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Degradation Effects of Ionizing Radiation on Commercially Available Spacecraft Components

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Degradation Effects of Ionizing Radiation on Commercially Available Spacecraft Components

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Physics Department
Utah State University

Narrative

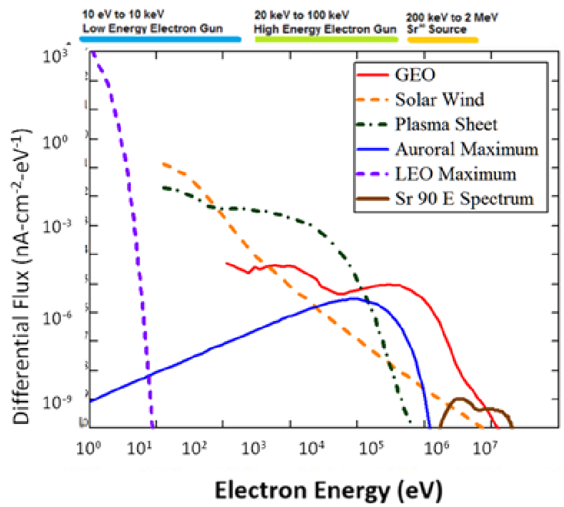

Fig 1. Representative space electron flux spectra for geostationary earth orbit, solar wind at the mean earth orbital distance, plasma sheet environment, maximum aurora environment, and low earth orbit. The Sr^{90} source emission spectrum is also shown. Bars above graphs show the ranges of the chamber source emissions. After [9].

Interactions with the space environment can cause unforeseen and detrimental effects to spacecrafts, sensors, components and materials. These components potentially will not operate as designed, or in the extreme case may fail altogether. Electronic components are particularly sensitive to radiation exposure [4] in space. There are three main damaging effects of radiation on electronics. The first is total ionizing dose, which is the dose (energy per unit mass) that is deposited into the electronics from ionization radiation, which strips electrons from constituent atoms in the materials. [11]. The second is displacement damage, which is where enough energy in imparted onto an atom to break its chemical bond inside a material, causing damage over time. Semi-conductors are particularly susceptible to this effect. The third main mechanism of damage are single event effects, which typically happen when high energy protons cause damage as the particles pass through the part. All these effects can adversely affect electronics [1] by modifying materials' electrical and mechanical properties [2]. These effects can be complex and difficult to accurately predict, thereby requiring extensive space [6,7] and ground-based [8-10] testing. Understanding how and why parts fail can lead to better designs to combat this damage.

The research I am proposing is exactly this: to test components that are, or could be, used in the space environment and determine how they respond to radiation and degrade under space-like conditions over time so that future designs for spacecraft can better withstand the conditions of space. More specifically, the objective is to determine how much total dose of beta radiation will lead to failure of common Commercial off-the-shelf (COTS) electronics parts.

The largest contributor to detrimental effects is high energy electron, or β, radiation [3], which is prevalent in space [see Fig 1], particularly in Low Earth Orbit (LEO) where most small satellites are sent. Small satellites are typically short term missions (6-8 months) and are likely to use untested COTS parts in order to save money and development time; these COTS parts are not specifically designed to withstand radiation as are much more expensive radiation hardened parts. It is difficult and expensive to send anything into space, and therefore it is extremely important that components used on spacecraft can adequately handle radiation exposure. Testing for potential environmental-induced modifications is increasingly more important as small satellite programs evolve to have longer mission lifetimes, extend to more harsh environments (such as polar or geosynchronous orbits), make more diverse and sensitive measurements, minimize shielding to reduce mass, and utilize more compact and sensitive electronics which

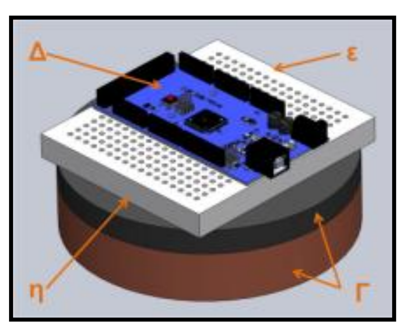

Figure 2. Radiation hardened breadboard.

often include COTS components. The most practical and economic approach to predicting and mitigating these harmful effects is to accurately simulate space environment effects through long-duration, well-characterized testing in an accessible, accelerated laboratory environment [6,8].

Figure 3 – The Space Survivability Test Chamber used to simulate the space environment in a controlled ground-based setting.

A simulated space environment is necessary to do this testing and is available with the Space Survivability chamber. The Space Survivability Testing chamber (SST) is a ground based test facility designed to mimic low earth orbit (LEO), geosynchronous orbit (GEO), and interplanetary space environments to test potential environmental-induced modifications to small satellites, components, and materials[5]. The effects of ionizing radiation damage on the mechanical, electrical, or optical properties of materials resulting can be studied from exposure in the SST with both *ex situ* (outside of chamber tests before and after radiation exposure) and *in situ* (tests done under vacuum and radiation, during exposure) experiments. Tests described here expose parts to a Sr^{90} ionizing beta radiation source at room temperature and in high vacuum. Sr^{90} emits a board range of of high energy electrons from ~250 keV to 2.5 MeV [Fig. 1]. A total dose of high energy electrons in LEO is approximately 100 krad/year. This is comparable to one month exposure in the SST chamber, which sets the timescale for the proposed research.

Circuitry mounted on PC boards, such as the microcontroller components described below, can be directly mounted on the chamber carousel [Fig. 5]. Alternately, another test fixture can be used with the SST chamber, [Fig. 2]; this includes a custom radiation hardened ceramic prototyping breadboard (>1400 tie points, 10 cm x 10 cm), with extensive vacuum feedthrough (78 lead) wiring capacity for *in-flux* and *in situ* monitoring of environment- and radiation-induced failures of custom circuits and COTS parts. Part of my project will be configuring custom wiring and cabling to lead from the COTS parts inside the chamber to the external data acquisition apparatus. This interface is a critical part of the experimental design and has to be high vacuum ($<10^{-7}$ Torr) compatible as well as being shielded from the radiation sources inside the chamber.

The focus of this research will be on these Commercial Off the Shelf (COTS) parts with *in-situ* radiation total dose tests to failure of electronic components. Performance tests for CPU(s), USB interfaces, SD memory cards, Bluetooth sender/receivers, magnetic sensors *etc.* can be measured *in situ* while under vacuum and/or exposed to radiation. *Ex situ* analysis of COTS parts will provide a multi-layered approach to testing degradation effects by testing before and after SST exposure as well. These parts will be supplied largely by SparkFun Electronics [see Figure 4], who has agreed to assist with this project by providing both hardware and software designed specifically for diagnostic tests until failure in the SST chamber. Custom LabVIEW code will be written for any tests that cannot be done with the SparkFun software.

Tests conducted will include continual CPU diagnostics, memory read/write tests, communication tests, and sensor tests. Failure will be determined when the readings from the COTS parts inside the chamber no longer correlate to those with the control parts outside of the chamber. This could be due to nonsensical data or complete failure to even acquire data. Tests will be conducted until both events happen to fully quantify the failure process.

The final report will have a list of COTS parts radiation safety rating for a given period of time. This will be a custom rating with an approximation for the lifespan of the part in various orbits in space. It will detail when the part is likely to function as expected, the time where performance begins decreasing, and the point in time where the part is likely to fail completely.

Figure 5 – SST Chamber with solar-cell degradation test setup. Sample carousel is visible through the chamber viewport.

Further work, beyond the scope of this URCO project, will be required to compare ground-based tests in the SST to the results of in-flight tests to establish a level of accuracy for the simulation results as well as quantify the ability of the chamber to mimic the space environment. This will be useful to predict potential radiation damage effects and allow us to refine our simulation environment and testing procedure to better determine how COTS parts behave in a space-like environment.

Timeline

The damage done to COTS parts will vary depending on the energy and total dose of the radiation bombarding it. A years' dosage from high energy (>100 keV) beta radiation can be simulated in the SST chamber in approximately one month. Thus, demonstration of survivability over typical 6-8 month mission lifetimes for CubeSats can be accomplished in 1-2 weeks. Table 1 provides an estimation for the timeline to complete the research and reach meaningful conclusions. Initial findings and a demonstration of capabilities will be presented at the Institute of Electrical and Electronics Engineers (IEEE) Small Satellite conference to members of the space community (NASA, SpaceX, JPL, *etc.*). Small satellite mission specialists and teams designing related components attending this conference will benefit by making additions or modifications to their spacecraft designs in response to my conclusions. A final presentation of completed work will be given at the Four Corners regional conference in October. Four Corners is a conference organized by the American Physical Society attended primarily by members of academia to share their work and strengthen broader perceptions of science.

Table 1: URCO Project Timeline

Objective	Completion
Design experiments to achieve goal	May. 2016
Configure the SST for COTS testing.	
Purchase COTS parts: CPU(s), USB interfaces, SD memory cards, Bluetooth sender/receivers	
Configure *in situ* testing apparatus.	June. 2016
Begin non-irradiated control tests	July 2016
Begin *in situ* measurements.	
Continue *in situ* measurements and analyze data	Aug. 2016
Present relevant completed research at Small Satellite Conference	
Complete full total dose tests	Sep. 2016
Compare control, beginning-of-life, *in situ*, and end-of-life test results	
Present at APS Four Corners Regional Meeting. (NM)	Oct. 2016
Final URCO Reporting Date	Nov. 2016

Educational Plan

The primary objective for this research is to quantify how common commercial parts respond to exposure in a space-like environment. This will provide valuable insight into types of failure for applications of these parts in space, such as for small satellites. A secondary outcome will be from the use of the Space Survivability Testing chamber. The work done for this project will help future projects involving the SST chamber by further specifying its capabilities and developing testing procedures. It may also make it possible to lower the cost of sensitive projects by determining which commercial parts have an adequate response to a space-like environment.

I also hope for some unexpected results. I will keep my eye out for any unusual or unexpected data and try to determine the logical cause of it. It seems that many of the biggest scientific breakthroughs originate with what was originally thought of as a 'mistake.' Researching unusual phenomenon seems to lead to the most interesting conclusions. I hope to learn how to overcome these unexpected challenges and ensure that I have useful and meaningful results at the conclusion of my research. I hope to provide a basis for future researches to expand on and use to their advantage.

Some of my personal goals from this project stem from the process itself. I hope to learn how to ask the right questions and discover the answers while improving my laboratory skills, presentation capabilities, and critical thinking processes. Learning to design the right experiments and gain an insight to the possible results is a valuable skill to have for future endeavors. Knowing how to begin the process which leads to further understanding is often times the most difficult part. In the future I hope to be the owner of an innovation lab which focuses on finding scientific breakthroughs as well as designing new and creative devices. A general curiosity and love of the discovery process is needed and a more full understanding of what it takes to be successful when choosing a project comes from experience; this URCO project will start me on the path towards a better physical intuition.

Personnel Overview

Alexander Souvall is a junior/senior undergraduate student majoring in both Physics with a Professional Emphasis, and in Mechanical Engineering with an Aerospace Emphasis at Utah State University. Alex has been a member of the Material Physics Group since spring of 2014 and has used both his Engineering and Physics education in his time with the MPG. Alex helped design and build the SST chamber and has experience in Piezoelectric Acoustic (PEA) measurement devices, optical testing, writing code for lab data acquisition and analysis, and designing apparatus.

Gregory Wilson is currently a graduate student at Utah State University (USU) in Logan, UT pursing a PhD in physics. He received BS degrees in physics and mathematics from USU in 2011 and an MS in Physics from Montana State University in 2015. He has worked with the Materials Physics Group for several years on electron emission and luminescence studies related to spacecraft charging, secondary electron emission and degradation of materials and electronic devices due to incident radiation. He also developed a composite model for electron range over a wide range of incident energies applicable to diverse materials.

J. R. Dennison is a professor in the Physics Department at Utah State University, where he leads the Materials Physics Group. He has worked in the area of electron scattering for his entire career and has focused on the electron transport and electron emission of materials related to spacecraft charging for the last two decades. He will provide project oversight and will work directly with Alex and Greg on experimental design, analysis methods, and interpretation of the data.

Funding

Table 2 lists the proposed budget for the Degradation Effects of Ionizing Radiation URCO project. Half of the funds will be used as a stipend during the summer and fall of 2016. Funds for test materials for the COTS electronics components and laboratory supplies are included in the URCO budget, as are funds to prepare presentations for two conferences. Matching funds come from the USU Materials Physics Group from account A07563. Additional funds for COTS electronics components have been committed by SparkFun Electronics, a major supplier of control hardware for CubeSat missions. Sparkfun has also agreed to provide technical expertise for the testing hardware, interface cabling, and control and monitoring software.

Table 2. Budget Summary

URCO BUDGET SUMMARY		
EXPENSES:	**VENDOR**	**AMOUNT:**
Supplies		
Poster printing and supplies	USU Engineering Lab	$120
Electronic components	Newark Electronics	$275
Vacuum feedthrough and wiring	MDC Vacuum	$355
Radiation sensors for calibration	Sun Nuclear	$250
Stipend		
Alexander Souvall		$1000
TOTAL BUDGET:		$ 2000
VP for Research URCO funds		$1250
Spark Fun matching funds for COTS electronic components		$310
Materials Physics Group matching funds (A07563)		$750
TOTAL FUNDING SOURCES		$2310

References

[1] A. Johnston, “Space Radiation Effects on Microelectronics, OPFM Instrument Workshop, June 3, 2008.

[2] JR Dennison, “The Dynamic Interplay Between Spacecraft Charging, Space Environment Interactions and Evolving Materials,” Abstract 125, *Proceedings of the* 13*th* *Spacecraft Charging Technology Conference,* (Pasadena, CA, June 25-29, 2014), 8 pp; *IEEE Trans. on Plasma Sci.*, accepted for publication.

[3] D. Hastings, and H. Garrett, *Spacecraft-environment Interactions,* Cambridge University Press, 1996.

[4] R.D Leach and M.B. Alexander, “Failures and anomalies attributed to spacecraft charging,” NASA Reference Publication 1375, NASA Marshall Space Flight Center, August 1995.

[5] Erik Stromberg, Crystal Frazier, Lisa Phillipps, Alex Souvall, JR Dennison, and James S. Dyer, “Small Satellite Verification and Assessment Test Facility with Space Environments Effects Ground-testing Capabilities,” *Proceedings of the 29th Annual AIAA/USU Conference on Small Satellites*, (Logan, UT, August 8-13, 2015), submitted.

[6] JR Dennison, John Prebola, Amberly Evans, Danielle Fullmer, Joshua L. Hodges, Dustin H. Crider and Daniel S. Crews, “Comparison of Flight and Ground Tests of Environmental Degradation of MISSE-6 SUSpECS Materials,” *Proceedings of the 11th Spacecraft Charging Technology Conference,* (Albuquerque, NM, September 20-24, 2010), 12 pp.

[7] J.R. Dennison, Joshua L. Hodges, J. Duce, and Amberly Evans, “Flight Experiments on the Effects of Contamination on Electron Emission of Materials,” Paper Number: AIAA-2009-3641, *Proceedings of the 1st AIAA Atmospheric and Space Environments Conference*, 2009. DOI: 10.2514/6.2009-3641[8] Robert H. Johnson, Lisa D. Montierth, JR Dennison, James S. Dyer, and Ethan Lindstrom, “Small Scale Simulation Chamber for Space Environment Survivability Testing,” *IEEE Trans. on Plasma Sci.*, **41**(12), 2013, 3453-3458. DOI: 10.1109/TPS.2013.2281399

[9] JR Dennison, Kent Hartley, Lisa Montierth Phillipps, Justin Dekany, James S. Dyer, and Robert H. Johnson, “Small Satellite Space Environments Effects Test Facility,” *Proceedings of the 28th Annual AIAA/USU Conference on Small Satellites,* (Logan, UT, August 2-7, 2014)..

[10] JR Dennison, “Characterization of Electrical Materials Properties Related to Spacecraft Charging,” Radiation Capabilities for the Europa Jupiter System Missions Instrument Workshop, Johns Hopkins Applied Physics Laboratory, Laurel, MD, July 2009, 13 pp.

[11] J.W Howard, Jr. and D.M. Hardage, “Failures Space Radiation and Its Effects on Electronic Systems,” NASA Reference, NASA Marshall Space Flight Center, July 1999.

Curriculum Vita

EDUCATION

B.S., Mechanical Engineering, Aerospace Emphasis May 2017
Computer Science Minor GPA 3.7

B.S., Physics, Professional Emphasis May 2017
Math Minor GPA 3.9
Utah State University, Logan, UT

TECHNICAL WORK EXPERIENCE

Research Technician 05/14 - current
USU Materials Physics Group Logan, UT

- Designed, built, and operated ultrahigh vacuum testing facilities
- Performed preparation and analysis of sensitive spacecraft materials
- Wrote and presented written documentation outlining work done at professional conferences
- Designed apparatus using SolidWorks and ran data analysis using Igor and MathCAD

OTHER WORK EXPERIENCE

A-Team Peer Mentor (International Orientation Chair) 11/13 – 11/14
Utah State University Logan, UT

- Guided incoming students through orientation
- Assisted students with registration and schedule planning
- Contacted hundreds of international students to ensure preparedness upon entering Utah State University
- Mentored a class of 30 students through their first year in college

COMPUTER SKILLS

SolidWorks	SolidEdge	MathCAD	C++	LabVIEW
Java	Igor	Microsoft Office	Rapid Prototyping Software	

LEADERSHIP EXPERIENCE

Treasurer of the Pi Kappa Alpha Fraternity 11/13 – 11/14

- Managed a budget of over $50,000
- Successfully brought the chapter from $7,000 of debt to $3,000 in the bank

President of the Pi Kappa Alpha Fraternity 11/14 – current

- Oversee the operations of a 60 man chapter, including philanthropy, community service, alumni support, brotherhood, and public relations
- Communicate closely with school officials, national headquarter executives, and local industries or media sources.
- Attended multiple conferences where essential leadership and managerial skills were taught

ACHIEVEMENTS & ACTIVITIES

Sigma Pi Sigma: Physics honors society
Order of Omega: Greek honors society
Concrete Canoe: Engineering club where a concrete canoe is designed, built, and raced against other schools. Took 5th place in the nation