Single Event Upset Testing of Commercial Off-The-Shelf Electronics for Launch Vehicle Applications

George M. Castillo
Radiation Effects Engineer
United Launch Alliance
george.m.castillo@ulalaunch.com

Brian A. Ratkevich
Space Based Range Chief Engineer
United Launch Alliance
brian.a.ratkevich@ulalaunch.com

Abstract—This paper presents the results and methodology of recent system-level proton testing which was performed on a COTS-based GPS receiver to be used in a launch vehicle application. Susceptibility to ionizing radiation was a concern due to a high part count and component sophistication. Testing was conducted using 50 MeV protons at the Lawrence Berkeley National Laboratory (LBNL). An approach for the testing of complex COTS components using protons of various energies is discussed in the literature, but was determined to be only partially applicable due to the design of the receiver. Therefore, a functional receiver was constructed which incorporated production components in a manner that allowed separation of the individual circuit cards and irradiation of different locations while the unit was operating as it would during flight. This approach allowed for an understanding of how upsets in isolated locations could affect the system-level response of the entire receiver. An analysis of the results allowed for a determination of a lower bound on the upset rate for a sample launch vehicle trajectory. Shortcomings and limitations to the approach described here are also discussed.

Keywords—Proton testing, GPS, system-level testing, launch vehicle, commercial off-the-shelf (COTS), upset rate estimation, EELV.

Table of Contents

1. Introduction

Use of COTS Components for Space Applications

As part of the transition from a ground-based to a space-based vehicle tracking system, a GPS Metric Tracking (GPS-MT) system was designed for the Atlas and Delta Evolved-Expendable Launch Vehicle (EELV) families. This system was developed in conjunction with the United States Air Force Space Command (AFSPC) as part of an effort to reduce range operational costs. The design philosophy behind this program was to leverage existing commercial off-the-shelf (COTS) components in order to reduce cost and shorten development time. In some cases, use of COTS parts was required due to a lack of availability of a military or space-grade equivalent.

The use of COTS components within the aerospace industry has become ubiquitous due to their low cost, short development cycle, and unique capabilities relative to components designed specifically for military and space applications. One of the challenges in using COTS components for spacecraft and launch vehicle applications is their unknown susceptibility to ionizing radiation. Test data for radiation tolerance of COTS components is often nonexistent. While individual piece part testing can address this in many cases, it can be expensive and time-consuming when the part density is high, as in the case of commercially available circuit cards. These difficulties are amplified when several such components are used together in complete avionics equipment. Some of the unique challenges with the use of COTS components, particularly circuit card assemblies (CCA), have been described in detail elsewhere [1], and are summarized here:

- Little to no die traceability for individual ICs
- Future boards can differ substantially from the tested article, potentially invalidating test results and requiring retest
- For complex circuit cards, firmware or software revisions can occur which may change the response of devices to an SEU
- Difficulty in developing a single radiation test to simulate the space environment adequately
- Limited test statistics, typically only one unit available for testing

Energetic Protons as a Substitute for Heavy Ion Testing

The interactions of energetic protons with silicon nuclei has been discussed elsewhere [2], [3]. In general, energetic protons lack the LET needed to directly cause single event effects in all but the most sensitive devices, optocouplers and some newer SRAM devices being notable exceptions [4], [5]. However, secondary particles created by the interaction of protons and nuclei within the device can have LET up to around

[1]978-1-4244-7351-9/11/$26.00 ©2011 IEEE
[2]IEEEAC Paper #1109, Version 6, Updated 11 January 2011

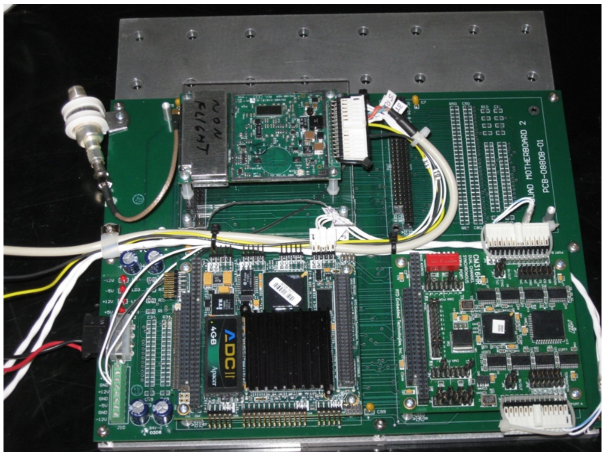


Figure 1. Test article showing circuit cards and wiring needed to reproduce electrical connections used in a production unit.

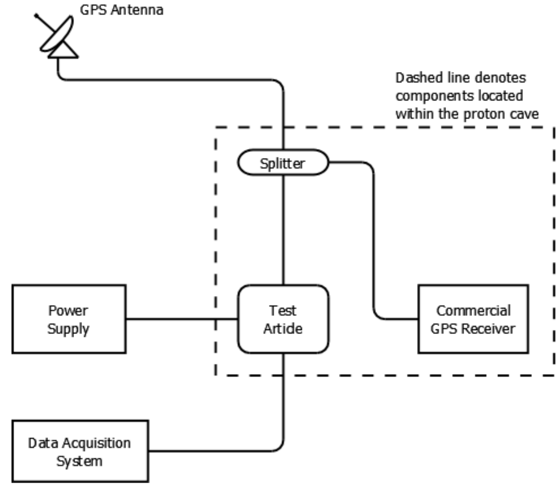


Figure 2. Block diagram showing hardware configuration for testing of GPS receiver

$14\,\mathrm{MeV}\cdot\mathrm{cm}^2/\mathrm{mg}$ which can then produce SEE. Thus, proton irradiation is only able to simulate a portion of most radiation environments, which can often include particles with LET of $50\,\mathrm{MeV}\cdot\mathrm{cm}^2/\mathrm{mg}$ or higher. It follows then that system-level failure rate estimates found as described in this paper are necessarily lower bounds on the failure probability during a mission. The additional contribution to the failure rate by higher LET particles is expected to be low due to the relatively short duration of launch vehicle missions, but remains unquantifiable using energetic protons alone. For this reason, proton testing in the manner described in this paper should not be used as a substitute for applying system-level radiation requirements, particularly in the case of mission-critical hardware.

2. Experimental Approach

Test Configuration

The unit to be tested included a commercially available serial communications card, CPU controller, and GPS receiver board (Table 1). CCAs from a production unit were removed from the housing and mounted to a commercially available PC/104 motherboard which provided power and serial interfaces to the CPU and serial communication cards. The Javad JNS100 was mounted to the motherboard and customized cabling was fabricated which reproduced all electrical connections present inside a production unit. The completed test article (Fig. 1) was then mounted to an aluminum plate which had been drilled to match the translation table in the proton chamber.

Power to the test article was provided by an external source which limited current levels to 120 percent of the nominal operating current and was configured to discontinue power if current levels were exceeded in order to mitigate against damage to the unit due to proton-induced SEL. Telemetry outputs were monitored by a proprietary data-acquisition system and a GPS signal was provided to the receiver using a rooftop mounted GPS antenna. To verify the GPS signal, the antenna signal was connected in parallel to the test unit with a hand-held commercial GPS receiver. A diagram of the test hardware configuration is shown in Fig. 2.

Irradiation of Test Article

SEU testing was performed with 50 MeV protons using the 88-inch cyclotron at the Lawrence Berkeley National Laboratory. The test article was mounted to the translation table and oriented perpendicular to the beam throughout the test. Four locations on the test unit were irradiated using 1-inch and 3-inch beam diameters in an attempt to isolate devices that were deemed particularly suspect due to high pin counts and part complexity [1]. All irradiation was performed in air at ambient temperature.

Total proton fluence at each location was held to 1.1×10^9 $\mathrm{particles}/\mathrm{cm}^2$ in order to limit the total dose to the unit. This was necessary since the components under irradiation were intended for use in another non-flight application. Instantaneous flux was approximately 1×10^6 $\mathrm{particles}/\mathrm{cm}^2\cdot\mathrm{sec}$. The test unit was powered and placed in a flight-like state before commencement of irradiation and was manually reset into that state via power-cycling after a change in telemetry output was witnessed.

Relationship of 50 MeV Proton LET Spectrum to Launch Vehicle Heavy Ion Environment

Launch vehicle radiation environments are highly variable due to the diversity in potential spacecraft trajectories. Design specifications typically incorporate worst-case flight trajectories and mission duration to estimate the potential radiation exposure of the vehicle. Depending upon the trajectory, the launch vehicle can be exposed to heavy ions, trapped pro-

Table 1. Circuit cards included in test unit

Manufacturer	Mfr Part Number	Component Description
Javad Navigation Systems	JNS100HDA	GPS receiver
RTD Embedded Technologies	CM316HR	Serial communication controller
RTD Embedded Technologies	CME137686LX333HR-512	CPU carrier
Parvus Corporation	PRV-0889	PC/104 motherboard

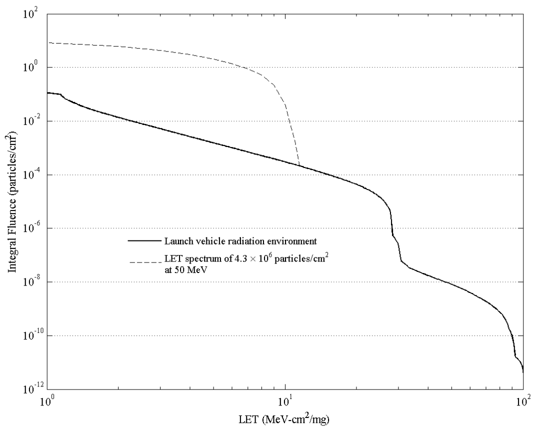


Figure 3. Launch vehicle radiation environment shown with scaled fluence of $50\,\mathrm{MeV}$ protons

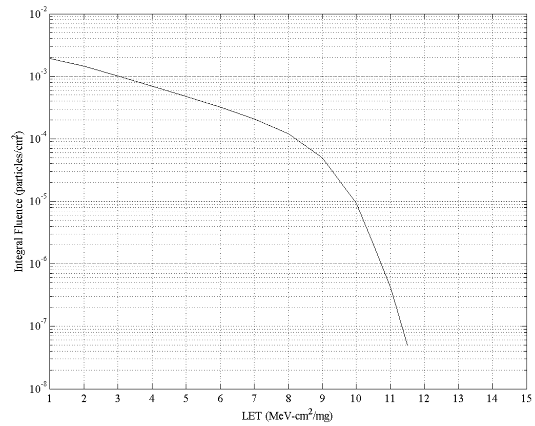


Figure 4. Integral LET spectrum of 1×10^{11} protons at $50\,\mathrm{MeV}$ derived from Hiemstra

tons, or some combination of both. For the present analysis, the radiation exposure of a launch vehicle during normal solar conditions was taken to be that of Fig. 3.

Calculations of the differential LET spectra for 50, 100, 200, and 500 MeV protons in silicon have been performed by Hiemstra and Blackmore [3]. An integral representation of the LET spectrum produced by a total fluence of 1×10^{10} $\mathrm{particles/cm^2}$ for 50 MeV protons is shown in Fig. 4. Scaling that integral LET spectrum derived from [3] yielded an equivalent launch vehicle proton fluence of 4.3×10^6 $\mathrm{particles/cm^2}$ per mission, where the radiation exposure per mission was assumed to be that shown in Fig. 3.

The total number of flights simulated during testing can be approximated as the total test fluence divided by the equivalent integral proton fluence per flight. From this, it follows that the total test fluence of 1.1×10^9 $\mathrm{particles/cm^2}$ corresponds to a simulation of 256 flights along the trajectory corresponding to the radiation environment in Fig. 3.

Upset Rate Estimate

The system-level upset rate per mission corresponding to the environment in Fig. 3 is then found as the ratio of the number of upsets observed during testing to the number of flights determined previously.

3. Results

The components tested and number of upsets observed during irradiation are shown in Table 2 along with a partial list of likely susceptible devices. Upsets occurring during irradiation of the receiver card caused a loss of solution for six to eight seconds, after which the system appeared to recover, before being manually reset. Irradiation of the CPU card caused a system crash which required power-cycling in order to clear. The serial communication card demonstrated no substantial change in output, though small current transients were witnessed during irradiation. At no time during testing was a false or incorrect GPS solution generated by the system. Soft errors manifested themselves only as a loss of positioning information or a system crash. Additionally, no SEL or high current conditions were observed during testing.

The total number of observed errors for the unit was found to be 21, where a single error for the serial communications card has been assumed. As discussed earlier, a lower bound on the failure probability during a mission was then calculated to be 0.082.

4. Discussion

Evaluation of Subsystem Performance

Since this device was intended as a range tracking asset, the primary concern during development was that soft errors due to radiation would lead to false position reporting. This phe-

Table 2. SEU results for COTS CCAs with list of potentially susceptible devices

Mfr Part Number	Upsets	Fluence ($\mathrm{particles/cm^2}$)	Suspect Devices
JNS100HDA	10	1.1×10^9	Javad JPSCore ASIC, NEC UPD442002F9-BB70X-BC1 SRAM, Intel GE28F320C3BD70 flash
CM316HR	0 (1)	1.1×10^9	Xilinx XC95288XL-7FG256I FPGA, Zilog Z8523016VEG serial comm. controller
CME137686LX333HR-512	10	1.1×10^9	AMD ALXD800EEXJ2VF processor, AMD CS5536AF LX companion, Micro MT46V32M16BN-6I SDRAM, Xilinx XC2C256 PLD

nomenon was not witnessed during testing and is not anticipated due to message structure and formatting. Failure modes observed during testing included system crashes requiring restart to clear and temporary loss of GPS solution for several seconds before reacquisition of signal. Such a loss of GPS information may or may not be a design concern, depending upon application.

Difficulties of System-Level Proton Testing

Several challenges exist for application of this method to other hardware. First, as mentioned previously, results obtained from proton testing omit contributions to upset rates by heavy ions with LET greater than $14\,\mathrm{MeV} \cdot \mathrm{cm^2/mg}$. For highly-inclined or high-altitude trajectories, it is expected that the failure rate in this environment (Fig. 3) will exceed that predicted using energetic protons alone. However, while unable to show that a particular design meets a given reliability requirement, proton testing at the system-level can still serve as a useful aid in identifying particularly susceptible components, though complex board layouts (e.g., double-sided boards) can impede this to some extent.

A shortcoming to system-level proton testing as described in this paper is the lack of a statistically significant sample size. Since radiation testing as outlined here essentially sacrifices an entire unit, the sample size can be limited by cost and availability considerations. Additionally, implicit in this discussion lies an assumption that all future units produced during the life cycle of the design, which can be often be decades, will necessarily be identical in terms of components, software, technology, etc. The degree to which the test specimen is representative of all units used on future vehicles, will have a large impact on the degree of applicability of any test results to units procured in the future. It should be noted that these issues are intrinsic to the radiation assessment of any hardware and can only be expected to grow as COTS electronics find greater application within the aerospace industry. Use of COTS components, particularly complex circuit card assemblies, in mission-critical applications will continue to be a significant challenge for system designers.

A final consideration for proton testing at the system-level is the construction and procurement of components to be used in the test article. In the case described in this paper, substantial work was performed in order to convert a flight-configured avionics component into the test article described earlier. This unit and support equipment needed to be designed in a way that replicated flight operation, but that differed significantly from the flight design (specialized cabling, different CCA mounting configurations, etc.). Since design and complexity of avionics hardware vary dramatically, no two design solutions for a test article will be identical. Additionally, testing of a component in this manner requires collaboration between the supplier and designer in order to fabricate a test article that is compatible with testing requirements. This can add significantly to cost and scheduling if not front-loaded into the development cycle, since two dissimilar qualification units are essentially being designed and constructed.

Recommendations for Future Testing

Two improvements to the test methodology described here should potentially be adopted for future testing. First, as mentioned previously, total ionizing dose was a concern, since the circuit cards from the test article were required for a separate non-flight application. This necessarily limited the total proton fluence which could be delivered to the unit during testing. To increase the accuracy of the error rate predicted, as well as to aid in the observation of less common failure modes (e.g., proton-induced latchup), a higher fluence of protons should be used. Obviously, an increase in proton test fluence must be tempered with the understanding that a substantial increase in TID can skew test results. During testing, it was assumed that COTS hardware could tolerate a TID level of several hundred rad(Si) [1], though the amount actually delivered during irradiation was less than $200\,\mathrm{rad}$(Si).

A second consideration for future testing is the use of alternate proton energies, particularly lower energy protons. Since only one test energy was used during testing, it remains unclear as to how the upset rate for the unit might depend upon proton energy. Determination of a saturation cross-section and upset threshold energy may enable a more quantitative understanding of the overall system response in various environments, particularly trapped particle environments. Additionally, system-level testing should also make an attempt to quantify the dependence of the upset rate on proton incidence angle. Both variables could be explored with minimal changes to test hardware.

5. SUMMARY

A novel approach for radiation susceptibility characterization has been demonstrated that allows for a clearer understanding of the impact of SEE at the system level. In the case described here, a lower bound on the mission failure rate was established by relating the results of 50 MeV proton irradiation to a sample radiation environment. This method is generallly applicable to other hardware, though some design-specific adaptations will need to be made. Challenges in applying it to other hardware were discussed and recommendations for future testing and hardware development have been made.

ACKNOWLEDGMENTS

The authors wish to thank Rocky Koga and Jeff George with The Aerospace Corporation as well as Michael Johnson and the staff of the 88-inch cyclotron at LBNL for their invaluable assistance.

This program is part of a larger collaboration between the AFSPC and ULA with the goal of reducing customer cost and support of the Space-Based Range Initiative.

REFERENCES

[1] K. A. LaBel, P. W. Marshall, T. D. Gruner, R. A. Reed, and B. Settles, "Radiation evaluation method of commercial off-the-shelf (COTS) electronic printed circuit boards (PCBs)," in *RADECS 99*, 1999.

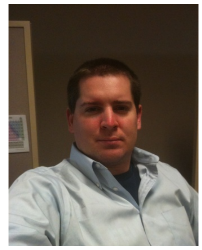
[2] P. O'Neill, G. Badhwar, and W. Culpepper, "Internuclear cascade-evaporation model for LET spectra of 200 MeV protons used for parts testing," *IEEE Trans. on Nuclear Science*, vol. 45, no. 6, pp. 2467–2474, December 1998.

[3] D. M. Hiemstra and E. W. Blackmore, "LET spectra of proton energy levels from 50 to 500 MeV and their effectiveness for single event effects characterization of microelectronics," *IEEE Trans. on Nuclear Science*, vol. 50, no. 6, pp. 2245–2250, December 2003.

[4] K. Label, "Proton-induced transients in optocouplers: Inflight anomalies, ground irradiation test, mitigation, and implications," *IEEE Trans. on Nuclear Science*, vol. 44, no. 6, pp. 1885–1892, December 1997.

[5] K. Rodbell, D. F. Heidel, and M. G. H.H.K Tang, "Low-energy proton-induced single-event-upsets in 65 nm node, silicon-on-insulator latches and memory cells," *IEEE Trans. on Nuclear Science*, vol. 54, no. 6, pp. 2474–2479, December 2007.

BIOGRAPHY



George M. Castillo received his B.S. degree in physics from Colorado State University in 2007 with an emphasis in mathematical methods. Since 2007, he has been with United Launch Alliance (ULA) as a radiation effects scientist for the Delta and Atlas families of evolved-expendable launch vehicles.

Brian A. Ratkevich received his B.S. in electrical engineering from the University of California, Santa Barbara in 1986, and a M.Eng in Computer Engineering from Stevens Institute of Technology, Hoboken, NJ in 1995. From 1990 to 1998 he was a member of the US Marine Corp Reserve (RF communications). From 1985 to present he has worked in the field of avionics design for space and army applications, concentrating in the areas of guidance and control systems and IRAD. He is currently the Chief Engineer of the Space-Based Range group with United Launch Alliance (ULA) of Centennial, CO where he works on future avionics systems for the Delta and Atlas launch vehicles.