Radiation and its effects on space systems

AcubeSAT-SYE-BH-021

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Contents

Changelog

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04/05/2019	1.1	INTERNALLY RELEASED	Minor formatting changes and spelling corrections.
03/05/2019	1.0	INTERNALLY RELEASED	Added AcubeSAT's radiation environment section and Discussion/SYE recommendations section.
01/05/2019	0.1	DRAFT	Initial revision

This is the latest version of this document (1.1) as of May 4, 2019. Newer versions might be available. Check <LINK TO PDF DOCUMENTATION>

1 Scope of this report

This report covers the topic of radiation and its effects on space systems with a focus on electronic and electrical components. Given the fact that our team designs unmanned spacecraft, biological effects are only briefly mentioned in this report. It is based on several resources, namely the ECSS-E-HB-10-12-A – Calculation of radiation and its effects and margin policy handbook, the Space Electronics: Challenges and Solutions by Prof. Alkis Hatzopoulos, the ECSS Standard ECSS-E-ST-10-04C – Space Environment and several internal ACubeSAT reports. It has been authored by the Systems Engineering team, in order to give an introduction into the near-earth radiation environment and give design guidelines both at subsystem and system level. This report alone cannot substitute the enormous amount of information which can be found in the above-mentioned documents, but it should be a good reference point both for ACubeSAT and future space missions. Readers from different subsystems will find useful information in this report and are encouraged to research relevant parts for themselves.

2 Introduction

In space, the radiation environment differs from earth, mainly because of the absence of the natural shielding provided by the Earth's magnetic field. In addition, components in unmanned spacecrafts cannot be repaired or replaced, highlighting the need for a careful evaluation of the radiation environment and the need for precautionary actions to be taken into the design. This procedure varies for every mission design: each spacecraft has a different orbit and the radiation environment mostly depends on the type of orbit. In contrast, countermeasures or in other words protection methods from radiation are well defined, therefore engineering teams could theoretically implement all protection methods in order to be safe (without knowing the final orbit), but this comes at a cost.

3 ECSS-E-HB-10-12-A

3.1 Compendium of radiation effects

In this section, an overview of all radiation effects is given. We can categorize these effects in five main categories. For further information readers should read the relevant references provided in the handbook. Effects on electronic and electrical systems can be found below.

3.1.1 Total ionizing dose (TID)

TID effects in semiconductor devices depend on the creation of electron-hole pairs within dielectric layers by the incident radiation and subsequent generation of: a) traps at/near the interface with the semiconductor and b) trapped charge in the dielectric.

Outcomes: Flat-band and threshold voltage shifts, surface leakage currents and noise.

3.1.2 Displacement damage

Energetic particles can create damage in semiconductor materials by displacing atoms in the crystal lattice. Secondary electrons produced by high-energy photons also produce displacement effects. The main result is that stable defect states are created within the bandgap that can give rise to a variety of effects, which are not analyzed in order to minimize the size of this report.

Outcomes: Thermal dark current in detectors, Reduction of minority carrier lifetime and effects in LEDs and laser diodes, Loss in charge transfer efficiency in CCDs, Carrier removal, Tunneling of carriers (increased current in reverse biased junctions)

3.1.3 Single event effects

With the term Single event effects (SEEs) we refer to the interaction of single particles with the semiconductor causing either destructive, potentially destructive or transient effects.

A) Destructive:

- **SEL**: Single event latch-up in CMOS circuits, potentially destructive triggering of a real of parasitic pnpn thyristor structure structure in the device
- **SESB**: Single event snapback in NMOS devices, destructive triggering of a lateral NPN transistor accompanied by regenerative feedback.
- **SEGR**: Single event gate rupture, formation of a conducting path triggered by a single ionizing particle in a high-field region of a gate oxide.
- **SEDR**: Single event dielectric rupture, destructive rupture of dielectric triggered by a single ionizing particle in a high-field region of a dielectric.
- **SEB**: Single event burnout in power transistors, destructive triggering of a vertical n-channel transistor accompanied by regenerative feedback.

B) Non-destructive:

- **SEU**: Single event upset in memories and registers, for example bit-flips, which leads to change of stored information.
- **MCU**: Multiple-cell upsets, single particle impacts affecting several adjacent bits due to large particle ranges in memories and registers.
- **SEFI**: Single event functional interrupt in control circuitry (processors, memories or ADCs), which result in a transient corruption of a control path
- **SEHE**: Single event hard errors in SRAM and DRAM devices, where semi-permanent damage is sustained by the memory cell due to micro-dose effect from the ionizing particle.
- **SET**: Single event transients in linear circuits, which can be interpreted as a false signal.
- **SED**: Single event disturb in digital circuits, a signal transient that is propagated

to cause an output error in combinatorial logic.

3.1.4 Effects on materials

Exposure to ionizing radiation at high doses can and will degrade polymers (including those used in thermal blankets) and optical materials. Radiolytic reactions occur in which the bonds in the polymer chains are broken and formed with other reactive fragments. The result can be degradation of mechanical and dielectric properties, coloration, and production of gases. Silica glasses can also suffer coloration and therefore degradation of their optical properties, depending upon the purity of the material.

3.1.5 Biological effects

Ionization produces free hydroxyl radicals which compromise one or more of the functions of the cell, this cellular damage becoming apparent after several cycles, or even resulting in immediate cell death. The effects of this can be deterioration of tissue or organ function, presenting within a matter of minutes to 30-60 days after exposure (early radiobiological effects). Stochastic radiobiological effects can occur over the duration of the life of the individual exposed and appears in the form of neoplastic diseases (tumours). These are very probably the results of DNA damage to, and subsequent mutation of, a single cell. In addition to long-term stochastic effects, deterministic late effects are possible, such as the development of eye cataracts, which definitely occur beyond a threshold dose. Individual relativistic high-Z particles can also produce light flashes in the retina.

3.1.6 Spacecraft charging

Spacecraft charging can arise from energetic plasmas, leading to surface charging, or from energetic electrons, which can penetrate the spacecraft skin and collect in insulators leading to deep dielectric charging. Subsequent discharges can couple into spacecraft systems leading to anomalies and damage.

3.2 Margin

3.2.1 Introduction

Section 4 introduces the reader to the concepts of margin. It is highlighted as a project management decision which may result in several problems for the development process of a spacecraft. There is no single margin to cover all the issues and decisions to reduce the margin shall be made only with an additional risk analysis. Several parameters contribute to margin decisions. It is also important to identify mission critical targets (components, experiment etc.), in order to impose a larger margin (Criticality) and if a target can be proven to be immune to radiation to a degree where the most conservative simplified assessment of the effects parameters is considerably below the expected problem threshold, little further analysis is needed (Immunity).

3.2.2 Environment uncertainty

The ECSS-E-ST-10-04 Space environment standard is the formal location for information on the uncertainties and margins associated with the environment of a space system and related models and data. All models are based on satellite data. In addition, the SYE team recommends to research models based on the International Space Station, since the environment will be almost identical at the start of the mission.

3.2.3 Effects parameters' uncertainty

In this segment, the process for deriving the radiation effects parameter (e.g. absorbed dose, SEE rates, dose equivalent and background rates) are given. The method of shielding is also discussed. For single event effects, ECSS documents assume that all the sensitive parts of "bits" on a chip are well approximated by identical rectangular parallelepipeds, which might be inaccurate for modern electronics but greatly simplifies the prediction of an upset. Information on how to interpret accelerator test data are also given.

3.2.4 Testing related uncertainties

For particle beam sources, it is important to know the energy, energy spread, flux, beam size, beam uniformity and composition. For radioactive sources, Cobalt 60 is commonly used for total doge testing, while Californium 252 is used for single event effects is considered a special case. The problem lies in the poor penetration capabilities of the ions emitted. Generally, radiation testing is costly and often the energies and particles used do not correspond to space conditions. Dose rates in testing are generally different from in space, and it is known that some devices respond differently to low and high dose rates. SEU testing with protons also degrades the behavior the device tested, which modifies the component's response.

It is also critical that the device flown should be as identical as possible to the one tested. This means that both devices should, if possible, come from the same manufacturing batch.

3.2.5 Derating

Derating is the "process of designing a product such that its components operate at a significantly reduced level of stress to increase reliability." If it can be demonstrated that de-rating improves the ability of the component to withstand radiation effects, it can usefully be employed.

System de-rating can also be useful. For example, in the presence of single event transients, filtering and slowing the response of the circuit or system to analogue signals can protect the system against invalid responses to erroneous analogue signals induced by SET.

3.3 Radiation Shielding

This section provides information on radiation shielding and how to select materials to protect the spacecraft. Due to the sizing constraints imposed by our mission, system-wide radiation shielding has to be ruled out. However, for performing equipment radiation effects analysis, we would initially need the ionizing dose-depth curve, information on NIEL as a function of depth and the LET spectrum (or for protons-induced SEEs, the proton flux) as a function of shielding. Furthermore, the importance of layout is also highlighted. Generally, the sensitive components should be placed in the middle and be surrounded by less sensitive materials and components. Batteries also provide some form of shielding (presumably larger batteries). The section 5.5.2 should be further investigated by the SYE team. Methods of On-PCB shielding are also discussed. Furthermore, descriptions of physical models for modeling of different particles are given.

3.4 Total Ionizing Dose (TID)

Total ionizing dose degradation in microelectronics results from the build up of insulating layers, and has a cumulative effect on electronics, resulting in a gradual loss of performance and eventual failure. TID also affects optical components such as cover glasses and fibre optics, and passive materials such as plastics. TID is defined as the amount of energy deposited by ionization or excitation in a material per unit mass of material. In SI it is measured in gray 1 Gy=1 J/kg.

$$D = \frac{dE}{dm} \tag{1}$$

TID mainly affects MOS structures, where the trapped charge causes a shift in the gate threshold voltage. Since the trapped charge resulting from ionization is positive, n-type MOSFETs experience a reduction in threshold voltage, while p-type MOSFETs experience an increase in threshold voltage. Mobility is also degraded, which can result in extremely large leakage currents if the threshold shifts are large enough to cause inversion. Field oxide failure is an important failure mode for many commercial CMOS devices. In optical materials, long-term ionization effects appear primarily as an increase in optical absorption. In quartz crystal used for precision oscillators or filters, long-term ionization effects can produce significant resonant frequency shifts. Here, there is a strong dependence upon the type of material used, with natural quartz showing the largest frequency shift for a given ionizing dose. An overview of TID effects can be found in the list below.

- **MOS devices**: threshold voltage shift, decrease in drive current and switching speed, increase in leakage current.
- **Bipolar transistors**: hFE degradation, especially at low collector current; leakage current.
- **Junction field effects transistors (JFETs)**: enhanced source-drain leakage current.
- **Analogue microcircuits**: offset voltage, offset current and bias-current changes, gain degradation.
- **Digital microcircuits**: enhanced transistor leakage, or logic failure due to decrease

in gain (bipolar devices) or changes in threshold voltage and switching speed (CMOS).

- **CCDs**: increased dark currents, some effects on CTE, effects on MOS transistor circuits.
- **APS**: changes to MOS-based circuitry or integer, including changes in pixel amplified gain.
- **Micro-electromechanical devices (MEMS)**: gradual change in response due to build-up of chargge in any dielectric located near to the micro-electromechanichal parts, resulting in deflection of the moving part. Also, amplifiers and and digital microelectronics on the chip can be susceptible to TID.
- **Quartz resonant crystals**: frequency shifts.
- **Optical materials**: increased absorption, variations in absorption spectrum (coloration).
- **External polymeric surfaces**: mechanical degradation, changes in dielectric properties.

Components most sensitive to TID are active electronic devices such as transistors and integrated circuits. *Their sensitivity thresholds typically range from 10 Gy to 10 kGy, depending on the technologies used*. To calculate the total ionizing dose, provided that the particle intensity and spectrum does not change significantly while traveling through the material, TID can be given from the following formula:

$$D = \frac{1}{\rho}\int_{E_1}^{E_2} \psi(E)\frac{dE}{dx}(E)dE \tag{2}$$

where ρ is the mass density of the material, ψ(E) is the differential energy spectrum defined between E1 and E2, and dE/dx is the stopping power in units of energy loss per unit particle pathlength. In section 5 of this handbook, example stopping powers for electrons, protons and heavier ions in common materials are given.

3.5 Displacement Damage (DD)

Displacement damage is a cumulative radiation damage effect which results from damage to the crystalline structure of semiconductors and some optical materials by energetic particle collisions. DD is predominantly an issue for semiconductors which rely on minority carrier current flow, such as opto-electronics, bipolar devices, solar cells etc. Particles traversing crystalline materials can deposit sufficient energy in a collision with an atom to displace the atom from its lattice position creating an interstitial. The empty position left by the atom is referred as a vacancy. Interstitials and vacancies are mobile and can cluster together or react with impurities in the lattice structure, creating stable defect centers.

Displacement damage is normally expressed as either:

1. Displacement damage equivalent particle fluence (DDEF) for mono-energetic spectra
2. The non-ionizing energy loss (NIEL) dose or total non-ionizing doge (TNID)

Technologies affected by displacement damage include:

- **Bipolar devices**: increased recombination of minority carriers.
- **Charge-coupled devices (CCD)**: charge transfer efficiency (CTE) is degraded, increased dark current, increased hot spots, increased bright columns, random telegraph signals.
- **Active pixel sensors (APS)**: increased dark current, increased hot spots, random telegraph signals, decreased responsivity.
- **Photodiodes**: reduced photo current, increased dark current.
- **LASER diodes**: reduced output power, increased threshold current.
- **Light emitting diodes (LED)**: reduced output power.
- **Optocouplers**: reduced current transfer ration
- **Solar cells**: reduced cell short circuit current, reduced open circuit voltage, reduced maximum power.

Readers further interested in the physical processes and modelling should read section 7.3 of this handbook. EPS users responsible for solar panels should pay attention to this section, as degradation of solar cells will affect power performance in late mission stages.

3.6 Single Event Effects (SEEs)

3.6.1 Introduction

In section 3.1.3 we defined Single Event Effects and the different categories they might belong into. In this section we will dive more in-depth to the modelling procedures and test methods for different Single Event Effects.

3.6.2 Modelling

Three important parameters are required in order to model the SEE response of a device. These parameters are:

- **Notion of LET**: The amount of energy deposited in the track per unit pathlength is called *linear energy transfer (LET)* and for SEE analysis is typically measured in $MeVcm^2/mg$. LET is used for very small sensitive devices and high-energy particles.
- **Cross section**: Cross section is the probability of a SEE occurring and is experimentally measured as the number of events recorded per unit fluence. For ions, cross section measures the LET-dependent sensitive area of the chip.
- **Effective LET**: Effective LET can be defined for devices exhibiting sensitive volumes with a large aspect ratio (large horizontal dimensions when compared to vertical ones). Sensitive volume is often modelled as a rectangular parallelepiped from which deposited charge can be collected in such manner as to produce SEE.

3.6.3 Test methods

The goal of SEE testing is to determine the model parameters capable of predicting the space environment (cross section plot vs heavy ion LET, or proton or neutron energy). The approach is to expose an operating device to a known particle beam (LET or energy parameter) and to observe the device response *(event counting)*. The radiation environment in space widely varies in composition and energy characteristics and is largely omnidircetional. Therefore, SEE testing cannot be appropriately performed without the use of an accelerator which can be operated with a variety of particles and energies.

It is important to know that every ground-based measurement remains at best only an approximation of the space enviroment. For galactic cosmic rays, relatively low energy heavy ions are used at accelerators to predict the response to much higher energy particles. For protons testing, it cannot be done without a very high energy generator. Some example testing procedures for Single Event Effects can be found below.

For Single Event Upsets (SEU): The part is exposed to the beam and a test system operates the component in order to check for the integrity of the stored information. Several test patterns are run to measure the sensitivity for both bit flip polarities (0 to 1 or 1 to 0 transitions). Thetesting can be performed while the device is exercised in static or dynamic mode. A 'low' bias level is the worst case for SEU response (lower critical charge and therefore LET threshold).

For Single Event Transient (SET) and Single Event Disturb (SED): The device is electrically and functionally exercised while being irradiated. Its output is monitored and compared to a reference response. SET/SED events are counted and registered. The SET/SED response is very dependent on electrical test conditions (e.g. power supply, charge, frequency) and it is therefore important to use existing data with care. If convenient, SET and SED can be split in several categories depending on their impact at system level.

If a technology from the figure below is used on a spacecraft, testing and precautionary actions must be taken into account during the entire mission planning.

Component type	Technology	Family	Function	SEL	SESB	SEGR	SEB	SEU	MCU/SMU	SEDR	SEHE	SEFI	SET	SED
Transistors	Power MOS					X	X							
ICs	CMOS or BiCMOS or SOI	Digital	SRAM	X*				X	X		X			
			DRAM/ SDRAM	X*	X			X	X		X	X		
			FPGA	X*				X		X		X		X
			EEPROM/ Flash EEPROM	X*						X		X		X
			µP/ µcontroller	X				X			X	X		X
		Mixed	ADC	X*				X				X	X	X
		Signal	DAC	X*				X				X	X	X
		Linear		X*						X			X	
	Bipolar	Digital						X					X	
		Linear						X					X	
Opto-electronics			Opto-couplers										X	
			CCD										X	
			APS (CMOS)	X								X	X	

*except SOI

Figure 1: Technologies affected by SEEs

3.6.4 Hardness Assurance

The method used to analyse the need for SEE risk reduction depends on the possibility of calculating a SEE rate. When SEE error rate calculations are possible, they are obtained by combining the experimental sensitivity curve with the appropriate environment parameters. In orbit predictions can be made using simulation software. CREME is most commonly used to evaluate upset rates. SPACERAD, OMERE AND SPENVIS are also widely used. OMERE and SPENVIS include the ISO standard for cosmic ray environment. A final analysis at a system level can be performed to check for SETs or SEDs, for which it is very hard to find applicable experimental data. A standard perturbation signal in the final electrical design is petrubated in order to study its influence at a system level.

4 Space electronics: Challenges and solutions

4.1 Introduction

The following information originate from a presentation titled Space electronics: Challenges and solutions, which was given by Professor Alkis Hatzopoulos. Professor Hatzopoulos is the director of the electronics lab at the department of Electrical and Computer Engineering at the Aristotle University of Thessaloniki. Some topics which are mentioned in this presentation have already been covered by ECSS Handbook ECSS-E-HB-10-12-A – Calculation of radiation and its effects and margin policy and therefore will not be further analyzed below. *Furthermore, this presentation also analyzes how electronics behave in cold and hot environments. While this topic is of high importance, it does not fall within the scope of this report and interested users tasked with the Thermal analysis should investigate on their own.*

4.2 Space Radiation Environment

We can identify three main sources of radiation in space, namely:

1. **Galactic cosmic rays**: protons and heavy ions.
2. **Solar energetic particles**: protons, heavy ions, electrons.
3. **Van Allen belts**: electrons, protons, heavy ions.

Concerning the Van Allen belts, which have been studied by the Van Allen Probes mission of NASA, we can conclude that:

- for trapped electrons, there is a maximum energy in the range of 10s of MeV.
- for trapped protons and heavy ions, there is a maximum energy in the range of 100s of MeV.

However, this is only a rough approximation. Energies of particles heavily depend on the geometry of the orbit and therefore it is crucial to further analyze the space radiation environment using simulation software. For Low Earth Orbits (LEO), the main area of concern is the South Atlantic Anomaly (SAA).

4.3 Case Study: Clementine failure

Clementine was a spacecraft which was launched on January 25, 1994, in order to qualify component technologies and make scientific observations of the Moon and a near-Earth asteroid. Clementine was placed in a polar orbit around the moon, with a periselene of 2162 km and an aposelene of 4594 km.

On May 7, 1994, its main on-board computer sent out an unintentional command that caused one of the attitude control thrusters to fire, before the computer crashed. By the time the ground control had rebooted the computer the attitude control fuel tanks were empty, and the spacecraft was spinning very fast. This made it impossible to continue the mission. *This failure was caused by a single event upset.*

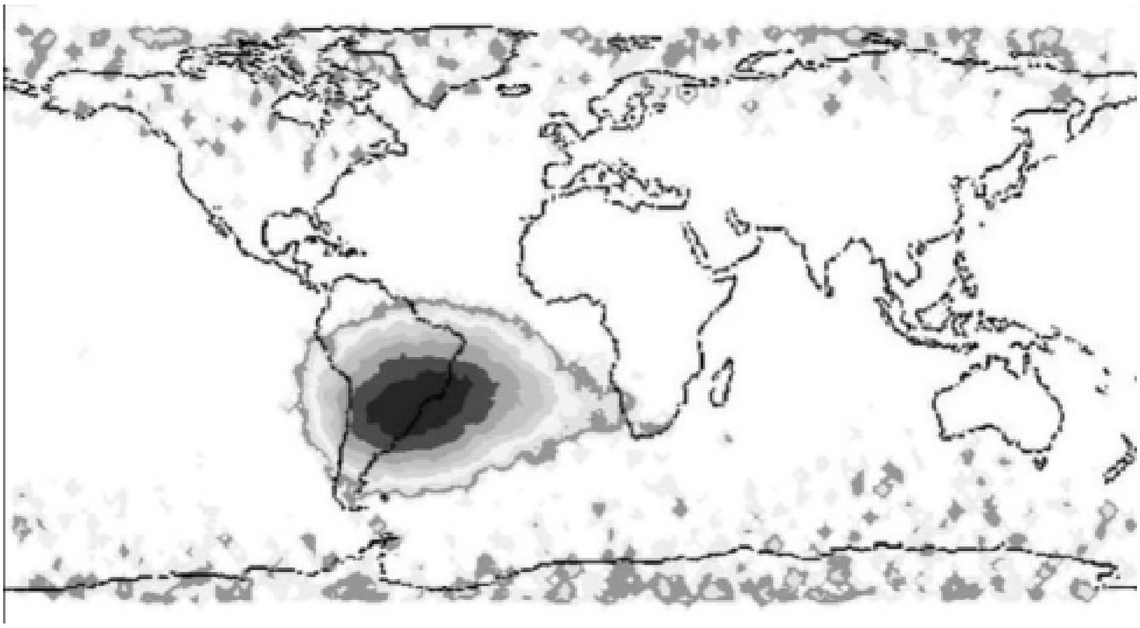

Figure 2: Mapping of SEU density (memory upsets). South Atlantic Anomaly can be easily identified.

4.4 Case study: Hitomi failure

NOTE: *This case study was not included in the presentation, but it is an interesting example worth mentioning.*

Hitomi was a spacecraft which was launched on February 17, 2016, in order to further investigate the hard X-Ray band above 10 keV. Hitomi was placed at an inclination of 31.01 degrees around the earth, with a perigee of 559.85 km and an apogee of 581.10 km, **an orbit which classifies as a Low Earth Orbit.**

On March 27, 2016, the U.S. Joint Space Operations Center announced that it had observed a breakup of the satellite into 5 pieces and that its orbit also suddenly changed. There has been no evidence that the spacecraft has been struck by space debris. The chain of events that led to the spacecraft's loss began with the ADCS system reporting a non existence rotation of 21.7 degrees, which the system attempted to counteract using the on-board reaction wheels. With no sign of the rotation disappearing, the system then tried to use the thrusters to counteract the rotation. *While it has not been proven as a fact*, JAXA's investigators conclude that the chain of events which led to the loss of the spacecraft most likely have been caused by a single event upset.

4.5 Radiation Countermeasures

- If possible, an orbit with a reduced level of radiation shall be chosen.
- Choose radiation hardened components (rad-hard), which are produced with special manufacturing processes of the electronics.
- Use shielding to lower the radiation dose level (e.g. Al, Cu, Tantalum, Tungsten). This solution will not protect against high energy particles

- Use system level error corrections, which might include error detection and correction of memory, triple redundancy and triple voting and watchdog timers.
- Turn off supply voltage before entering a part of the orbit where high radiation is expected, like the South Atlantic Anomaly.

4.6 Technology Trends

Technology trends have different effects on the magnitude of Single Event Effects (SEEs). The miniaturization of electronics and the scale down of the gate oxide thickness decreases the TID effects, while SEU increases with scaling. Miniaturization of spacecraft also reduces the shielding from the spacecraft structure.

In addition, as circuit speeds increase, SETs become SEUs, which result in SETs becoming more critical. While the number of complex circuits and devices on a spacecraft increases, there is also an increase on possible failure modes.

The use of COTS components also imposes some risks. COTS components are generally much more sensitive to radiation and component testing becomes crucial in order to prove the functionality of the spacecraft.

4.7 Redundancy

Redundancy remains a hot topic in space systems design. Ultimately, the decision to use or not use redundant elements must be taken by the project management or systems engineering team. An in-depth trade-off analysis must be made before final design decisions are made.

4.7.1 System level

At a system level, three or even five separate microprocessor boards may be used in order to independently compute an answer to a calculation and compare their answers. Any microprocessor system which produces a minority result will recalculate. Logic may be added, such that if repeated errors occur from the same system, that board is shut down. System level voting between processor systems generally needs to use some circuit-level voting logic to perform votes between the three processor systems. This can be done using Fault-tolerant FPGA-based design. **This alternative works equally well with rad-hard components and it it cheaper, but it complicates the design and uses much more space.**

4.7.2 Circuit level

A single bit may be replaced with three bits and separate voting logic for each bit to continuously determine its result. This increases the area of a chip design by a factor of 5, so it is not practical for smaller designs. It has the secondary advantage of also being a "fail-safe" in real time. In the event of a single bit failure, the voting logic will continue to produce the correct result without resorting to a watchdog timer.

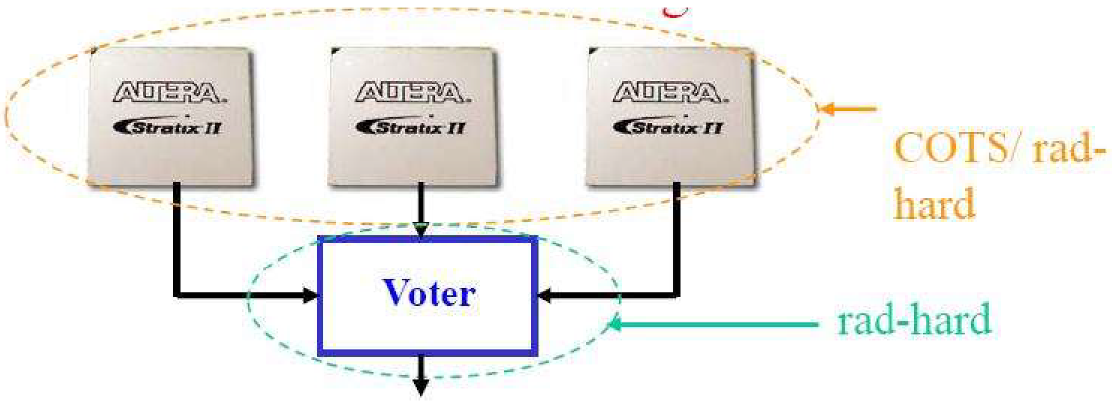

Figure 3: Voting system using FPGAs

4.8 Re-configurable Computing

RC technology allows new hardware circuits to be uploaded via a radio link. This is important, because if a part of an FPGA fails, the circuitry can be reprogrammed to make use of the remaining functional portions of the chips.

There are some potential problems with this approach. Ionizing radiation causes soft-errors in the static RAM cells used to hold programming information in FPGAs. Longer-term ionizing radiation causes hard errors in the electronic circuitry. In addition, radio links to spacecraft are often low bandwidth and high error rate. This is not suitable to the relatively large configuration files of order of 1 Mbit required for modern FPGAs. Some short and long term solutions are further analyzed. Interested readers should refer to the presentation.

5 AcubeSAT's radiation environment

5.1 Introduction

This section is based on document AcubeSAT-TRA-EH-010 Preliminary Radiation Environment Report. In that document, the OMERE simulation software is used in order to simulate the International Space Station orbit for different altitudes which AcubeSAT will pass throughout its mission (400, 380, 350, 300, 250, 200, 150 km), The goal of that report was to give an initial approximation on the flux of trapped electrons and protons, the flux of solar particles and the total ionizing dose (TID). The trapped particle models and the solar particle fluences that were used for the simulations are in compliance with ECSS Standard ECSS-E-ST-10-04C.

5.2 Trapped particles

The following simulations were performed for a specific values of energy. OMERE allows the user to select the desired value of energy and therefore further simulations that are based on theoretical research for specific areas of the energy spectrum will be needed. Below you can find the simulations for the altitude of 380 km, which will be the altitude where our satellite will spend the majority of its orbital lifetime. The South Atlantic Anomaly can be easily identified in both cases, which remains a problem for orbits with inclinations over 15 degrees.

5.2.1 Trapped electrons

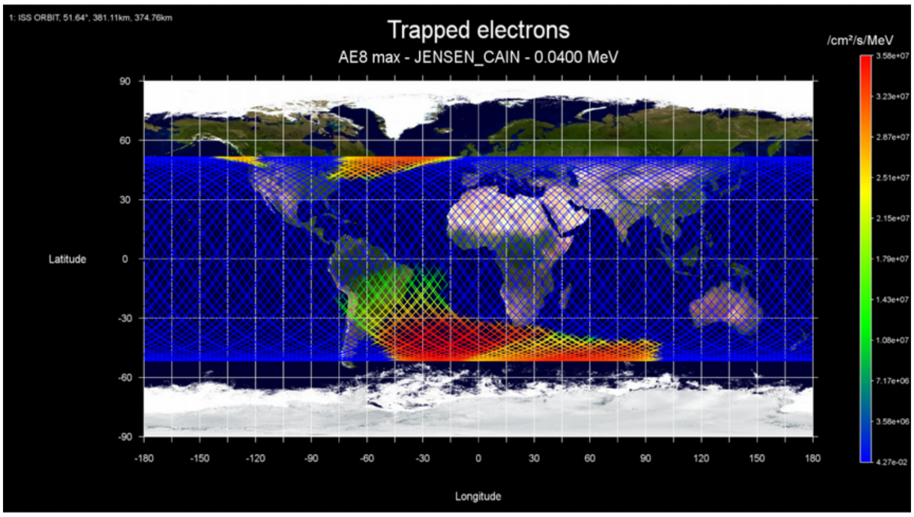

Figure 4: Energy spectrum of trapped electrons with 0.04 MeV (380 km)

5.2.2 Trapped protons

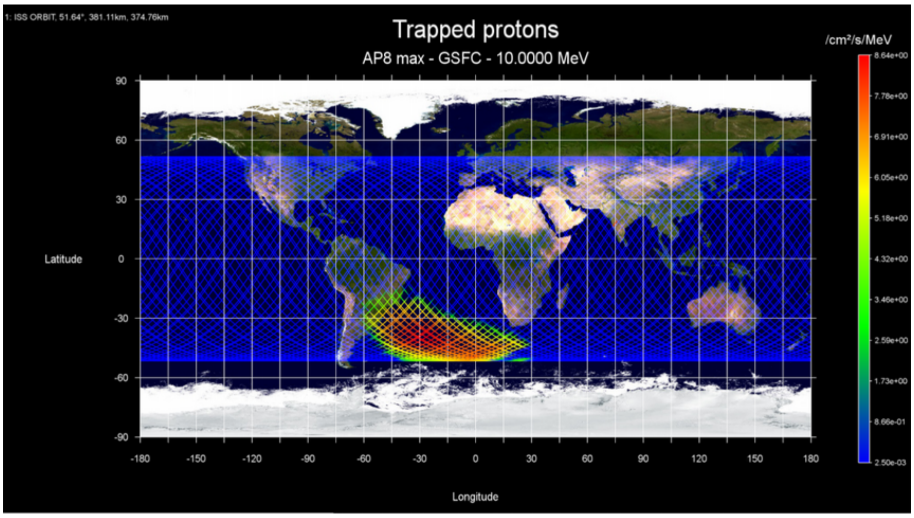

Figure 5: Energy spectrum of trapped protons with 10 MeV (380 km)

5.3 Solar particles

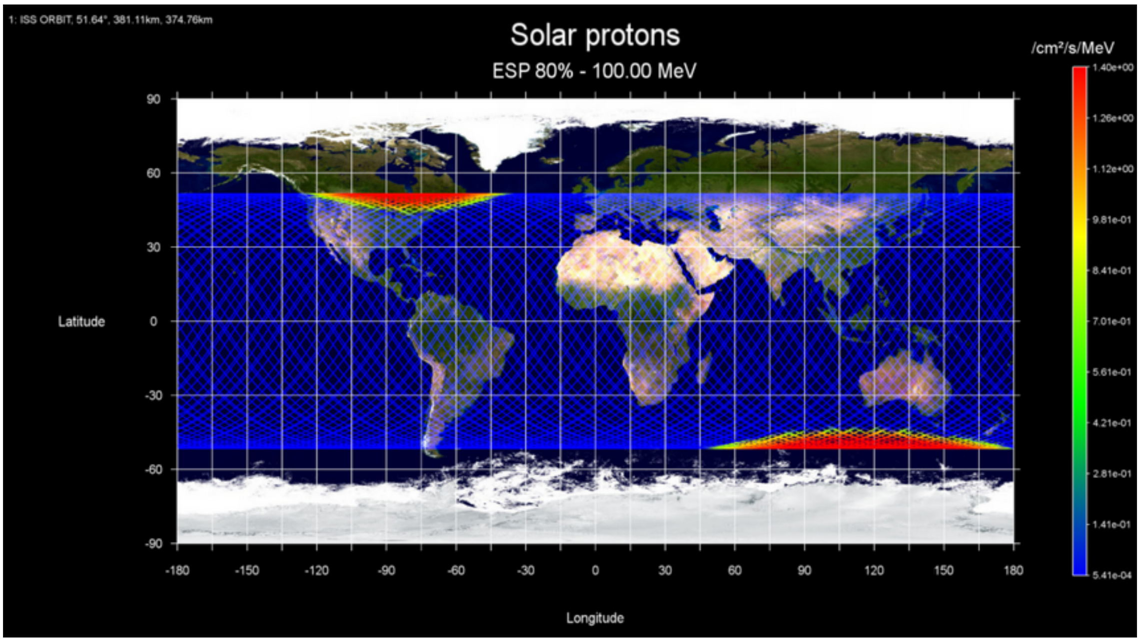

Figure 6: Energy spectrum of solar particles with 100 MeV assuming a stormy magnetospheric cutoff (380 km)

5.4 Total Ionizing Dose (TID)

Reminder: *1 Gy= 100 rad*

Regarding the Total Ionizing Dose, an Aluminum slab was used in order to simulate a component. Further investigation is required and we can use the actual components in order to perform accurate simulations which will translate into useful results.

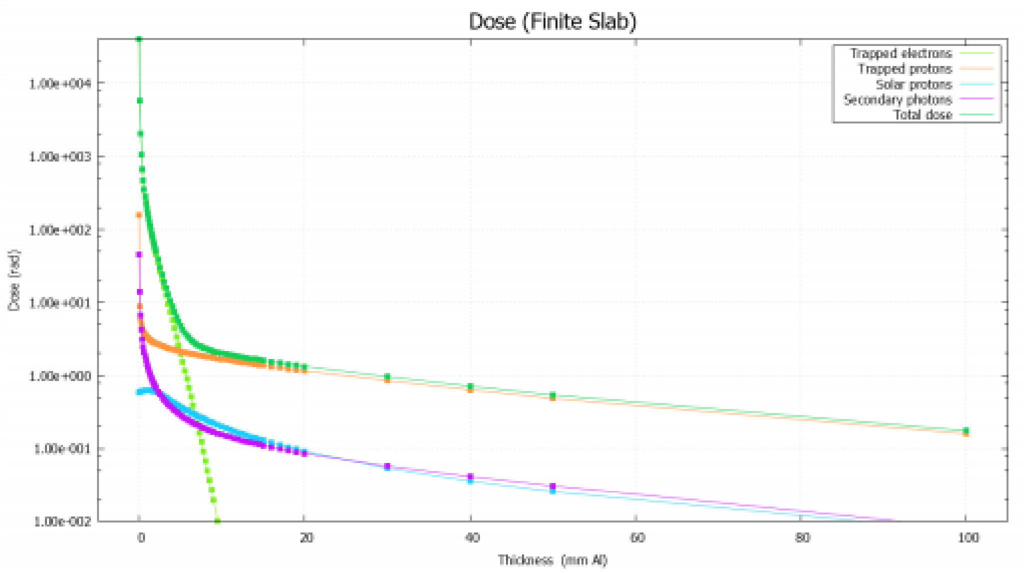

Figure 7: Total dose relative to the thickness of a finite Aluminum slab (380 km)

We can now assume a typical 3.705 mm average thickness to study the total dose along the orbit, as shown in the Figure below.

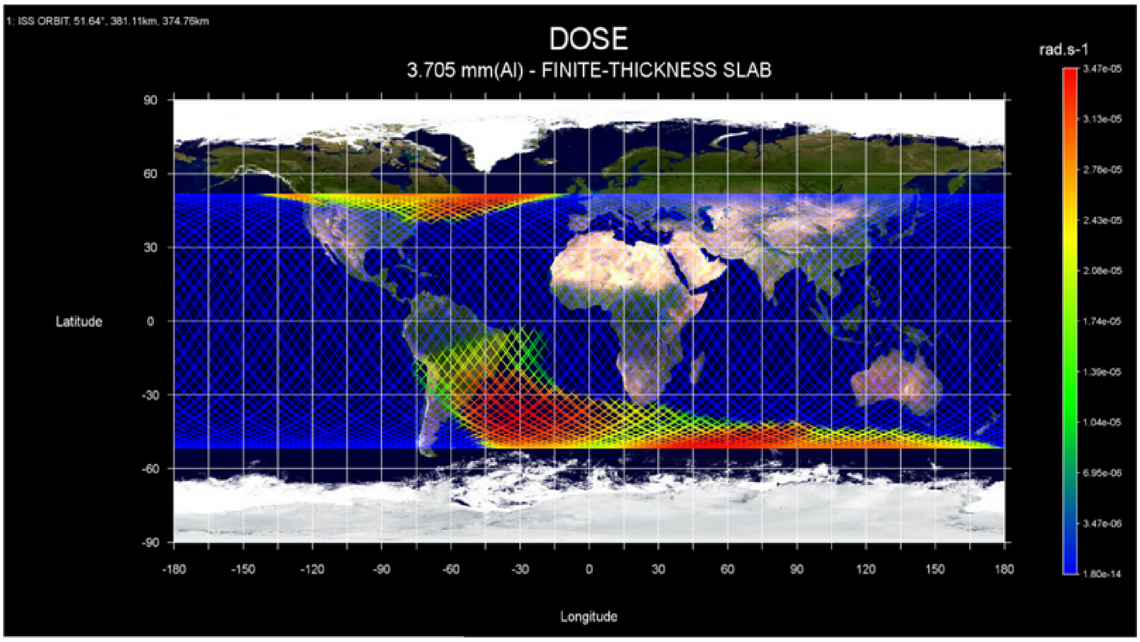

Figure 8: Total dose of an Aluminum finite slab with 3.705 mm thickness (380 km)

6 Discussion/SYE recommendations

Disclaimer: *This section provides an analysis based on my personal understanding of the subject, which has been developed during the past few months. Several inputs have been taken into account and have influenced this section, including: a) my participation in ESA Academy's CCEW 2019, b) related ECSS standards and handbooks, c) design of other CubeSat missions, d) meetings with members of Libre Space Foundation and UPSat developers and e) internal discussions with members of OBDH.*

6.1 For AcubeSAT

1. EPS should take active measures to prevent the circuitry boards from radiation, such as using Tantalum capacitors.
2. Critical components must be identified. Supply voltage to these components should be turned off when passing through the South Atlantic Anomaly. This solution will use the GPS sensor to be used by ADCS to determine if the CubeSat is inside the SAA.
3. OBC should prepare a detailed report on the methods used to protect the satellite from radiation. The SYE engineering team will assist in this effort.
4. Initial testing for components can start since design has been finalized for some parts (components to be used have been chosen). Initially, Trajectory members will perform simulations in SPENVIS and OMERE for the components.
5. Contacts must be made with professors from the physics department in order to see the capabilities of in-house testing within AUTh. If these talks hit a dead end, contacts with other Greek Institutions shall be made.
6. Testing procedures mainly concerning for SEEs in micro-controller units should be established after the computer simulations have been finished. This task has to be assigned to OBC and SYE subteam members.
7. The camera solution to be used by the science unit in order to observe the cells must be selected. Technologies which will be used for this must be radiation tolerant, in order to not compromise the mission integrity. SU team members should refer to this document to find out more about the impact of radiation on imaging sensors. If possible, the camera shall also be tested both in computer software and in an accelerator.
8. Further research in the fields of Space Environment and testing procedures is required. The SYE team should read the relevant Space Environment standard and the calculation of radiation and its effects and margin policy standard, which accompanies ECSS-E-HB-10-12-A.

6.2 For future missions

The high cost of radiation hardened components remains a major problem in efforts to shield space systems from the harsh radiation environment. According to a Prisma Electronics representative, a rad-hard FPGA module they have used costs 25000€ while the COTS version of the same module costs 2500€. This has a major impact, especially for low cost mission.

Concerning orbit geometry, for Low Earth Orbit missions, areas like the South Atlantic Anomaly and the Van Allen radiation belts in general must be avoided if possible in order to minimize the effects of radiation on the system. However, given that most launch opportunities which provide low cost access to space dictate either an ISS orbit with an inclination of 51.6 deg or a polar orbit, secondary measures must be taken in order to protect the spacecraft from radiation.

Solutions like triple voting system provide interesting alternatives to radiation hardened components. The total costs comes at a significantly lower price, since only the voter which could be a simple logic gate is radiation hardened. Future team members are encouraged to research these kind of techniques and implement them in a future CubeSat.

7 Conclusions

We have investigated all effects caused by radiation in electrical and electronic systems using a variety of sources as guidelines. Methods to protect space systems from radiation have also been analyzed, while testing methodologies have been briefly mentioned. Members from ADCS, COMMS, OBC, EPS, SU are encouraged to discuss any concerns and ideas with the systems engineering team in order to further advance the radiation tolerance of our CubeSat system design.

Figure 9: A high energy meme

...if it's not fun, why bother?

Reggie Fils-Aimé