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Novel Radiation Design Approach for CubeSat Based Missions

Justin J. Likar
Lockheed Martin Space Systems
100 Campus Drive Newtown PA 18940; 215-497-2614
justin.j.likar@lmco.com

Stephen E. Stone
Lockheed Martin Space Systems
100 Campus Drive Newtown PA 18940; 215-497-2112
stephen.stone@lmco.com

Robert E. Lombardi
Lockheed Martin Space Systems
100 Campus Drive Newtown PA 18940; 215-497-2918
robert.e.lombardi@lmco.com

Kelly A. Long
Lockheed Martin Information and Global Services Enterprise Integration Group
Philadelphia PA 19101; 610-531-5910
kelly.long@lmco.com

ABSTRACT

Spacecraft design innovations enabled by nanosatellite, and CubeSat-based, missions often requires a greater-than-desirable amount of risk associated with space radiation design. The accelerating rate of technology advancement in this smaller form factor introduces more advanced / sensitive payloads wherefore a novel approach to radiation environment modeling and design is required in order to minimize risk associated with the development and deployment of advanced / strategic payloads. The space radiation dose to which spacecraft at Low Earth Orbit altitudes (for CubeSats typically 400 km to 800 km) are subjected is dominated by contributions from geomagnetically trapped protons (typical energy range 0.1 MeV to >100 MeV) and electrons (typical energy range 0.1 MeV to 6.0 MeV). The present paper describes a radiation design approach based upon commonly available design tools as well as proposes a novel mission concept, sufficiently executable via a low power 1U vehicle, for purposes of characterizing the anisotropic total radiation dose at Low Earth Orbit altitudes. Analyses and discussions summarized herein demonstrate the importance of focusing on accurate determination of the radiation environment in the presence of spacecraft structure.

INTRODUCTION

The evolutionary spacecraft design paradigm enabled by CubeSat-based, and derivative / similar, missions often assumes a greater-than-desirable amount of risk associated with many design elements, including space radiation effects. The current small satellite marketplace includes a diverse set of universities, legacy space industry stalwarts, next generation space industry companies, small business, space agencies, and government / military entities, bringing similarly broad ranging radiation design practices thereby demonstrating a lack of one-size-fits-all solution. It should certainly be recognized that the variety of customers and / or funding sources can be anticipated to have different expectations from a radiation design standpoint. Further, with the accelerating rate of innovation and technology development leading to more advanced payloads a novel approach to radiation environment modeling and design may be required in order to minimize risk associated with the development and deployment of advanced / strategic payloads.

Recent funding opportunities from US government agencies have sought spacecraft mission lifetimes of 1 yr, with desired lifetimes of 2 yr, and potentially longer "design" lifetimes. Such requirements necessitate the need for a more robust radiation effects design process.

The natural space radiation environment threat to which spacecraft at LEO altitudes (for CubeSats typically 400 km to 800 km) are subjected includes contributions from geomagnetically trapped protons (typical energy range 0.1 MeV to >100 MeV) and electrons (typical energy range 0.1 MeV to 6.0 MeV); other lower level contributions can be expected from particles generated by solar flares, coronal mass ejections, and galactic cosmic rays. It is realistic to baseline a total accumulated ionizing dose of 1-10 kRad/yr for well shielded applications (100 mil or 2.54 mm) [1] however given the design challenges associated with CubeSat based systems and priorities for low mass mechanically optimized systems it is typical that minimal attention is paid to optimizing the effective radiation shielding design.

Table 1. Trade study orbital elements.

Parameter	Value
Semimajor Axis	7051 km
Apogee	680 km
Perigee	680 km
Eccentricity	0 deg
Inclination	98 deg
Argument of Perigee	0 deg
RAAN	0 deg
True Anomaly	0 deg
Period	98.2 min
Mission Lifetime 1	1 April 2008 – 1 April 2009
Mission Lifetime 2	1 April 2010 – 1 April 2011
Mission Lifetime 3	1 April 2013 – 1 April 2014

Ultimate verification of modeling and analysis method utility is achievable with a CubeSat based mission. The paper summarizes a simple mission concept designed to measure *in situ* total ionizing dose levels within a CubeSat spacecraft structure; such a mission would thereby capture documented anisotropic effects as well as enveloping realistic (rather than idealistic) radiation shielding levels and materials. The proposed mission concept leverages publically available software and models and forgoes the need for highly advanced or dedicated sensors by implementing sensors which incorporate well-characterized radiation sensitive microelectronics such as LM139 or LM93 bipolar comparators, LM124 bipolar amplifier or similar (as well as their low dose rate sensitivity immune counterparts) [2].

In lieu of a standardized, and likely conservative, space radiation design approach for CubeSat missions, the present paper provides a overview of a robust and verifiable design approach using industry standard tools and methods including a technically valuable novel mission design concept readily achievable by an academic institution.

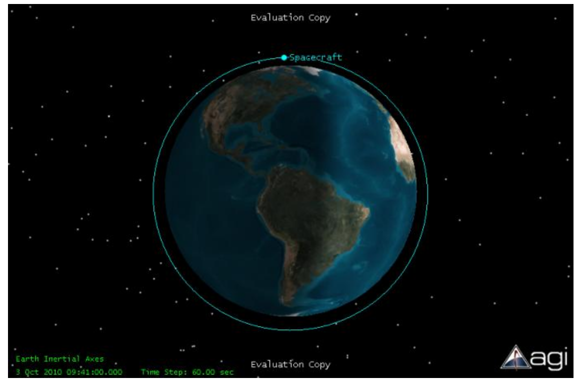

Figure 1. Representative orbit (described in Table 1); generated with STK Version 9.0.

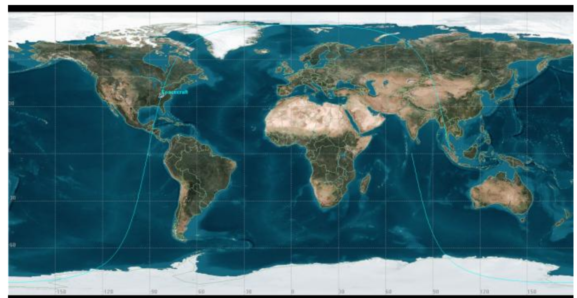

Figure 2. Ground trace of representative orbit (described in Table 1); generated with STK Version 9.0.

DESCRIPTION OF ANALYTICAL TOOLS

STK SEET

Recently AGI Satellite Tool Kit (STK) has incorporated a comprehensive space and atmospheric environment and interactions module. The Space Environment and Effects Tool (SEET), developed by Atmospheric and Environment Research, Inc. (AER), enables modeling of the space environment along with capability to predict relevant effects on space vehicle performance. SEET includes the following (sub) modules, several of which have been adapted / incorporated directly from the AFRL AF-GEOSpace V. 2.1P software suite:

1. Radiation Environment.
2. Particle Impacts.
3. Vehicle Temperature.
4. Magnetic Field.

Although all above modules and effects directly apply to the design and operation of CubeSats (and of course all spacecraft) only a comprehensive discussion of the *Radiation Environment* module is provided herein.

The *SEET Radiation Environment* module enables computation of radiation dose rate and accumulated total ionizing dose as a result of exposure to relativistic electrons and protons for default or user-defined shielding thicknesses. In doing so it also allows for computation of trapped electron / proton fluencies for a range of incident energies. The module incorporates a number of modules from the *AF-GEOSpace* software suite.

The *Radiation Environment* module is exercised via selection of one of five available computational modes. At a higher level the computational modes can be arranged as summarized here under.

Received Dose

1. Computations directly leveraging on-orbit / empirical observations. Several computational modes, namely *Radiation Only*, *APEXRAD*, and *CRRESRAD* compute dose rates and integrated doses based on data measured by the APEX Space Radiation Dosimeter and the CRRES Space Radiation Dosimeter, both of which include predetermined shielding thicknesses.

    a. *CRRESRAD*: 82.5 mil, 232.5 mil, 457.5 mil, and 886.5 mil.
    b. *APEX*: 4.29 mil, 82.5 mil, 232.5 mil, and 457.5 mil.

    Selection of the *Radiation Only* mode yields only APEX+CRRES results for default shielding thicknesses offered by both instruments.
2. Higher fidelity environment and radiation transport calculations can be performed via the CRRES (PRO and ELE) and NASA (AP8 and AE8) computation modes. Trapped electron / proton fluencies or fluxes can be determined for given orbit parameters using industry standard CRRES or NASA models [3]. Some limitations are placed on results, however, as only the particle energies supported by the models are included in the results.

    Added utility is available, however, as both modules also enable radiation transport "dose-depth" determinations via *SHIELDOSE-2* methods. The *SHIELDOSE-2* ray-tracing method is well documented within the space radiation effects community and affords determination of total ionizing dose at up to 70 user defined equivalent shielding depths. Common equivalent aluminum shielding geometries of finite slab, semi-infinite slab, and solid sphere are offered with a range of selectable detector / material types as well as nuclear attenuation options.

SPACE RADIATION

Space Radiation Version 1.0 for MS-DOS was released 20 yr ago; the software is a tool that is widely utilized in the space radiation effects community. *Space Radiation* models the ionizing radiation environment in space and the atmosphere including trapped protons and electrons, solar protons, galactic cosmic radiation, and neutrons.

Version 5.0, utilized herein, includes present state of the art in U.S. AE8 and AP8 trapped particle models as well as a number of commonly used solar flare models.

The environments may be integrated along any orbit or trajectory. Radiation effects include single-event upsets, total ionizing dose, solar cell damage, and single-event latchup. Similar to *SEET* dose-depth calculations are performed using *SHIELDOSE* methods.

NOVICE

Developed approximately 30 yr ago, the *NOVICE* radiation transport code is used primary by government and aerospace organizations for purposes of radiation transport analyses / predictions for space systems [4-5]. *NOVICE* capabilities include three dimensional modeling, "straight ahead" ray-tracing / sectoring for rapid engineering design and Adjoint (reverse) Monte Carlo radiation transport for design verification. The software was developed for applications including total ionizing dose, non-ionizing dose, and determining upset levels in space systems exposed to trapped radiation belts, solar flares, galactic cosmic rays, and onboard nuclear power systems.

CASE STUDIES

Typical CubeSat Orbit

General trapped particle flux and dose-depth calculations were performed using the analytical / software methods summarized in previous sections for the typical common CubeSat reference orbit shown in Table 1.

Hermes

With cooperation from the University of Colorado, Boulder (Boulder, CO) and the Colorado Space Grant Consortium (COSGC) radiation transport modeling and total ionizing dose calculations were performed using a typical CubeSat design as represented by the Hermes spacecraft [6, 7]. Fig. 3 depicts the Hermes spacecraft expanded engineering model. Mission objectives include [6]:

1. Create modular and extensible subsystems.
2. Utilize S-band frequency to communicate at data rates higher than those obtainable with Ultra-High Frequencies (UHF).
3. Characterize orbital environment and satellite status to validate models and design.

The spacecraft is a typical 1U CubeSat with a mass of ~1 kg. The Hermes spacecraft, and project in general, offers a wonderful representation of a “traditional” or “heritage” CubeSat program in that it is primarily student led, COTS-based, modular, with reliability and risk goals appropriate for ≥1 yr mission lifetime and a budget on the order of $10,000.

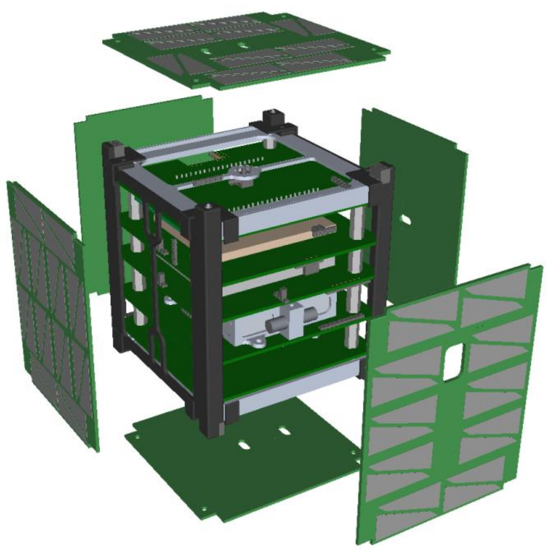

Figure 3. HERMES CubeSat, SolidWorks model.

ANALYSIS RESULTS

Two types of space radiation / radiation transport analyses were performed. Analyses vary in their level of detail.

1. Generation of general dose-depth curves based on industry standard AE8 / AP8 trapped radiation models, general target geometry, kernel, and ray-tracing methods.
   a. Comparisons are presented for STK based *SEET*, commonly available to universities, at least in the U.S., with *SPENVIS*, an online software sponsored by ESA and Belgian Federal Science Policy Office, and *Space Radiation*, a commercially available software program commonly used in the U.S.
2. Detailed ray-tracing and / or Monte Carlo radiation transport and total ionizing dose calculations within actual spacecraft structure. Calculations include all spacecraft structural details captured in mechanical models as well as material definitions and densities.

STK SEET

Radiation Only, *APEXRAD*, and *CRRESSRAD* simulations were performed for the three mission lifetimes identified in Table 1. These modules do not return particle fluxes but rather compute combined total ionizing dose. All simulations included an STK step size of 60 s and implemented the *Fast-IGRF* model for the International Geomagnetic Reference Field; *Fast-IGRF* offers optimized computational speed with accuracy within 1% (non-author verified but rather per STK *SEET* user manual). *SEET* default / recommended IRGF update rate of 1 d was used.

Fig. 4 summarizes such results, along with NASA AP8 / AE8 results described hereunder.

SEET *NASA*, *NASAELE* (AE8), and *NASAPRO* (AP8) modules provide higher accuracy, and more computationally intensive, results as they compute particle flux at each orbital step / element via AE8 / AP8 and then inputs results directly into *SHIELDOSE-2* to determine the absorbed total dose of a detector as a function of depth. Results shown in Fig. 4 include *NASA* module results performed for 1 mo mission duration extrapolated to units of Rad(Si)/yr; calculations assumed spherical kernel.

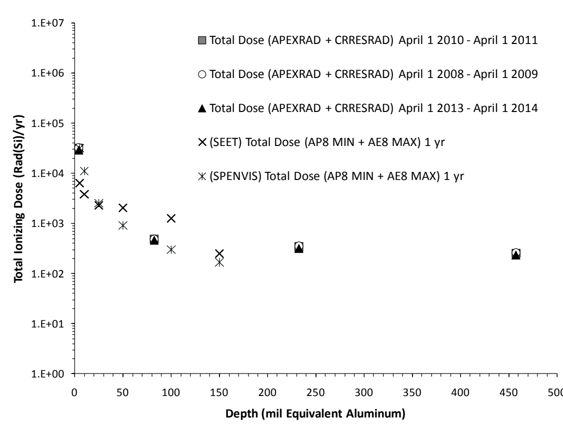

Figure 4. Total Ionizing Dose (TID) as computed by various SEET modules; TID includes contributions from only trapped particles and bremsstrahlung.

Agreement between the two *SEET* modules appears relatively good with the exception of the smallest effective shielding depths (<25 mil) where the computed trapped radiation dose (per 1 yr mission) differs by ~5×.

Given their fast computation time the *SEET NASA* simulation results are in adequate agreement (within 2-5×) with those general calculations presented in [1] at depths of ~100 mil and ~200 mil equivalent aluminum.

Space Radiation

Similar calculations were performed using *Space Radiation Version 5.00.02* available from Space Radiation Associates. Orbital parameters summarized in Table 1 were used along with a step size of 100 points/orbit.

AE8 electron and AP8 proton trapped particle fluxes were generated for a variety of conditions including MAX, MIN, and peak flux. Fluxes were determined for a mission duration of 1 yr with IGRF / DGRF (International Geomagnetic Reference Fields / Definitive Geomagnetic Reference Fields) default conditions utilized throughout.

As shown in Fig. 5, TID dose-depth curves were generated for a variety of geomagnetic activity levels via *SHIELDOSE*. Fig. 5 illustrates the influence on deposited dose due to fluctuations in geomagnetic activity levels as well as the elevated peak-flux levels associated with passages through the polar regions for electrons and the South Atlantic Anomaly (SAA) for protons.

Comparisons of *Space Radiation* dose-depth curve results with the dose values calculated via *SEET* methods is presented in Fig. 6. In all analyses, the environment considered included AE8 MAX and AP8 MIN which, as shown in Fig. 5, represents the most conservative time-averaged conditions for the 1 yr mission lifetime.

It is immediately observed that dose-depth values determined using *Space Radiation* software are significantly higher (8-10× for depths <200 mil) than those determined via *SEET* methods and *SPENVIS* (see next section). Reasons for the higher values are not immediately known but can likely be attributed to selection of IGRF model and the default shielding kernel assumed by *Space Radiation*.

SPENVIS

Also shown in Fig. 6 are dose-depth results generated via the online Space Environment Information System (*SPENVIS*). *SPENVIS* [8] is an online project funded by the European Space Agency (ESA) with contributions from a number of universities, laboratories, agencies, et cetera with a strong history of space radiation environmental effects expertise including Qinetiq, AFRL, NSSDC, BIRA-IASB, NASA, JPL, NIST, NRL, and many more.

Equivalent dose-depth calculations were performed using *SPENVIS* along with identical mission parameters for a 1 yr mission, analyzed with 20 representative orbits (default maximum), and an aluminum spherical geometry. Default magnetic field models, Jensen and Cain (1962), were used. Certainly, the *SPENVIS* results are in very good agreement with *Space Radiation* results.

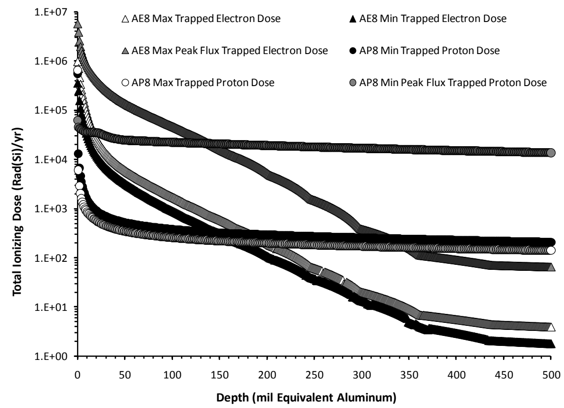

Figure 5. Total Ionizing Dose (TID) dose-depth curve for typical AP8 and AE8 trapped radiation environments for candidate orbit. Data for 1 yr mission.

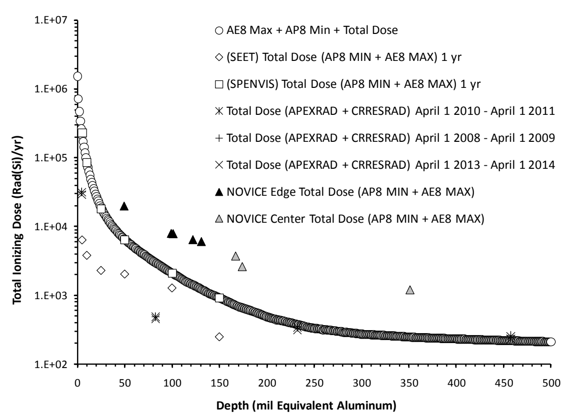

Figure 6. Total Ionizing Dose (TID) dose-depth curve for typical AP8 and AE8 trapped radiation environments for candidate orbit; depths relevant for CubeSat missions are plotted. Data for 1 yr mission. NOVICE total dose data points are described in the following section.

Summary of STK SEET, Space Radiation, and SPENVIS Results

General results upon comparison of quick-look trade studies for a typical CubeSat orbit using three readily available software packages are somewhat non-definitive. Predictions of TID level vary by 8-10× for moderate depth of 100 mil (0.6 kRad to 2 kRad) but seem to converge at increasing thicknesses. Although scientifically unsettling, the ultimate design significance of the higher variance at small shielding depth thicknesses (<50 mil) may be small as the following sections demonstrate that most radiation sensitive components are likely located at effective shielding depths of 100 mil or more. Such values envelope the general results presented by [1] but omit the presence of actual spacecraft geometries and materials. The importance of determining the radiation dose internal to the spacecraft considering actual vehicle materials and mechanical geometries is illustrated in the following paragraphs.

NOVICE

As described in the earlier paragraphs, the *NOVICE* radiation transport software permits the importing of detailed spacecraft mechanical design aspects, thereby permitting a much more realistic prediction of the dose at specific locations within the spacecraft.

Shown in Fig. 7, a complete 3-D *Solidworks* (CAD) engineering / mechanical model of the Hermes CubeSat was fully translated to generate a 3-D *NOVICE* model from using CADlook conversion software.

Such analysis methods allow for inclusion of specific design features that can be expected to influence the dose at microelectronic devices internal to the spacecraft:

1. No aluminum (or other high-atomic-number metallic) walls are present. The spacecraft exterior chassis walls are common PC board; nominally 60 mil with internal copper ground plane(s).
2. There is a good bit of effective structural shielding apparent in the aluminum spacers, brackets, standoffs, and rails in the structural frame.
3. There are a few small holes, likely for venting purposes, in the PC boards; such holes may contribute to appreciably higher doses at specific locations.
4. Locations of the 5 internal boards allow for a detailed distribution of dose points – specific X, Y, Z locations where TID was calculated.

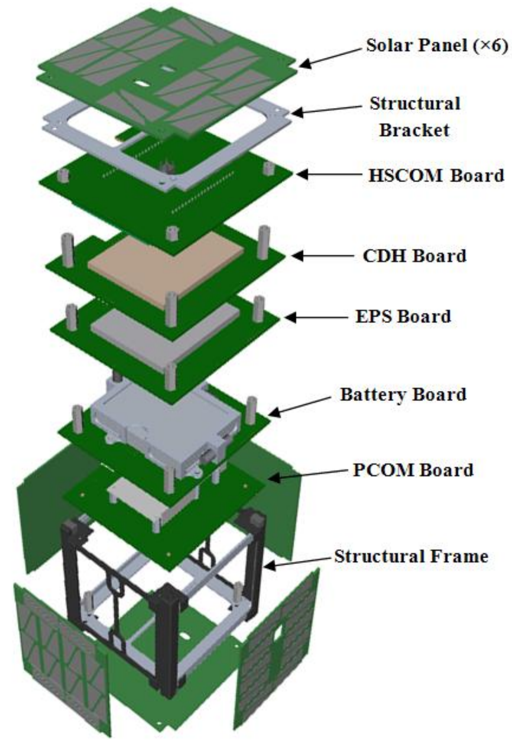

Figure 7. Hermes CubeSat engineering model; expanded view prior to conversion into radiation transport 3D model.

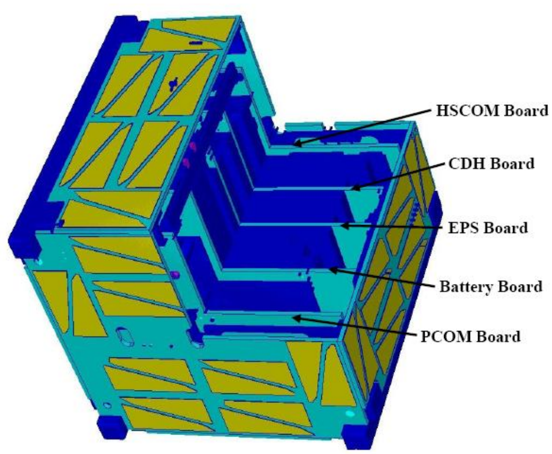

Figure 8. Hermes CubeSat engineering model (cutaway view) as converted into radiation transport 3D model.

In lieu of detailed microelectronic device location details TID detector points were placed at five general locations on the least-shielded side of each board. Due to lack of board-level details and only minimal board-level material / mass information many smaller objects were modeled as uniform density mass objects; for example the total battery mass and geometry was known therefore permitting modeling as a uniform density objective of equivalent mass / volume. Detector locations were selected to be selected board edges and at board center, with each detector offset 40 mil from the board plane to simulate a realistic part height. Edge detector locations were offset 0.25 in from the board edge. Thirty detectors were used in total, which accounts for both sides of the center board (EPS) plus the outer sides of the remaining four boards. As in other analyses summarized herein the input radiation environment consisted of AE8 MAX electron and AP8 MIN proton model spectra. Further, additional simulations were performed which included the occurrence and dose contributions from one October 1989 solar flare event. The two cases were performed separately, each as a ray-trace analysis, and the worst case TID for 1 yr mission for each of the boards is presented in Table 2 and Table 3.

Also presented in Table 2 and Table 3 are the calculated equivalent aluminum shielding depths for each detector. These values represent the amount of effective spacecraft shielding (in terms of equivalent aluminum thickness) between the dose point at the spacecraft exterior. The equivalent aluminum thicknesses can be used to compare *NOVICE* results with the general dose-depth curve results shown in Fig. 6 and in fact *NOVICE* generated doses have been included in Fig. 6.

Table 2. Calculated TID at edge locations on each of the internal boards included in the 1U CubeSat trade study; also shown are calculated equivalent aluminum shielding depths.

Edge of Board	Equivalent Aluminum Depth (mil)	Dose (kRad/yr) Without Flare	Dose (kRad/yr) With 1 Flare[1]
HSCOM	122	6.5	6.8
CDH	49	19.8	20.3
EPS (CDH side)	101	7.9	8.3
EPS (Battery side)	101	7.9	8.3
Battery	99	8.0	8.4
PCOM	131	6.1	6.5

[1]Solar flare fluence includes contributions from 1 October 1989 solar flare

Table 3. Calculated TID at center locations on each of the internal boards included in the 1U CubeSat trade study; also shown are calculated equivalent aluminum shielding depths.

Center of Board	Equivalent Aluminum Depth (mil)	Dose (kRad/yr) Without Flare	Dose (kRad/yr) With 1 Flare[1]
HSCOM	351	1.2	1.5
CDH	524	0.9	0.6
EPS (CDH side)	881	0.4	0.6
EPS (Battery side)	897	0.4	0.6
Battery	174	2.6	2.9
PCOM	167	3.7	4.0

[1]Solar flare fluence includes contributions from 1 October 1989 solar flare

SUMMARY OF RADIATION ANALYSES RESULTS

Review of the trade study and analyses results presented herein enables several observations:

1. TID as calculated for specific microelectronic device locations considering detailed spacecraft mechanical design was 2-4× higher at equivalent shielding thickness when compared to worst-case general dose-depth curves as calculated via equivalent *SHIELDOSE* methods.
2. Relying on general dose-depth curves without consideration of detailed spacecraft mechanical design likely necessitates the introduction of conservatism / margin due to variability in simulation results.
3. TID at well shielded, spacecraft center locations, determined to be 1-4 kRad(Si); TID nearest to internal board edges is higher at 6-20 kRad(Si).
    a. Such levels are not insignificant. Procurement of radiation hardened devices allows for Radiation Hardness certified electronics to levels of 20 kRad and above.
4. Effective spacecraft shielding for microelectronics on boards internal to CubeSat spacecraft will certainly vary by design and location however first-look values of 50 mil to 100 mil at worst-case edge locations and nearly 1000 mil equivalent aluminum at spacecraft center locations was determined.
5. Effective shielding / thicknesses are of strong significance when assessing operational

susceptibility due to passage through peak-flux environments; electron flux induced internal / deep charging and SAA proton induced Single Event Effects (SEE) and in risk determination and mitigation.

A NOVEL MISSION CONCEPT

The preceding paragraphs demonstrate the significance of characterizing the radiation environment within the spacecraft structure, at the location of radiation sensitive microelectronics. In fact, at least one recent funding opportunity has sought to equip the desired CubeSat 3U busses with a dosimeter-based safe mode detector. Although seemingly somewhat mutually exclusive with obvious CubeSat Size, Weight, and Power (SWaP) design requirements, the use of more rigorous and thoughtful radiation design methodology and analyses methods enables the use of more advanced payloads electronics elements and reduces mission risk.

At least two near-term missions [9, 10] will characterize the space radiation environment in the presence of a 1U CubeSat. Although the student-led, Montana State University and Montana Space Grant Consortium (MSGC) Explorer 1 [Prime] mission is highly unique and interesting from a historical perspective, it is the ROBUSTA mission that will offer sufficient utility to future CubeSat spacecraft designers and end-users.

The Institut d'Electronique du Sud student-led mission is supported by CNES and utilizes a novel TID radiation monitoring payload using well characterized radiation sensitive microelectronic integrated circuits (ICs) – specifically LM139 voltage comparators and LM124 operational amplifiers. The group has selected devices with very well studied / documented [2] radiation induced performance effects. The payload design shall utilize these effects, specifically radiation degradation in device input current, output voltage, positive supply current, and negative supply, along with necessary device temperature corrections, to measure TID.

Selection of LM139 and LM124 devices for use in a TID monitoring payload is quite reasonable as devices exhibit a known Enhanced Low Dose Rate Sensitivity (ELDRS) with dose rates predicted to be 0.1-1.0 mRad(Si)/s using values determined from previous sections. [2] summarizes testing performed per the recently released MIL-STD-883G TM1019.7 at the Ultra-low Dose Rate (UDR) of 1 mRad(Si)/s for purposes of characterized device performance in as realistic a dose rate as can be reasonably achieved in ground laboratories.

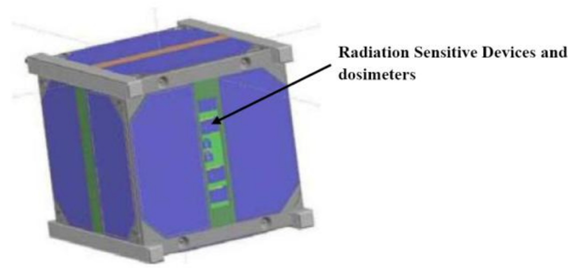

Figure 9. ROBUSTA 1U CubeSat TID radiation monitoring payload [9].

Expected radiation dose or dose rate precision for the ROBUSTA payload is not immediately known however payload calibration will be achieved on-board via an additional Optically Stimulated Luminescence (OSL) dosimeter [11] and via additional ground characterization.

Shown in Fig. 9, ROBUSTA implements its radiation sensing payload via an unshielded face of a 1U spacecraft, presumably to ensure the highest possible dose / dose rates. It is unknown at the time of publication the amount of equivalent shielding from device packages, and possible additional shielding for dose-depth purposes, that the payload will include. Certainly an interesting and valuable follow-on experiment can be performed to include characterization at additional thicknesses to better represent the likely location of radiation sensitive devices and also to study the effects of the proton flux (and thereby dose) anisotropy present at LEO altitudes.

Use of a unique dosimeter or radiation sensitive electronics assembly chassis with selectable lid thicknesses permits characterization of at multiple relevant points along the dose-depth curves shown in Fig. 6. An example of such an assembly is shown in Fig. 10 while [12, 13] describe the use of a similar dosimeter assembly at GEO.

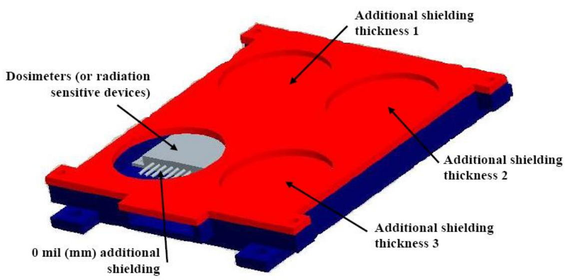

Figure 10. Novel dosimeter of radiation sensitive device assembly packaging enables characterization of radiation dose / dose rate at multiple thicknesses.

Further utility can be achieved if a 3-axis stabilized spacecraft is possible. Incorporation of multiple radiation monitoring / dosimeter assemblies on the east and west facing sides of the vehicle would permit dose characterization of the LEO proton anisotropy. Due to proton motion in the low altitude magnetosphere, the LEO proton flux anisotropy has been studied at altitudes from <400 km to 1600 km by various methods, most recently via the CEASE instrument on-board the TSX-5 spacecraft [14]. The gyroradii of trapped protons with energies above ~1 MeV are comparable to the atmospheric scale height therefore during gyration motion they encounter different atmospheric densities. As a result, proton fluxes depend on arrival direction in the plane perpendicular to the local magnetic field vector (as well as on their pitch angle). As a consequence of the anisotropic flux distribution, radiation doses received by components in various locations on a 3 axis stabilized spacecraft can vary significantly. Identical radiation sensitive devices located behind the same amount of shielding material will experience different radiation doses and also difference Single Event Effects (SEE) environments [14].

Although not explored further herein, the CubeSat design and operational effects related to the LEO flux anisotropy may be non-negligible. Given the traditional lack of resources available to harden designs to TID effects and SEE it is of value to recognize the possibility of added reliability / performance that could be achieved by optimally located, as an example an SEU susceptible memory or FPGA.

CONCLUSIONS

The innovative technologies and advanced mission areas enabled by nanosatellites will require prudent, and at times creative, methods for assessing the radiation environment and effects on electronics and spacecraft performance. The reduction in SWaP characteristic of nanosatellite class spacecraft is somewhat inversely related to traditional methods of ensuring radiation related reliability and robustness in the presence of trapped electrons and protons.

Analyses and discussions summarized herein demonstrate the importance of focusing on accurate determination of the radiation environment in the presence of spacecraft structure.

Acknowledgments

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