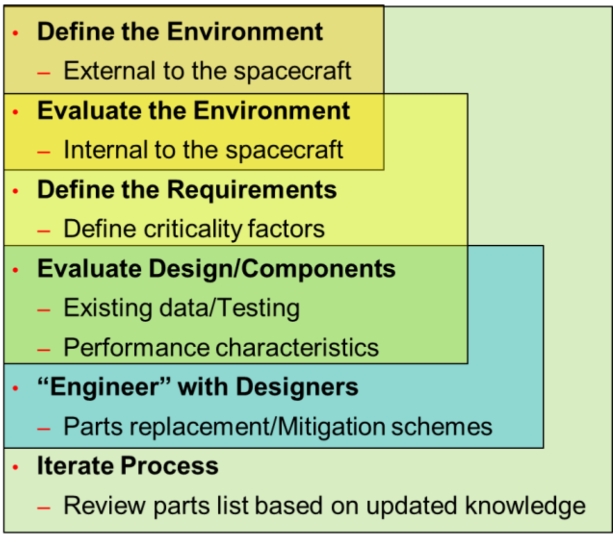


Fig. 17. RHA flow diagram is an iterative loop, if anything in the process changes, each step must be assessed for impact, or changes to mitigation schemes [47]

A top-level outline and grouping of activities associated with RHA are shown in Fig. 17. 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 working on RHA can increase the likelihood of success by identifying or removing unbound risks to the system. It can also reduce design costs by anticipating problems before they become difficult and expensive to mitigate.

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 [48]. The true cost savings to *NewSpace* missions is going to come from requirements that allow the identification and acceptance of risks without the expense of eliminating them entirely.

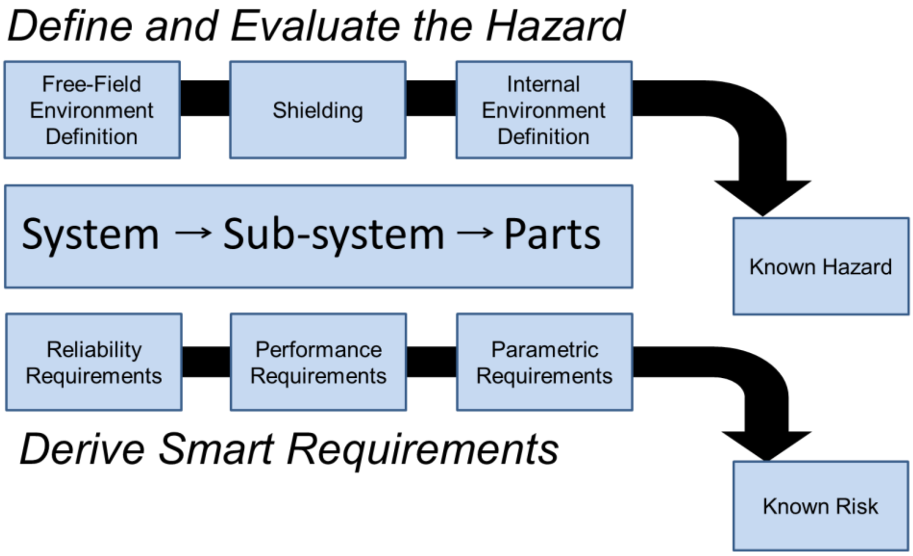


Fig. 18. Block diagram of efforts and detail needed to get to a known environmental hazard and a known risk to the system [49].

Orbits and their radiation environments are often determined by underlying 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, altitude and trajectory of the spacecraft. For the context of this course, radiation contributors in three selected orbits and mission durations for missions with COTS components in mind.

Because each environment is 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 SAA can lead to high doses or time dependent SEE threats, while the protection from Earth's magnetic field can attenuate the number of GCRs that reach the spacecraft.

5. RHA Challenges

Many RHA challenges have been forecasted, and this section seeks to build upon the examples from those documents and presentations [47][50][51][52]. Difficulties in successful RHA work can stem from the technology at the component level, but the challenge can also come from implementation/approach of RHA practices due to mission system architecture. Both of these have ramifications on quantifying the risk to a system, but are necessary areas of guidance when considered alongside the changes of *NewSpace* missions.

A. In new technologies

New devices and processes will present the challenge of new radiation effects. The physics of failure must be determined in order to predict what will occur on orbit when designers choose a COTS component or system. Most prevalent at the devices level is ever-decreasing feature sizes, but there are other complexities emerging from an effort to reduce cost and add capabilities. For example, stacking structures, or integrating process layers to create 3D parts or stacked die [53]. These type of structures present different risks from what has been discovered in past planar technologies or even dense memories.

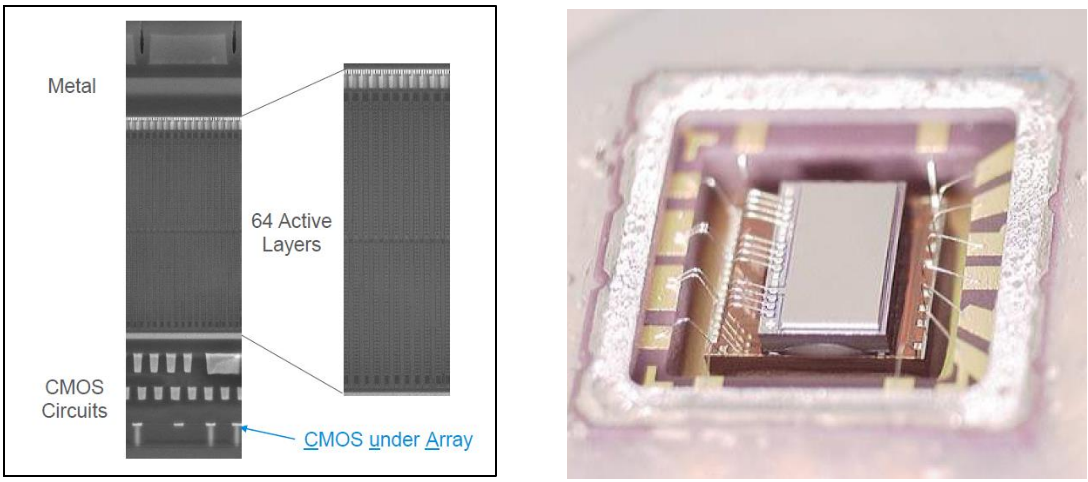


Fig. 19. Pictorial examples of 3D (internal) and 2.5D structures [54], NASA report.

The overall structure and size of some of the new devices, such as the ones depicted in Fig. 19 ultimately have the track structures with recombination, nuclear displacement, and oxide charge trapping, as mentioned earlier, in new vicinities with respect to the sensitive volumes of the device. This can lead to radiation effects that are only responsive from parasitic structures, or only exist within these technologies. The particles causing nuclear displacement have products that are dependent on the material being directly impacted. In addition the interconnects and materials close to the sensitive volume can have an impact on rates and the hazard to the semiconductor devices. Something like gold within the device that is close to a SV could increase a part's susceptibility. Consider some design changes such as increasing the density or adding gold or tungsten plugs within devices that are being stacked, such as in Fig. 20.

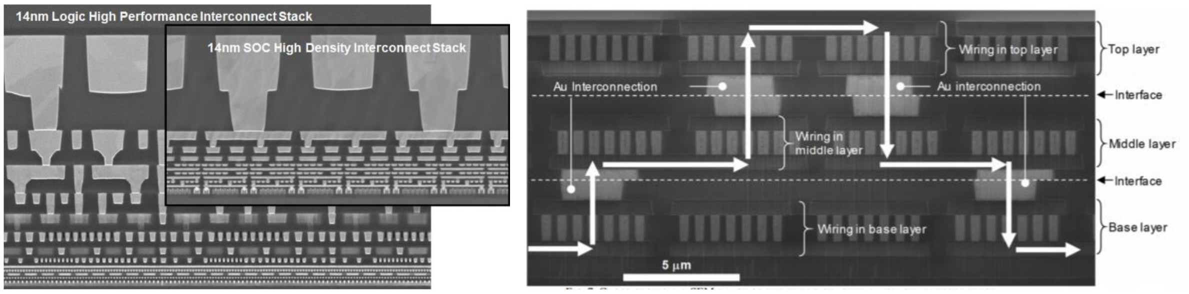


Fig. 20. Device Scaling and materials will both play a role in the radiation response of a device [55][56].

Changes to device architectures that our standards have been written to presents a whole other challenge in keeping up to date. We can only make predictions and conduct screening for the physics of failure that we understand, and we can only identify and investigate with the help of data. In some instances, our test facilities lack particle range or energy to penetrate the layers of the device that don't respond, making obtaining the data we need difficult even when we have the budget/schedule to conduct testing [57]. In other cases technology advancement or progress can lead to radiation susceptibilities that aren't accounted for such as direct ionization from protons [57] and the impact on the rate [59].

B. In new architectures

New mission architectures contribute to the tailoring that radiation requirements must undergo. If you have allowable spacecraft loss in constellations you are going to have the opportunity to accept destructive or highly interrupting events with no need for mitigation. Just as short missions have been able to justify some of the use of COTS components due to relief from the TID contrast of a long mission, there needs to be a new definition of criticality to the system and at different taxonomic levels.

Fig. 21 shows the concept of how allowable losses can reduce the risk of destructive SEE but would not avoid the risk of cumulative effects at the system level. A more hazardous environment would be one that is in a relatively high particle population such as a radiation belt, or even a benign environment where the mission life is extended. In both instances increasing the mission duration will increase the cumulative effects of radiation towards the end of mission life.

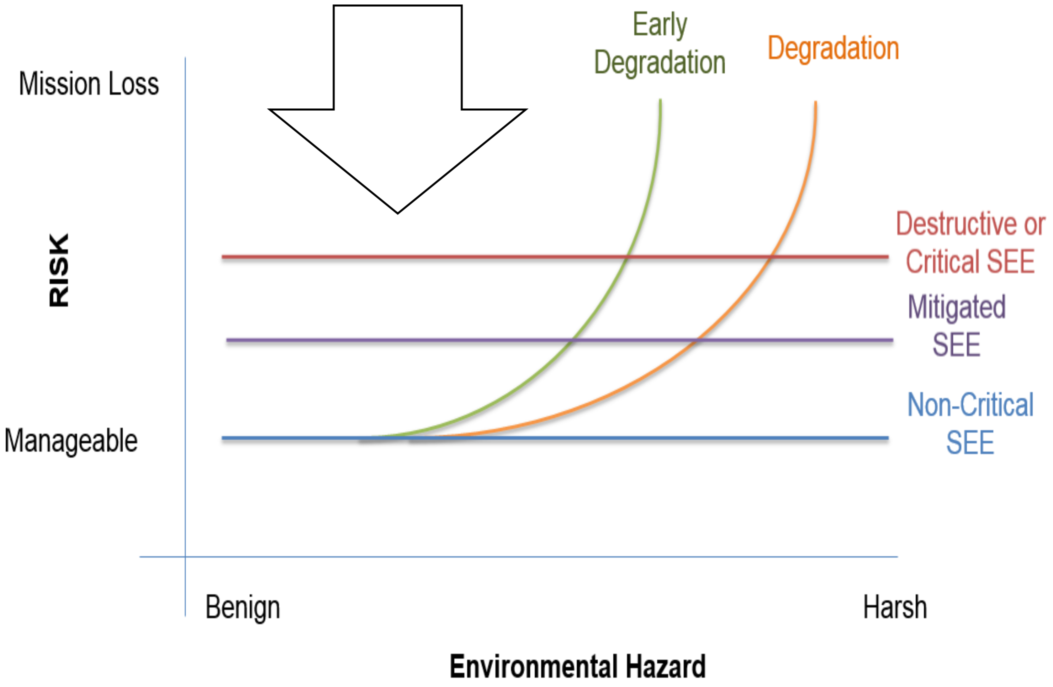


Fig. 21. Allowable losses have an impact on how redundancy can positively add reliability to a mission. SEE consequences can be reduced by implementing some redundant parts or architectures, but common failure modes can still be a present hazard if not understood or screened for [60]

Most importantly, we need to understand that while redundancy may achieve a reduction in threat, a common failure mode will be shared on a different level and could still present a threat to the systems or mission objectives and cannot be ignored. Suggestions of diverse redundancy are well pointed to, and could benefit greatly missions that aim to extend mission life.

6. Building Requirements to Accept Risk

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 schedule 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 cost savings on both fronts: analysis resources and the need for testing.

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.

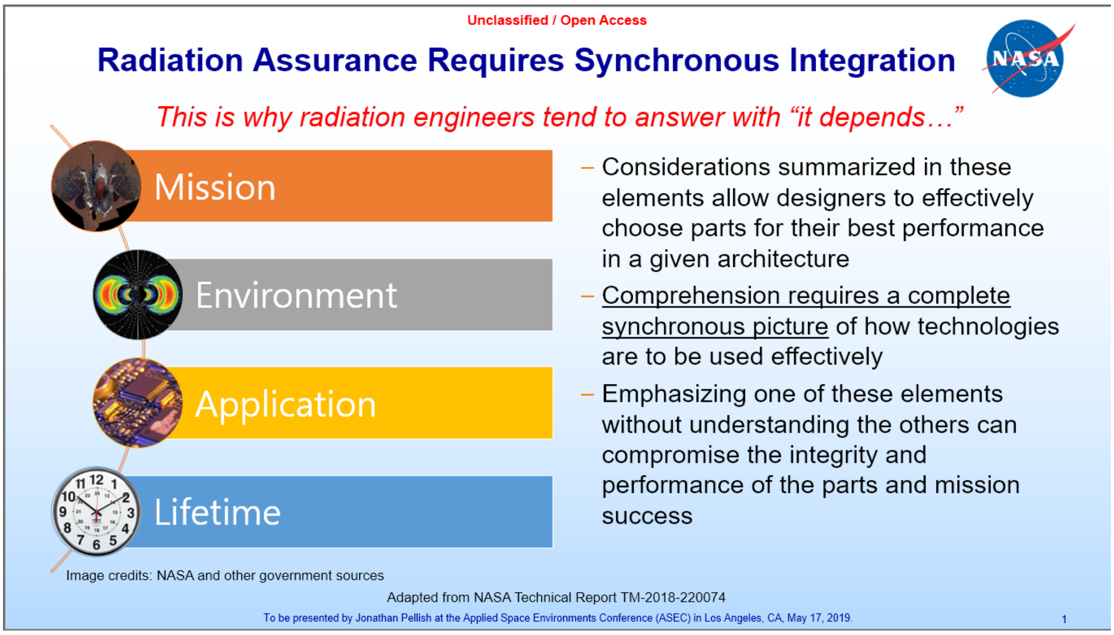
Requiring that all parts survive with large margins ignores the failure mechanisms for different types of parts, and can invoke requirements on materials or subsystems that cannot meet them without analysis or testing that may not benefit the on-orbit mission risk. As such, the mission radiation requirements need to be flowed down to the appropriate technologies.

A. Failure Awareness

Defining your risk posture in order to determine when you would deem a radiation effect a failure or not is integral to the process of risk buy-down and tracking. If there are identifiable failure modes that are not acceptable to the mission, be that for the availability, or criticality carrying known unknowns may allow for accepted risks later, but if you already know that the outcome is mitigated higher in the system architecture you may have justification for the component's employment. On the other hand, fault propagations may be the problem that you wish to mitigate. This can include cumulative effects, fault injection tests may not be able to cover the state space. No matter the situation, failure awareness is tightly partnered with the mission requirements, and good requirements have the potential to identify susceptibilities to the system early on in the mission lifecycle.

B. Smart requirements

In order to make requirements useful to engineers across the board, they need to be tied to the environment as well as the technology of the devices. For MEAL to be accounted for, it is specific requirements that are invoked where they make sense that are the easiest to reconcile and track. Requirements when clear help select the best parts for the job, not just the most robust/expensive.



Unclassified / Open Access

Radiation Assurance Requires Synchronous Integration

This is why radiation engineers tend to answer with "it depends…"

Mission

Environment

Application

Lifetime

- Considerations summarized in these elements allow designers to effectively choose parts for their best performance in a given architecture
- Comprehension requires a complete synchronous picture of how technologies are to be used effectively
- Emphasizing one of these elements without understanding the others can compromise the integrity and performance of the parts and mission success

Image credits: NASA and other government sources

Adapted from NASA Technical Report TM-2018-220074

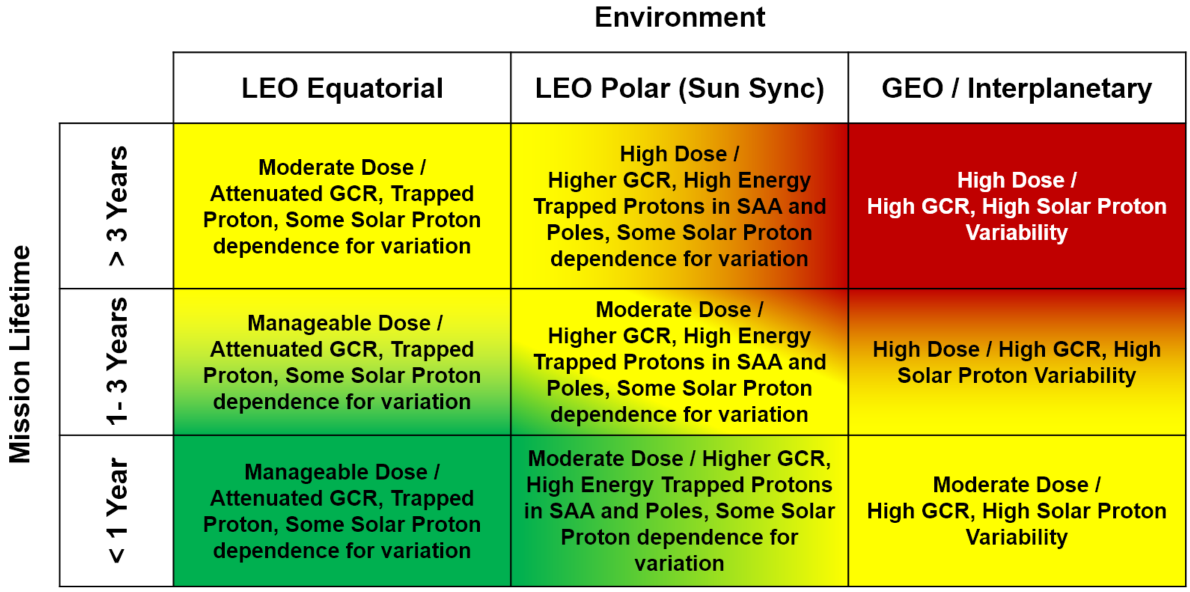
To be presented by Jonathan Pellish at the Applied Space Environments Conference (ASEC) in Los Angeles, CA, May 17, 2019.

Fig. 22. Slide presented by Jonny Pellish at the Applied Space Environments Conference [61]

The criticality and availability of the mission architecture is communicated through the concept of operations, and can give insight to where the radiation hazard and device performance limitations meet the mission requirements. Only when taking the complete synchronous picture into account, we can derive requirements enabling trades that allow for accepted risks.

a. Requirements tied to the environment

Radiation belts at a destination planet can be a driver to the total mission dose and the single event rates; the time spent in the belts can quickly add to the mission hazard in particular when passing through high concentrations of charged particle radiation. The South Atlantic Anomaly is a case of just that, high concentration at lower altitude than would be predicted by a symmetric model. As you leave the magnetic field of a planet, you no longer benefit from the magnetic attenuation of GCR, and so you will have a higher background rate of upsets. All of these location nuances need to be accounted for when the mission requirements are being created. One way to compare the hazards from radiation sources on spaceflight missions for intended environments can be seen in the following:



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

Fig. 23. Radiation Hazard for typical environments [61]

b. Requirements tied to the device technology

Technologies exhibit specific physics of failure, and it is not easy to group them all. When writing requirements for radiation, know that you want to achieve objectives that have an impact that varies given the device technology [63][64][65][66]. 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 some of the known risks to given technologies, 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): Temporal response to charge injection. Can be rail-to-rail voltage or current changes that damage downstream or 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 may occur, masking these upset cells or the blocks/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 string, and if it is critical, can determine the path to mission success.

c. Requirements on radiation test data

Because radiation effects test campaigns are often necessarily done with application like conditions, it can be hard to know what available data apply or are representative of the parts you intend to use. What's more, representation of the flight parts must be understood because the testing is destructive. At best you are testing parts that are traceable to the flight lot or wafer (this is extremely difficult to guarantee based on COTS flow and production/packaging methodologies). When you have sufficient data, you are able to apply methodologies that can determine success with confidence in mind [65][66] [67]. Beyond that, historical data on the parts from other flight lots (or even that of similar parts) may not adequately represent your application. Shown in Fig. 24 is the relationship of these data categories, and a conceptual relationship to the mean and variability in the process or relation to the flight lot, as you get further off-center, you are less representative.

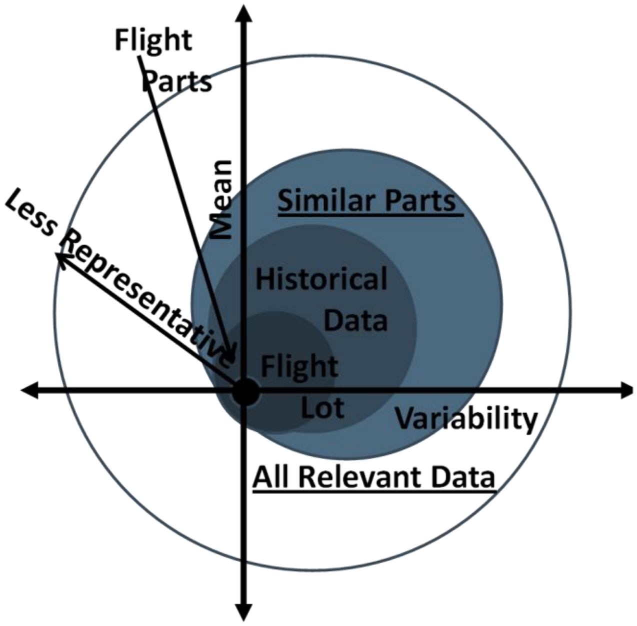


Fig. 24. Data relationships and representation of the flight lot [66]

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 Fig. 25. It should be noted that, in some instances, ruling out destructive single event effects alone may provide mission assurance.

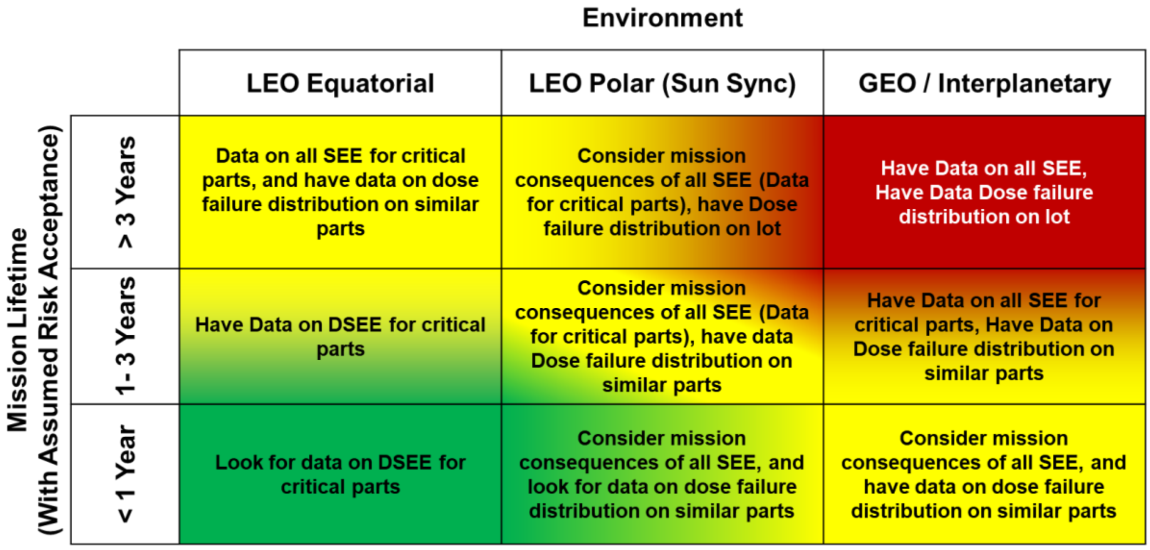
Using available data, rather than conducting a radiation test campaign, can be a cost saver. Radiation facilities are expensive to maintain and the costs show (cyclotron facility costs can be thousands of dollars per hour). But caution and information need to be employed when extrapolating previous results 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.

Suppose there is data available for your device in its application that is acceptable for use, and is representative of your flight lot. There is an increasing need for failure distributions not just an average, often without a large enough sample size. Things to keep in mind for statistics on datasets:

- Destructive effects are just that, fatal, and one part can only be one data point.
- Rate calculations that are being done need error bars on the cross-section curves we have.
- TID needs to be a distribution in order to optimize shielding

The figure below gives a recommendation on radiation data needed in order to track risks to the mission. Working from a known MEAL, the distinctions that are driven by the radiation hazard can be compared to one another.



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

Fig. 25. Radiation test data needed to accept risk [61]

C. Accepting Risk

In order to accept risk to a system it must be tracked with assumptions in order to weigh options in terms of mitigation approaches and reuse on follow on missions. Even if the risk is unquantifiable in terms of probability of success it must still be tracked and traded with other mission risks through iterations to the design or mitigation strategies. This section provides information on how to track the risk, the assumptions, and notionally how to relate that risk relatively to other risks in an effort to increase reliability.

a. Risk tracking – NASA

Identifications of risks to the system during the design phases are cost dependent. Design changes later in a mission lifetime only lead to more work and rework of integrated electronics. And while this is not a concern for some SmallSat designs, it may be to others. The more risk assurance efforts that are removed, the later defects are likely to be caught *(if they are caught)*, the more work that has to be "undone", the more testing that has to be redone, and the more likely the project is to suffer severe programmatic impact and/or to fly with added residual risk [68]. The costs associated can come in the form of schedule and/or budget. *NewSpace* may not be able to afford these type of scope increases, and so the need for early mission assurance activities is paramount.

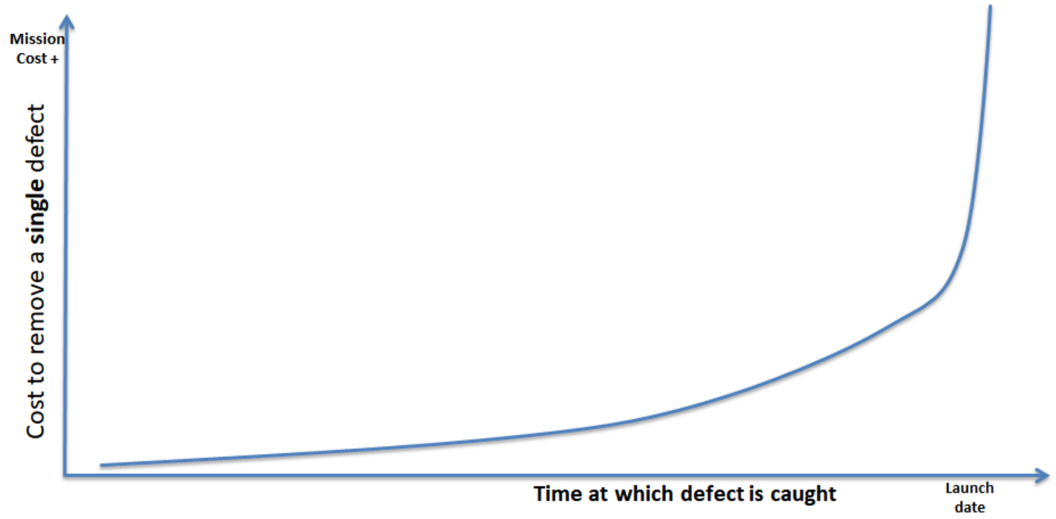
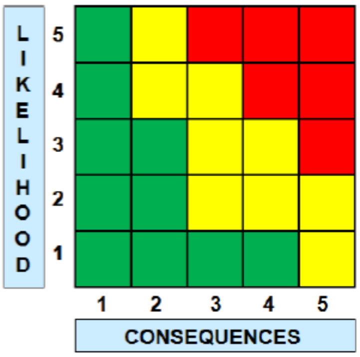


Fig. 26. Mission costs to removal of defect or risk to the system [68]

Different risks to a system will be tracked at the mission level and can be risks to safety, technical (radiation risks fall into this category), or cost/schedule (radiation risks and assurance activities can have impact here as well). When tracking risks and risk reduction activities, a categorization based on likelihood and consequence is often useful to raise awareness at the mission level in order to be proactive.

Likelihood	Safety Estimated likelihood of Safety event occurrence	Technical Estimated likelihood of not meeting performance requirements	Cost Schedule Estimated likelihood of not meeting cost or schedule commitment
5 Very High	$(P_{SE} > 10^{-1})$	$(P_T > 50\%)$	$(P_{CS} > 75\%)$
4 High	$(10^{-2} < P_{SE} \le 10^{-1})$	$(25\% < P_T \le 50\%)$	$(50\% < P_{CS} \le 75\%)$
3 Moderate	$(10^{-3} < P_{SE} \le 10^{-2})$	$(15\% < P_T \le 25\%)$	$(25\% < P_{CS} \le 50\%)$
2 Low	$(10^{-5} < P_{SE} \le 10^{-3})$	$(2\% < P_T \le 15\%)$	$(10\% < P_{CS} \le 25\%)$
1 Very Low	$(10^{-6} < P_{SE} \le 10^{-5})$	$(0.1\% < P_T \le 2\%)$	$(2\% < P_{CS} \le 10\%)$



LIKELIHOOD	1	2	3	4	5
5	🟩	🟨	🟥	🟥	🟥
4	🟩	🟨	🟨	🟥	🟥
3	🟩	🟩	🟨	🟨	🟥
2	🟩	🟩	🟨	🟨	🟨
1	🟩	🟩	🟩	🟩	🟨

CONSEQUENCES

Fig. 27. Risk tracking can be done by ordering the likelihood and consequence of that risk. Likelihood probabilities should be determined by mission requirements [69].

Project guidelines and governance that are in use at NASA can be found within:

- NPR-7120.5 – NASA Agency Program Management
- GPR-8705.4 – NASA Goddard Risk Classification Guidelines
- NASA-STD-8739.10 – NASA Parts Assurance Standard

While risk tracking is essential, *NewSpace* demands that we not only track what the risk is, but our assumptions that go with the activities and the tailoring that we do to our standard practices.

b. *Goal Structured Notation (GSN)*

GSN provides a framework for capturing goals and their assumptions, tracking and documenting these things enables an analysis of trades and can feed into other tools readily. This simple practice can provide documentation that is useful going forward, with RHA practices and assumptions to build on for future missions.

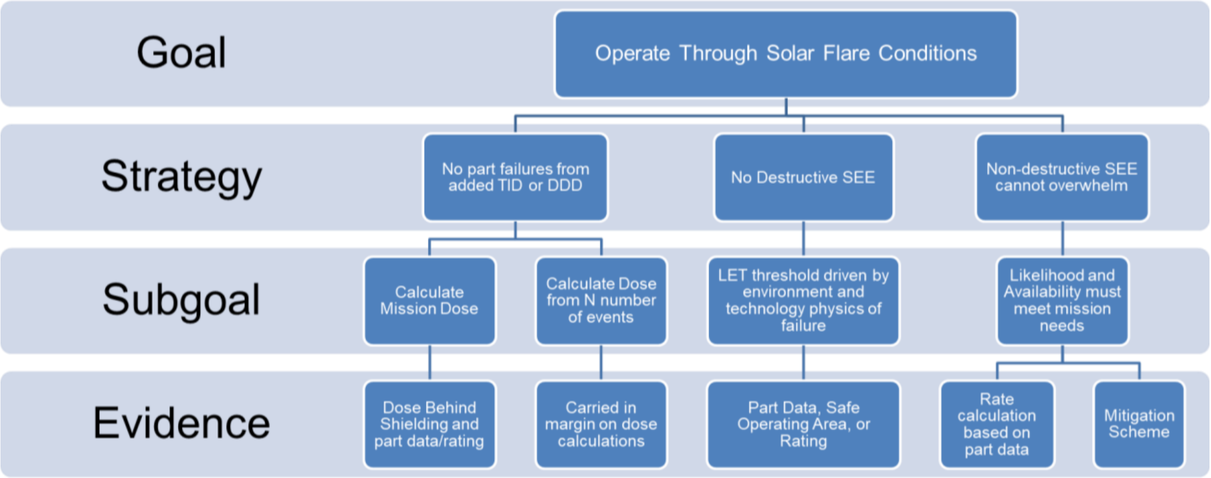


Fig. 28. GSN Example of operation through a solar flare [70]

One of the key elements that can put GSN to use over static documentation is that it can be tailored and updated based on the concept of operations for a mission, the radiation requirements we use should be called when the devices are in use and not when they are in an unused or safe state with respect to the radiation hazard.

c. *Relative Risk*

Adoption of system reliability methods such as FIDES or MIL-HDBK-217 can be applied to RHA specifically to understand the overall risk budget to a system [71][72]. This can be done by assigning quality factors for time (duty-cycle in threatening application) and criticality in an application. If you have data on the known failure mode, $P_{failure}$, you can sum over applications the risk from using that the device. For multiple applications the relative reliability is then the sum of all applications with the part criticality taken into account:

$$R(P) = \sum \sum_{Application} Q_{Time-On} \cdot Q_{Criticality} \cdot P_{failure}$$

An example would be that of latch-up in CMOS device that is critical to mission success, a destructive single event effect. If the component were used in two applications with varied criticality, assume that application one has to work, application two has a cold spare that can be selected for use if the first fails. Suppose that SEE data suggests a 0.5 probability that a device latches during the mission life at a 90% confidence level – however in the critical application the device is only on for 0.25 of the mission –

mission critical $Q_{criticality} = 1$, $Q_{time\text{-}on} = 0.25$. In the cold spare application, the device is always on, therefore $Q_{criticality}=0.5$, $Q_{time\text{-}on}=1$. The relative risk of latch-up goes down based on the system description.

You could of course have multiple instances of an application that would also be summed over. This effort could then be extended to all of the parts in all of their applications, and the risk tracked down to the tall poles. You could also consider a mission architecture such as a constellation where another factor may be that you have allowable losses of entire spacecraft, say only 70% of the spacecraft are necessary to achieve mission success: $Q_{architecture} = 0.7$. As we change the mission architecture, we may no longer be able to tolerate that many losses. The $Q_{architecture}$ would go up. Our mitigation might be to have the device in an off state, or increase the number of spacecraft in the constellation to change either the $Q_{time\text{-}on}$ or the $Q_{architecture}$ to get to the acceptable risk. In this way you could track or investigate where system threats outweigh one another, and where testing or changing the architecture may be of consequential benefit to the overall reliability.

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.

7. Summary

The practice of radiation hardness assurance anticipates competing failure modes based on the physics of failure associated with charged particles interacting with components in their application. The effects can be cumulative or instantaneous, and will depend on the architecture of the device and the system at large. There are basic efforts within the discipline that can help determine threats to the system and describe the hazard for a given environment. Although there are typical outputs of environments when modeled, the natural space radiation environment is dynamic in nature, bounding the environment at the destination must be done.

NewSpace changes and challenges the standard practices of RHA by thriving with new COTS technologies, new mission architectures, and a smaller budget. Each of these has an impact whether it be the new materials and device topologies in COTS components, allowable losses, or less radiation testing, respectively. Radiation hardness assurance must evolve to keep with the coming missions. In order to accommodate or designs/designers need to be aware of the hazards and potential failures, and our requirements need to be developed in such a way that takes into account the technologies themselves, the environment and useful data that already exists. In doing so we can track risk to the system utilizing tools like GSN or relative risks to improve overall assurance, accepting risks where the end product is mission success.

8. Acknowledgements

Many thanks to talks/editing with Ray Ladbury, Ted Wilcox, Megan Casey, and other members of the radiation effects and analysis group at NASA GSFC.

9. References

[1] M. N. Sweeting, "Modern Small Satellites-Changing the Economics of Space," in Proceedings of the IEEE, vol. 106, no. 3, pp. 343-361, March 2018.

[2] J. Fink, "PEMs: they are used successfully in Hi-Rel avionics," Proceedings of the 1999 Joint Meeting of the European Frequency and Time Forum and the IEEE International Frequency Control Symposium (Cat. No.99CH36313), Besancon, France, 1999, pp. 540-543 vol.1.

[3] M. Swartwout, https://digitalcommons.usu.edu/cgi/viewcontent.cgi?referer=&httpsredir=1&article=1687&context=smallsat

[4] M. Swartwout, "The first one hundred CubeSats: A statistical look", J. Small Satellites, vol. 2, no. 2, pp. 213-233, 2013.

[5] M. Swartwout, "Secondary spacecraft in 2016: Why some succeed (And too many do not)," 2016 IEEE Aerospace Conference, Big Sky, MT, 2016, pp. 1-13.

[6] C. A. Feuchter, C. A. Van Meter, K. M. Neuman and K. J. Sparrow, "When is a satellite not a toaster? (satellite repair costs)," 1991 Winter Simulation Conference Proceedings., Phoenix, AZ, USA, 1991, pp. 499-508.

[7] CubeSat Database, https://sites.google.com/a/slu.edu/swartwout/home/cubesat-database

[8] Seradata SpaceTrak, https://www.seradata.com/spacetrak3

[9] C. S. Ruf et al., "The CYGNSS nanosatellite constellation hurricane mission," 2012 IEEE International Geoscience and Remote Sensing Symposium, Munich, 2012, pp. 214-216.

[10] G. Panegrossi et al., "Use of the GPM Constellation for Monitoring Heavy Precipitation Events Over the Mediterranean Region," in IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 9, no. 6, pp. 2733-2753, June 2016.

[11] M. Richharia, P. H. Hansel, P. W. Bousquet, M. O'Donnell, "A feasibility study of a mobile communication network using a constellation of low earth orbit satellites", Globcom'89, pp. 773-777, 1989.

[12] B. R. Bertiger, P. A. Swan, R. J. Leopold, "Iridium is in the works", Aerospace America, pp. 40-42, February 1991.

[13] C. Ward, T. Phillips, T. Chang, A. Khan and P. R. Acuff, "LEO satellite constellation performance analysis," Proceedings of MILCOM '93 - IEEE Military Communications Conference, Boston, MA, USA, 1993, pp. 742-747 vol.2.

[14] Z. Manchester, M. Peck, A. Filo, "Kicksat: A crowd-funded mission to demonstrate the worlds smallest spacecraft", Small Satellite Conference, 2013

[15] https://www.nanosats.eu/#figures

[16] O. Gonzales, Guidelines for Verification Strategies to Minimize RISK Based on Mission Environment, -Application and -Lifetime (MEAL), https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180007514.pdf

[17] K. LaBel, “SEECA Single Event Effect Criticality Analysis, SEU propagation analysis: system level effects,” http://radhome.gsfc.nasa.gov/radhome/papers/seecai.htm, 1996.

[18] NASA FERMI X-ray telescope**,** https://fermi.gsfc.nasa.gov/

[19] Solar Dynamics Observatory, https://sdo.gsfc.nasa.gov

[20] J. L. Barth, K. A. LaBel and C. Poivey, "Radiation assurance for the space environment," 2004 International Conference on Integrated Circuit Design and Technology (IEEE Cat. No.04EX866), Austin, TX, USA, 2004, pp. 323-333.

[21] M. Xapsos, "A Brief History of Space Climatology: From the Big Bang to the Present," in *IEEE Transactions on Nuclear Science*, vol. 66, no. 1, pp. 17-37, Jan. 2019.C. Poivey, IEEE NSREC Short Course, “Radiation Hardness Assurance for Space Systems,” Phoenix, July 2002.

[22] S. C. Notebook, “2002 IEEE Nuclear and Space Radiation Short Course Notebook From Particles to Payloads 2002 IEEE Nuclear and Space Radiation Short Course Notebook Radiation Effects – From Particles to Payloads,” NSREC Short Course, 2002.

[23] Xapsos RADECS s/c 2007, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080039420.pdf

[24] Brock J. LaMeres, Colin Delaney, Matt Johnson, Connor Julien, Kevin Zack, Ben Cunningham Todd Kaiser, Larry Springer, David Klumpar, "Next on the Pad: RadSat – A Radiation Tolerant Computer System," Proceedings of the 31st Annual AIAA/USU Conference on Small Satellites, Logan UT, USA, Aug. 5-10, 2017, paper: SSC17-III-11

[25] https://www.ti.com/seclit/ml/sgzy002a/sgzy002a.pdf

[26] D. M. Fleetwood, "Total ionizing dose effects in MOS and low-dose-rate sensitive linear-bipolar devices", IEEE Trans. Nucl. Sci., vol. 60, no. 3, pp. 1706-1730, Dec. 2013

[27] J. R. Srour, C. J. Marshall, P. W. Marshall, "Review of displacement damage effects in silicon devices", IEEE Trans. Nucl. Sci., vol. 50, no. 3, pp. 653-670, Jun. 2003.

[28] M. Kruglanski et al., "Last upgrades and development of the space environment information system (SPENVIS)," 2009 European Conference on Radiation and Its Effects on Components and Systems, Bruges, 2009, pp. 563-565.

[29] Spenvis https://www.spenvis.oma.be

[30] OMERE http://www.trad.fr/OMERE-Software.html.

[31] D. Chen, SFT2222 test report, radhome.gsfc.nasa.gov

[32] M. Campola, HSSR-7111 test report, radhome.gsfc.nasa.gov

[33] J. A. Pellish *et al.*, "Criticality of Low-Energy Protons in Single-Event Effects Testing of Highly-Scaled Technologies," in *IEEE Transactions on Nuclear Science*, vol. 61, no. 6, pp. 2896-2903, Dec. 2014.

[34] E. Normand, "Single-event effects in avionics," in *IEEE Transactions on Nuclear Science*, vol. 43, no. 2, pp. 461-474, April 1996.

[35] R. C. Baumann, "Radiation-induced soft errors in advanced semiconductor technologies," in *IEEE Transactions on Device and Materials Reliability*, vol. 5, no. 3, pp. 305-316, Sept. 2005.

[36] J. H. Adams, A. F. Barghouty, M. H. Mendenhall, R. A. Reed, B. D. Sierawski, K. M. Warren, J. W. Watts, R. A. Weller, "CREME: the 2011 revision of the cosmic ray effects on micro-electronics code", IEEE Trans. Nucl. Sci., vol. 59, no. 6, pp. 3141-3147, Dec. 2012.

[37] G. P. Ginet, D. Madden, B. K. Dichter and D. H. Brautigam, "Energetic Proton Maps for the South Atlantic Anomaly," *2007 IEEE Radiation Effects Data Workshop*, Honolulu, HI, 2007, pp. 1-8.

[38] D. Chen, VRG8662 test report, radhome.gsfc.nasa.gov

[39] T. Wilcox, Micron Flash test report, radhome.gsfc.nasa.gov

[40] M. C. Casey et al., "Failure Analysis of Heavy Ion-Irradiated Schottky Diodes," in IEEE Transactions on Nuclear Science, vol. 65, no. 1, pp. 269-279, Jan. 2018

[41] Bob Gigliuto

[42] J. L. Barth, K. A. LaBel, and C. Poivey, “Radiation assurance for the space environment,” 2004 Int. Conf. Integr. Circuit Des. Technol. (IEEE Cat. No.04EX866), pp. 323–333, 2004.

[43] J. R. Schwank, M. R. Shaneyfelt and P. E. Dodd, "Radiation Hardness Assurance Testing of Microelectronic Devices and Integrated Circuits: Radiation Environments, Physical Mechanisms, and Foundations for Hardness Assurance," in IEEE Transactions on Nuclear Science, vol. 60, no. 3, pp. 2074-2100, June 2013.

[44] National Aeronautics and Space Administration Headquarters, “NASA Space Flight Program and Project Management Handbook,” 2014.

[45] G. L. Hash, M. R. Shaneyfelt, F. W. Sexton and P. S. Winokur, "Radiation hardness assurance categories for COTS technologies," 1997 IEEE Radiation Effects Data Workshop NSREC Snowmass 1997. Workshop Record Held in conjunction with IEEE Nuclear and Space Radiation Effects Conference, Snowmass Village, CO, 1997, pp. 35-40.

[46] A. I. Mrigakshi, D. Matthiä, T. Berger, G. Reitz, and R. F. Wimmer-Schweingruber, “How Galactic Cosmic Ray models affect the estimation of radiation exposure in space,” Adv. Sp. Res., vol. 51, no. 5, pp. 825–834, 2013.

[47] K.A. LaBel, A.H. Johnston, J.L. Barth, R.A. Reed, C.E. Barnes, “Emerging Radiation Hardness Assurance (RHA) issues: A NASA approach for space flight programs,” IEEE Trans. Nucl. Sci., pp. 2727-2736, Dec. 1998.

[48] B. D. Sierawski, K. M. Warren, A. L. Sternberg, R. A. Austin, J. M. Trippe, M. W. McCurdy, R. A. Reed, R. A. Weller, M. L. Alles, R. D. Schrimpf, L. W. Massengill, D. M. Fleetwood, A. Monteiro, G. W. Buxton, J. C. Brandenburg, W. B. Fisher, R. Davis, "CubeSats and crowd-sourced monitoring for single event effects hardness assurance", IEEE Trans. Nucl. Sci., vol. 64, no. 1, pp. 293-300, Jan. 2017.

[49] Gigliuto

[50] J. R. Schwank, M. R. Shaneyfelt, and P. E. Dodd, “Radiation hardness assurance testing of microelectronic devices and integrated circuits: Test guideline for proton and heavy ion single-event effects,” IEEE Trans. Nucl. Sci., vol. 60, no. 3, pp. 2101–2118, 2013.

[51] P. E. Dodd, M. R. Shaneyfelt, J. R. Schwank, and J. A. Felix, “Current and Future Challenges in Radiation Effects on CMOS Electronics,” IEEE Trans. Nucl. Sci., vol. 57, no. 4, pp. 1747–1763, Aug. 2010.

[52] H. Quinn, “Challenges in testing complex systems,” IEEE Trans. Nucl. Sci., vol. 61, no. 2, 2014.

[53] C. Zhang and G. Sun, "Fabrication cost analysis for 2D, 2.5D, and 3D IC designs," 2011 IEEE International 3D Systems Integration Conference (3DIC), 2011 IEEE International, Osaka, 2012, pp. 1-4.

[54] https://www.micron.com

[55] Y. Honda *et al.*, "Triple-Stacked Au/SiO2 Hybrid Bonding with 6-μm-pitch Au Electrodes on Silicon-On-Insulator Substrates using O2 Plasma Surface Activation for Three-Dimensional Integration," in *IEEE Transactions on Components, Packaging and Manufacturing Technology*.

[56] K. Fischer *et al.*, "Performance enhancement for 14nm high volume manufacturing microprocessor and system on a chip processes," *2016 IEEE International Interconnect Technology Conference / Advanced Metallization Conference (IITC/AMC)*, San Jose, CA, 2016, pp. 5-7.

[57] M. Cabanas-Holman, “2019 IEEE Nuclear and Space Radiation Short Course Notebook SEE test and analysis of complex devices in advanced technologies from cells to systems” NSREC Short Course, 2019.

[58] N. A. Dodds, J. R. Schwank, M. R. Shaneyfelt, P. E. Dodd, B. L. Doyle, M. Trinczek, E. W. Blackmore, K. P. Rodbell, M. S. Gordon, R. A. Reed, J. A. Pellish, K. A. LaBel, P. W. Marshall, S. E. Swanson, G. Vizkelethy, S. V. Deusen, F. W. Sexton, M. J. Martinez, "Hardness assurance for proton direct ionization-induced SEEs using a high-energy proton beam", IEEE Trans. Nucl. Sci., vol. 61, no. 6, pp. 2904-2914, Dec. 2014.

[59] B. D. Sierawski et al., "Impact of Low-Energy Proton Induced Upsets on Test Methods and Rate Predictions," in IEEE Transactions on Nuclear Science, vol. 56, no. 6, pp. 3085-3092, Dec. 2009.

[60] M. Campola, "RHA for SmallSats" Presentation, NEPP ETW 2017.

[61] Pellish 2019, https://sti.usra.edu/ASEC2019/program/ASEC%202019%20Presentations.zip

[62] M. Campola, “Taking SmallSats to the Next Level-Sensible Radiation Requirements and Qualification that won't Break the Bank,” Proceedings of the Annual AIAA/USU Conference on Small Satellites, August 2018.

[63] M. Boscherini et al., “Radiation damage of electronic components in space environment,” in Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2003, vol. 514, no. 1–3, pp. 112–116.

[64] K. A. LaBel and M. M. Gates, “Single-Event-Effect from a System Perspective,” *IEEE Trans. Nucl. Sci.*, vol. 43, no. 2, 1996.

[65] R. L. Ladbury and M. J. Campola, “Bayesian methods for bounding single-event related risk in low-cost satellite missions,” *IEEE Trans. Nucl. Sci.*, vol. 60, no. 6, pp. 4464–4469, 2013.

[66] R. L. Ladbury and B. Triggs, “A bayesian approach for total ionizing dose hardness assurance,” in *IEEE Transactions on Nuclear Science*, 2011, vol. 58, no. 6, pp. 3004–3010.

[67] M. A. Xapsos, et al., “Inclusion of Radiation Environment Variability in Total Dose Hardness Assurance Methodology,” IEEE TNS, vol. 64, Jan 2017.

[68] J. Leitner, "Risk-based SMA for CubeSats", internal NASA meeting presentation, 2016.

[69] NPR-7120.5 – NASA Agency Program Management

[70] R. A. Austin, N. Mahadevan, B. D. Sierawski, G. Karsai, A. F. Witulski and J. Evans, "A CubeSat-payload radiation-reliability assurance case using goal structuring notation," *2017 Annual Reliability and Maintainability Symposium (RAMS)*, Orlando, FL, 2017, pp. 1-8.

[71] Reliability qualification of Semiconductor devices based on Physics of failure risk and opportunity assessment, JEDEC Solid State Technology Association, January 2014.

[72] P. Carton, M. Giraudeau and F. Davenel, "New FIDES models for emerging technologies," *2017 Annual Reliability and Maintainability Symposium (RAMS)*, Orlando, FL, 2017, pp. 1-6.