Radiation Effects on CubeSats

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UNSW Canberra Space are launching two CubeSats in collaboration with the Royal Australian Air Force. It is the intent of UNSW Canberra Space to optimize the power efficiency of the CubeSat subsystems in order to maximize the operational duty cycle of the spacecraft. To achieve this, they aim to use high efficiency Switch Mode Power Supplies (SMPS) using MOSFET switching elements instead of linear regulators for the second mission. MOSFETs are known to be susceptible to radiation damage and analysis is required to determine if the MOSFETs would survive for the duration of the mission without further shielding. This radiation analysis was completed with OMERE to generate the specification of the radiation environment and FASTRAD, to produce total ionising doses at different points within the CubeSat. It was found that there are particular MOSFETs that would maintain performance requirements for mission specifications and without further shielding, however they would require further shielding if the CubeSat was placed in a medium earth orbit instead of a low earth orbit. This project also established that particular LED components on the outer side of the spacecraft would require a thin layer of shielding to display a better light output for the mission. This investigation produced a body of work that can be built on to further develop the space situational awareness and intelligence, surveillance and response for UNSW Canberra Space and the Royal Australian Air Force.

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I. Introduction

A. Aim.

The aim of this project is to determine if the power efficiency benefits of using metal-oxide semiconductor field-effect transistors (MOSFET) based switch mode power supply (SMPS) over linear regulators can be realized in CubeSat spacecraft power supplies given their higher susceptibility to radiation damage when using commercially off the shelf (COTS) components. This project will determine if the MOSFETs can maintain performance requirements for a year in the orbital environment and whether further shielding is required. If they can maintain performance or if appropriate shielding can be constructed, then it will be an efficient design decision. Secondly, it will be determined if LEDs require shielding to sustain a light output without catastrophic degradation for the duration of the mission.

B. Scope.

This project is being conducted to assist the collaborative project between UNSW Canberra Space and the Royal Australian Air Force (RAAF). They are launching two CubeSat missions, M1 launching in early 2018 and M2 approximately one year later. Both missions will only last for a year. This investigation has studied the M1 design which is currently in the build phase.

A literature review determined the methods of radiation damage and the radiation environment was estimated based on the known mission parameters in a program called OMERE. The dose depth curve produced by OMERE was used to gain estimates of the total ionising dose (TID) at particular locations in the CubeSat. This enabled simulations of silicon MOSFETs inside the CubeSat with and without added shielding, in order to see the difference in the TID they received.

II. Background

A. CubeSat.

A CubeSat is a small satellite standard that was developed to allow people to conduct space missions, and research on a budget with no restrictions based on organisation history [1]. The first CubeSat was deployed in 2002 and since then, universities, space agencies and government organisations have continued to launch them for education, research and operational deployment [2]. The physical standard adopted was 1U (10 cubic cm), with a volume of one litre and mass of 1.33kg or less from CalPoly and NASA standards [1]. The orbital deployer currently in use can cater for a 3U (three times all dimensions of a 1U) CubeSat, allowing flexibility for payload development [1]. The standard imposes design constraints that reduce the size, weight and power of the CubeSat and the payload. Conventional designs of spacecraft use radiation hardening components, whereas CubeSats are generally restricted in cost, use COTS components and therefore the operational lifetime can be reduced. The challenge for the designer is to find radiation tolerant, COTS components to balance the trade-off between reliability in the space environment and procurement costs [1].

B. UNSW Canberra/RAAF Missions.

M1 and M2 are CubeSat missions being operated by a joint research agreement between the ADF and UNSW Canberra Space. M1 is a 3U CubeSat with off the shelf and UNSW designed payloads and spacecraft platform systems and is scheduled to launch in early 2018. M1 is designed to monitor automatic identification system (AIS) and automatic dependant surveillance broadcast (ADS-B) beacons from ships and aircraft, to test and develop Australian Space Situational Awareness capability to track low earth orbit (LEO) spacecraft and to develop building-block technologies for future ADF space capabilities. The UNSW Canberra Space project team developed payload is a software defined radio (SDR) with antenna systems used to support the AIS and ADS-B monitoring. The other payload on M1 includes AIS and ADS-B receivers.

M1 has been designed to avoid components with low radiation tolerances for critical applications, however this has resulted in components with lower performance characteristics. The secondary power supply of M1 currently uses linear regulators, which are inefficient. This investigation will look at improving the power efficiency by replacing the linear regulators to SMPS using MOSFETs. A MOSFET that will maintain performance requirements in the radiation environment with or without shielding, will be considered as an update for M2 to improve the power efficiency.

C. Power Efficiency.

The disadvantage of using linear regulators in M1 is their low power efficiency. A study undertaken to compare the efficiency of linear regulators to MOSFETS, concluded that the use of linear regulators in M1, result in power efficiencies of 68% and 37.5% for different circuits. The power is dissipated as heat in the linear regulator. This result is inefficient when compared to SMPS, which typically range from 70-90% [3]. Using an example of a SMPS at 80%, the circuit would lose only 1.77W of power, instead of 11.85W (at 37.5%). The MOSFETs of consideration for M2 have efficiencies of 90% and above, implying a more efficient result.

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D. Radiation Environment.

The radiation experienced by the CubeSat is heavily influenced by the orbit and particles it encountered. The parameters specific to this CubeSat and its mission are:

1. **Van Allen Belts.** The M1 CubeSat will be situated in an orbit of 550 km which means it will be within the Van Allen Belts. It will be subject to radiation from the trapped particles but also protected from some radiation by the earth’s magnetic field. Van Allen Belts extend from 100 km to 650000 km and are made up of energetic electrons and ions (primarily protons) which are magnetically trapped. These electrons can reach a few MeV energy and the protons can reach several hundred MeV energy [4]. The inner belt contains mostly protons, whereas the outer contains mostly electrons [5]. In LEO, objects are still within the protection of the magnetic field, however a CubeSat is still at risk of trapped protons and electrons. Aiming to find the maximum radiation shielding effectiveness is essential for preserving the CubeSat during its time in space. AE8 and AP8 are two models which exist as the standard for trapped radiation, measuring electrons and protons respectively within the Van Allen Belts [4]. These models display the proton or electron flux at both the solar maximum or minimum. They have been the standards used to model the Earth’s radiation belts since being released in 1983 (AE8) and 1976 (AP8), whilst they are of long heritage, they are still the most up to date and are applicable to this investigation [7]. AE8 and AP8 are the newest models since AE1 and AP1 were first created in 1966 [8]. Updates were required to improve the fidelity of the models due to advances in understanding and additional experimental data. The AE8 and AP8 models account for the natural radiation experiment, however an event can temporarily alter the composition of particles. An example of a significant event is the Starfish nuclear explosion which occurred in 1962 [8]. This was conducted for multiple reasons relating to nuclear effectiveness for defence purposes but also to determine the feasibility of testing nuclear weapons in outer space. However, the experiment resulted in a temporary increase of electrons at low orbit and around 1 MeV [8]. The types and quantities of particles in an objects radiation environment contribute to the dose received by the object.

2. **Ionising Particles.** The particles of most concern in this investigation are the trapped electrons and protons within the Van Allen Belts due to the CubeSats LEO. These high energy particles lose energy through ionisation. Electrons can have large path deviations when interacting with orbital electrons as their mass is the same, resulting in a greater energy loss in one instance of ionisation [9]. Their radiative loss is known as bremsstrahlung which refers to the electromagnetic radiation produced by the acceleration or deceleration of an electron [9]. These losses are only significant in materials of higher atomic number due to the number of electrons to interact with and produce radiation [9]. Electrons can cause harm to insulation, circuit boards and ungrounded metallic parts after penetrating thin shields, making them a potential danger to CubeSats [4]. High-energy protons can cause radiation levels that are dangerous to humans inside an aircraft and at high altitudes within the Earth’s atmosphere [6]. This means that without proper radiation hardening, CubeSats can be at risk of radiation that causes functional and/or performance degradation. High fluxes of protons are present during periods of high solar activity. Protons break down the nucleus, with the resulting energy transfer potentially disrupting and damaging memory or the functioning of CubeSat components [4].

3. **Components.** MOSFETs and LEDs are the two components of interest in this investigation that will be at risk of the radiation described above. A MOSFET is a metal-oxide semiconductor field-effect transistor which can be used in a SMPS and is made primarily of silicon. Radiation damage caused to MOSFETs can be due to the charge being trapped in the oxide layer due to ionisation [10]. The accumulated dose can cause performance changes and ultimately functional failure [11]. Radiation damage can also be caused by a single event burnout (SEB) (a type of single event effect). SEB causes the destructive failure of MOSFETs [12].

   LEDs suffer from radiation damage characterised by displacement damage (DD) which produces similar effects to the natural age degradation. Both will cause a decrease in emitted light of the device. A study done at the California Institute of Technology discovered that the radiation damage is mitigated when the device is under high bias currents and that different LED devices show different susceptibility levels to DD [13]. It was concluded that most LED types can survive in space with little degradation. They found that the LEDs fabricated with InGaAsP were less affected by DD than AlGaAs heterojunction LEDs and are therefore a better choice for use in the space environment [13]. Another study done in California examined the proton DD on LEDs and concluded that whilst double-heterojunction LEDs are less degraded, the amphoterically doped diffused LEDs have a higher efficiency for the space environment [14].
E. Shielding.

Radiation shielding effectiveness depends on atomic and nuclear cross sections, which in turn depends on the density of electrons per unit volume, electronic excitation energy and the binding corrections of the inner shell electrons [15]. More effective radiation absorbing materials, have high electron density, low electron excitation energy and small binding corrections [15]. Electron density is the most important parameter [15]. NASA mainly uses aluminium for radiation shielding because it is strong, lightweight, corrosion resistant and able to shield from harmful radiation [16]. Materials of higher hydrogen content actually have a greater radiation tolerance than aluminium, because the hydrogen atoms are good at absorbing and scattering radiation [17]. Polyethylene is a good example because of its high hydrogen content [17]. However, a balance between weight, cost and radiation tolerance is required for choosing an appropriate shielding. The choices of materials used in this investigation were determined by members of the UNSW Canberra Space project team. This investigation will examine the difference in aluminium, lead, tungsten and tantalum for shielding purposes. The table below displays the differences between these materials in weight and density. Table 1 demonstrates that aluminium is the best choice for weight and its known that it’s better for corrosion resistance. Higher density materials generally perform better as radiation shielding due to their ability to absorb it. Lead has a higher density than aluminium but a lower yield strength and would be more difficult to mechanically integrate with the rest of the CubeSat.

<table>
<thead>
<tr>
<th>Material</th>
<th>Weight (amu)</th>
<th>Density (g/cm³)</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al (aluminium)</td>
<td>26.982</td>
<td>2.70</td>
<td>1-3mm</td>
</tr>
<tr>
<td>Pb (lead)</td>
<td>207.2</td>
<td>11.34</td>
<td>1mm</td>
</tr>
<tr>
<td>W (tungsten)</td>
<td>183.84</td>
<td>19.3</td>
<td>0.5mm</td>
</tr>
<tr>
<td>Ta (tantalum)</td>
<td>180.95</td>
<td>16.4</td>
<td>0.5mm</td>
</tr>
</tbody>
</table>

III. Methodology

A. Derivation of Environment Specifications.

OMERE [19] is a software tool used to model the space radiation environment. In particular it is able to develop a dose depth curve in response to mission parameters set by the user. Originally, the intention was to use SPENVIS [8], an online tool to estimate the environment. However, on commencement of the simulations in FASTRAD [20], it became clear that the file format was not compatible. Hence OMERE was utilized instead. The mission parameters used for this project include: 550km altitude, 97.6 degrees inclination, 10am local time in January 2018 and for 1 year duration. The OMERE software mapped this orbit over the earth and displayed areas of electron or proton flux as per the AE8 and AP8 models for those mission parameters, Fig 1 displays the electron flux for AE8 Max.
B. CubeSat Model.

The CubeSat model was analyzed in a software tool called FASTRAD. It is a 3D CAD, Monte Carlo radiation simulation tool that is used for radiation shielding analysis [20]. The CubeSat model used in this investigation is a realistic representation of M1. Materials were assigned to the geometric elements of the model within FASTRAD. The majority of the structure is made of aluminum, while the boards inside the stack are FR4 (glass epoxy), the panels on the outside are glass and the antennas are made of copper.

C. Dose Depth Curve.

A radiation dose is energy deposited by a particle during ionization per unit mass. A dose depth curve is for a given radiation environment, the average absorbed dose for a given material, as a function of depth. The complete dose depth curve results produced by OMERE is located in Appendix A. Fig 2 displays for a given material, the estimated dose delivered by trapped electrons and protons and the total dose at a certain thickness of aluminum at the orbit radius. This dose depth curve is used to estimate the TID’s in FASTRAD when examining the CubeSat.

In order to verify the use of the dose depth curve results from OMERE in FASTRAD, a simulation was conducted. The simulation involved a silicon detector inside a hollow aluminum sphere in the FASTRAD program. By using the dose depth data produced in OMERE from the mission specifications, TID at the detector for different thicknesses of the sphere were calculated. This simulation gave TIDs that were consistent with the TID from the dose depth curve. This was the sum of trapped electrons, trapped protons, solar protons and gamma photons as seen in Fig 2. Therefore, this verified the use of the dose depth curve to calculate TIDs at points in the CubeSat in FASTRAD. The results from the simulation can also be found in Appendix A.

D. LED Light Output.

Data on the radiation susceptibility of typical LEDs was necessary to form conclusions on LED performance, however the data available was in proton fluence. The Bethe formula was utilized to convert the fluence to a radiation dose. The formula represents the linear stopping power for charge particles in a given absorber [9]. It was used to gain estimates of the light output for four different LEDs in Fig 3 at varying radiation doses.

Figure 2 – Dose Depth Curve 550km

Figure 3 – LED Light output graph [13]
Equations 1-6 have been gained from Knoll’s “Radiation detection and Measurement” [8] and Sigmund’s “Particle Penetration and Radiation Effects” [21].

\[
S = -\frac{dE}{dx} = \frac{4\pi^2 ne^4}{m_e c^2 \beta^2 (4\pi \epsilon_0)^2} \left( \ln \left( \frac{2m_e c^2 \beta^2}{I(1-\beta^2)} \right) - \beta^2 \right) 
\]

\[
-I = 10eV \times Z 
\]

\[
n = \frac{N_A Z m_p}{A \times \mu} 
\]

\[
\beta \text{ can be found from its corresponding } \gamma \text{ (Lorentz Factor). Where } \beta = \sqrt{1 - \left(\frac{1}{\gamma^2}\right)^2} \text{. } [22]
\]

Furthermore, \( \gamma \) can be found using the relativistic energy equation:

\[
E = (\gamma - 1)m_0 c^2 \text{. } [22]
\]

The values are displayed in Table 2.

### Table 2 – Bethe Formula Values

<table>
<thead>
<tr>
<th></th>
<th>Aluminium</th>
<th>Silicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na (Avogadro’s no.)</td>
<td>6.02E+23</td>
<td>6.02E+23</td>
</tr>
<tr>
<td>Z (Atomic Number)</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>A (Relative atomic mass)</td>
<td>26.98</td>
<td>28.0855</td>
</tr>
<tr>
<td>Mu (Molar mass constant g/mol)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>p (density g/m^3)</td>
<td>2700000</td>
<td>2329000</td>
</tr>
<tr>
<td>c (speed of light m/s)</td>
<td>2.99E+08</td>
<td>2.99E+08</td>
</tr>
<tr>
<td>z (charge)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Me (electron rest mass kg)</td>
<td>9.11E-31</td>
<td>9.11E-31</td>
</tr>
<tr>
<td>Mo (rest mass of proton kg)</td>
<td>1.67E-27</td>
<td>1.67E-27</td>
</tr>
<tr>
<td>B (speed m/s) Refer to Eq. (5)</td>
<td>3.15E-01</td>
<td>3.15E-01</td>
</tr>
<tr>
<td>y (Lorentz value) Refer to Eq. (6)</td>
<td>1.05E+00</td>
<td>1.05E+00</td>
</tr>
<tr>
<td>E (electron charge coulombs)</td>
<td>1.60E-19</td>
<td>1.60E-19</td>
</tr>
<tr>
<td>E0 (vacuum permittivity F/m)</td>
<td>8.85E-12</td>
<td>8.85E-12</td>
</tr>
<tr>
<td>Energy (MeV)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>I (mean excitation potential) Refer to Eq. (3)</td>
<td>2.58E-17</td>
<td>2.76E-17</td>
</tr>
<tr>
<td>n (electron density) Refer to Eq. (4)</td>
<td>7.83E+29</td>
<td>6.993E+29</td>
</tr>
<tr>
<td>DE/DX (J/m) Refer to Eq. (2)</td>
<td><strong>4.24E-10</strong></td>
<td><strong>3.75E-10</strong></td>
</tr>
<tr>
<td>MeV/mm</td>
<td>2.648</td>
<td>2.34</td>
</tr>
</tbody>
</table>

Figure 4 – Bethe Curve [23]
The data was cross checked with the Bethe curve for aluminum, represented by the cross marked in Fig 4. Fig 4 shows that a proton particle with energy of 50MeV corresponds with approximately 2.65MeV/mm in aluminum which matches the value received from the Bethe formula, therefore verifying the values to be used to convert the proton fluence to total dose.

Fig 4 is a result of research done in the California Institute of Technology. To reproduce the graph using radiation dose instead of proton fluence, the formula in Eq. (7) from the National Physical Laboratory (NPL) in the United Kingdom [24] can be used:

\[
\text{Dose} \left( \frac{J}{kg} \right) = \text{proton fluence} \left( \frac{\text{p}}{\text{cm}^2} \right) \times \left( \frac{\text{LET}}{\text{density} \left( \frac{\text{rad}}{\text{kg}} \right)} \right)
\]

Using Eq. (7) to convert the proton fluence into the equivalent dose, the following example can be followed:

\[(1 \times 10^9 \times 10^4) \times \left( \frac{3.24 \times 10^{-10}}{2329} \right) = 1.61 \times 10^7 \text{ rad} \times 1 \text{ rad} = 0.01 \text{J/kg}.
\]

Therefore, for a proton fluence of $1 \times 10^9 \text{ p/cm}^2$, the equivalent dose is $1.61 \times 10^2 \text{ rad}$. Table 3 displays the converted values from Fig 4 for the four different types of LEDs.

![LED Radiation Damage](image)

**Figure 5 – LED light Output Degradation**

From the graph in Fig 5, the radiation dose that leads to degradation of light output to the four types of LEDs in this investigation is noted. There is no radiation test data available for the LED’s on M1, as a result the following data was used to gain an idea of relative sensitivities for LED’s in that radiation environment.

### IV. Results & Discussion

#### A. MOSFETs

In order to estimate the TID received by a MOSFET inside the CubeSat, the FASTRAD program was utilized. Using the dose depth curve from OMERE, FASTRAD produced TIDs of radiation at detectors placed inside a silicon MOSFET in the model. The CubeSat model in FASTRAD is displayed in Fig 6.

As with the LED’s, there was no data available for the MOSFETs to be used in M2, therefore typical data for the component was utilized. Members of the Institute of Electrical and Electronics Engineers (IEEE) tested two different types of MOSFETs and determined their failure rates. The first was labelled STS3P6F6 and manufactured by STM and the second labelled SPD04P10PG and manufactured by Infineon. Table 4 displays the details of the two MOSFETs.

<table>
<thead>
<tr>
<th>Part</th>
<th>Manufacturer</th>
<th>Failure Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>STS3P6F6</td>
<td>STM</td>
<td>5krad</td>
</tr>
<tr>
<td>SPD04P10PG</td>
<td>Infineon</td>
<td>5krad</td>
</tr>
</tbody>
</table>

Table 4 – MOSFET Failure Dose

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Both MOSFETs failed at a total dose of approximately 5krad [25]. Appendix B contains the TID data received from FASTRAD when examining MOSFETs within the CubeSat. These results show that without shielding, the maximum total dose a MOSFET may receive at an orbit of 550km for one year is 0.112krad. Therefore, if either of the MOSFETs mentioned above were installed in M1 or M2 they would maintain performance requirements without damaging degradation for the duration of the mission, without shielding. The results in Appendix B demonstrate that shielding would enable the MOSFETs to maintain performance without degradation for a longer period of time if required. Out of the tested shielding, 1mm of lead provides the best results, giving the lowest total dose of radiation to the MOSFET. However, as all the shielding options ensure the survival of the MOSFETs, 1mm of aluminum would be a more ideal choice due to its advantages in the background.

It is important to note the impact of its performance in different orbits. LEO has a smaller footprint in comparison to MEO. In a MEO you can cover a larger area over the same orbital period, this better coverage would improve the operation of the CubeSat, especially in communications. The MOSFETs survivability in a MEO is important as this orbit will be looked into for use in future space projects due to this improved operability.

It was determined that if the CubeSat was in a medium earth orbit (MEO), the MOSFETs mentioned above would receive 6.6krad and would require shielding to endure the mission. All of the shielding designs utilized in this investigation would ensure their survival. 1mm of aluminum would be the best option due to its lighter weight and superior performance. It would only receive 1.7krad with this shielding. Tests were also conducted for the mission for 2yrs in a LEO and a MEO. The results showed that the MOSFETs would still survive in a LEO for a second year with the received dose doubled to 0.223k rad. This demonstrates that the MOSFETs could survive for a large number of years within a CubeSat in a LEO and without shielding. In a MEO orbit for 2yrs however, the dose the MOSFETs receive with 1mm of aluminum shielding is significantly closer to the failure rate of 5krad, at 3.4krad. Therefore, an increased amount of aluminum shielding should be considered for this type of mission. With a 2mm aluminum shield, it would receive 1.9krad, which is a safer result. These results are consistent with the information presented in the background above, specifically that objects in LEO are still under a certain amount of protection from radiation, this is not the case in a MEO and the results demonstrate this.

B. LEDs

The LED is located on the underside of the front face which is directed down toward the Earth during orbit. The results for the LED detector can be found in Appendix C. It was determined that in the orbit of M1, without shielding, the LED would receive an approximate dose of 294.7krad. Further analysis was performed to see if this can be reduced with shielding. Due to the operational use of an LED, the shielding is required to be clear. Thus, 1mm shield of glass was placed over the LED detector and it received only 1.615krad. When comparing this value to the four LED’s tested by the California Institute of Technology [13] and mentioned above in the methodology, it can be seen that without shielding, three LED’s would degrade to 0% before or by the time the mission was complete. However, the 820nm Optodiode would display a light output until the completion of the mission. With the shielding, all four types of the LEDs would survive the entire mission with 80-100% light output. The results in Appendix C also display the total doses the LED would receive if it was in a MEO orbit. In this case, all four LEDs would degrade without shielding early in the mission, as they would receive a total of 48.16Mrad. Only the better performing LED would have a light output for the first half of the mission with shielding, receiving a dose of 679.9krad. However, their light output would be reduced to 0% at or before the halfway mark of the mission.

It is important to note here that LED’s failure mechanism is displacement damage, whereas the Bethe formula is the stopping power due to ionization, this indicates that the data for the particular LED’s gained in the methodology have certain uncertainties.
C. Solar Maximum.
   The M1 and M2 missions will be launching in a period approaching solar minimum and therefore solar protons are not a major design driver unless there are unexpected solar flares or a spontaneous moment of higher solar activity. OMERE produced the next periods of solar activity being a minimum in 2020 and at maximum in 2024. As the mission will not be impacted, the same mission parameters were set for 2024, a period of solar maximum, to determine the contribution solar protons may have to the degradation of components. This produced solar protons which influenced the results as seen in Appendices B and C for MOSFETs and LEDs respectively. The additional protons increase the dose received only slightly. The MOSFET in 2018 receives 111.7 rads, and in 2024, it receives 146.2 rads without shielding. Therefore, it would not impact upon the mission.

D. Component Test Data.
   In order to meet the aim for this investigation, data was sought for failure rates in MOSFETs and LEDs. Radiation test data on the actual component types would have added great value to the current work however actual testing of components within the scope of this project was not feasible. As mentioned in the background, the CubeSats design philosophy generally accepts lower power efficiency in return for a higher radiation tolerance, and therefore material and component selection is based on factors such as weight, mechanical integration, radiation tolerance and performance. The chosen factors influence how the data received is then interpreted. For example, the choices of shielding material and their thicknesses were determined by the UNSW Canberra Space team based on what they can accommodate for factors such as weight and mechanical integration. When determining which shielding to use, 1mm of lead proved to be the better radiation shielding for the mission. However, if aluminium could ensure the survival of a component for the mission, it would be chosen instead because of its lighter weight, ease of integration, corrosion resistance and performance.

V. Conclusions
   This report summarises radiation effects on CubeSats, with particular focus on certain components with known susceptibilities within a CubeSat in the orbit of the M1 and M2 missions. During the conduct of this investigation, a number of important results were obtained. The mission details allowed the production of a dose depth curve for that orbit in OMERE. Using that curve, TIDs for the mission were established in FASTRAD for particular points in the CubeSat. As a result, it can be concluded that certain MOSFETs will maintain performance requirements without damaging degradation for M1 and M2 missions, and without shielding. Out of the different shielding types and thicknesses that were investigated, it was determined that aluminum was the best choice for shielding for the MOSFETs. Shielding would be required in a MEO orbit. Using the Bethe Formula, particular LEDs light output in space were graphed with a received radiation dose. Two of the LEDs would not maintain light output for the mission duration, while the other two would degrade by the end of the mission. It was determined that they will display a better light output for longer and for the whole mission with shielding. Therefore, the type of LED chosen should take these results into account. It was determined that solar protons are not of consequence to this mission and wouldn’t impact it if they were. These results will allow UNSW Canberra Space to make an adaption to the design of M2 in using MOSFETs instead of linear regulators to increase the power efficiency of the CubeSat. It will also allow them to discuss shielding to the LED and what type of LED to place in the CubeSat.

VI. Recommendations
   There is scope for further research into the area of radiation effects on satellites in space. From the investigation, the following recommendations have been made:
   
   1. There is opportunity for providing further validation of the FASTRAD results when M1 is in space. For example, examining the light output of the LED over the year duration will give an indication of the radiation dose it may be receiving.
   2. With access to the right facilities, more MOSFETs could be tested for a failure dose of radiation as this would give a better indication of what type of MOSFET to choose for use in M2 based on its mission parameters.
   3. Given the increased use of space, it would be useful to study a radiation enhanced environment and the effects this may have on satellites and other useful space assets. OMERE allows the user to simulate an environment of increased radiation based on previous events such as solar flares. This can be utilized for further research in this area.
   4. There is large scope for further investigation into shielding against radiation effects. NASA is continually researching improvements for this. When designing a CubeSat from a university point of view, weight and design integration are significant factors and therefore further research can be done into the best combination of shielding for a CubeSat.
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References