Road Vehicle Functional Safety in Ground-Level Radiation Environments

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## Acronyms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>ADAS</td>
<td>Advanced driver assist systems</td>
</tr>
<tr>
<td>AIA</td>
<td>Atmospheric Imaging Assembly</td>
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<tr>
<td>AIEE</td>
<td>American Institute of Electrical Engineers</td>
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<tr>
<td>CME</td>
<td>Coronal mass ejection</td>
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<tr>
<td>COTS</td>
<td>Commercial-off-the-shelf</td>
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<tr>
<td>CTO</td>
<td>Chief Technology Officer</td>
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<tr>
<td>EEE</td>
<td>Electrical, electronic, and electromechanical</td>
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<tr>
<td>ESA</td>
<td>European Space Agency</td>
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<tr>
<td>EVE</td>
<td>Extreme Ultraviolet Variability Experiment</td>
</tr>
<tr>
<td>FIT</td>
<td>Failures in time</td>
</tr>
<tr>
<td>FMEDA</td>
<td>Failure modes, effects, and diagnostic analysis</td>
</tr>
<tr>
<td>FPGA</td>
<td>Field programmable gate array</td>
</tr>
<tr>
<td>GCR</td>
<td>Galactic cosmic ray(s)</td>
</tr>
<tr>
<td>GPU</td>
<td>Graphics processing unit</td>
</tr>
<tr>
<td>GSFC</td>
<td>Goddard Space Flight Center</td>
</tr>
<tr>
<td>HMI</td>
<td>Helioseismic and Magnetic Imager</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>IRE</td>
<td>Institute of Radio Engineers</td>
</tr>
<tr>
<td>JEDAC</td>
<td>(independent semiconductor engineering trade organization)</td>
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<tr>
<td>LASCO</td>
<td>Large Angle and Spectrometric Coronagraph</td>
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<tr>
<td>MAPLD</td>
<td>Military and Aerospace Programmable Logic Devices (Workshop)</td>
</tr>
<tr>
<td>MBMA</td>
<td>Model-based mission assurance</td>
</tr>
<tr>
<td>MBSE</td>
<td>Model-based systems engineering</td>
</tr>
<tr>
<td>MBMA</td>
<td>Model-based mission assurance</td>
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<td>MBSE</td>
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<tr>
<td>MBU</td>
<td>Multiple-bit upset</td>
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<tr>
<td>MCU</td>
<td>Multiple-cell upset</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>NASEM</td>
<td>National Academies of Sciences, Engineering, and Medicine</td>
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<tr>
<td>NPSS</td>
<td>Nuclear and Plasma Sciences Society</td>
</tr>
<tr>
<td>NSREC</td>
<td>(IEEE) Nuclear and Space Radiation Effects Conference</td>
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<tr>
<td>QRT</td>
<td>Quality, Reliability, Technology (company)</td>
</tr>
<tr>
<td>SDO</td>
<td>Solar Dynamics Observatory</td>
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<tr>
<td>SEB</td>
<td>Single-event burnout</td>
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<td>SEE</td>
<td>Single-event effect(s)</td>
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<tr>
<td>SEFI</td>
<td>Single-event functional interrupt</td>
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<tr>
<td>SEGR</td>
<td>Single-event gate rupture</td>
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<tr>
<td>SEL</td>
<td>Single-event latchup</td>
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<tr>
<td>SERESSA</td>
<td>School on the Effects of Radiation on Embedded Systems for Space Applications</td>
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<tr>
<td>SET</td>
<td>Single-event transient</td>
</tr>
<tr>
<td>SEU</td>
<td>Single-event upset</td>
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<tr>
<td>SIP</td>
<td>System-in-a-package</td>
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<tr>
<td>SoC</td>
<td>System-on-a-chip</td>
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<tr>
<td>SOHO</td>
<td>Solar and Heliospheric Observatory</td>
</tr>
<tr>
<td>SoM</td>
<td>System-on-module</td>
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<tr>
<td>$SWaP$</td>
<td>Size, weight, and power</td>
</tr>
<tr>
<td>TID</td>
<td>Total ionizing dose</td>
</tr>
<tr>
<td>TNID</td>
<td>Total non-ionizing dose</td>
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Acknowledgements

• Mr. Sung, CTO at QRT
• NASA Electronic Parts and Packaging (NEPP) Program
  • https://nepp.nasa.gov/
• Many additional contributors across academia, government, and industry
Outline

• Natural space radiation environment and linkage to ground-level environment

• Radiation effects in ground-based electronic systems
  • Focus on single-event effects (SEE)
  • Excludes cumulative effects like total ionizing and non-ionizing dose (TID, TNID)

• Current areas of focus for commercial-off-the-shelf (COTS) electronics in reliable systems

• Future needs for COTS electronics in reliable systems

• Conclusion / Question & Answer
01
Space and Ground-Level Radiation Environments
Natural Space Radiation Environment

- Galactic Cosmic Rays (GCRs)
- Trapped Particles
- Protons, Electrons, Heavy Ions
- Solar Protons
- Heavier Ions

After J. Barth, 1997 IEEE NSREC Short Course; K. Endo, Nikkei Science Inc. of Japan; and K. LaBel private communication.
Sun-Earth Connection

- Space weather is driven by changes in the Sun’s magnetic field and by the consequences of that variability in Earth’s magnetic field and upper atmosphere.
  - Space weather is generally mild but some times extreme.
  - Societal interest in space weather grows rapidly.
  - Space weather is an international challenge.
  - Mitigating against the impacts of space weather can be improved.
  - Existing observatories that cover much of the Sun–Earth system provide a unique starting point.

The Sun Controls Space Weather

Coronal Mass Ejection and Filament (24-Feb-2015)


Courtesy of NASA/SDO and the AIA, EVE, and HMI science teams.

Courtesy of SOHO/LASCO consortium. SOHO is a project of international cooperation between ESA and NASA. (Mercury transit in background)
Energetic Particles in Earth’s Atmosphere

- High-energy particles impact Earth’s atmosphere and create air showers, which generate a variety of particles that reach ground level -- anisotropic
- Depends on latitude/longitude, atmospheric depth, and solar activity


Alpha (\(^{4}\text{He}\)) Particle Radiation

- \(^{232}\text{Th}\) and \(^{235/238}\text{U}\) are relatively abundant in terrestrial materials used in electronics processing and active enough to be a radiation effects concern

Radiation Effects Overview
What Makes Radiation Effects So Challenging?

• Field is still evolving as are the technologies we want to use (e.g., process nodes, level of integration, etc.)

• A problem of dynamic range
  • Length: $10^{16}$ m $\rightarrow$ $10^{-15}$ m (1 light year $\rightarrow$ 1 fm)
  • Energy: $10^{19}$ eV $\rightarrow$ 1 eV (extreme energy cosmic ray $\rightarrow$ silicon bandgap)
  • Those are just two dimensions; there are many others.
    • Radiation sources, electronic process technologies (e.g., Si vs. GaN), etc.

• Variability and knowledge of the local radiation environment
What Are Radiation Effects?

- Energy deposition rate in a “box”
- Source of energy and how it’s absorbed control the observed effects
Common Energy Deposition Processes at Ground-Level

• Direct and indirect ionization, examples

From radioactive impurities ($^{232}$Th, $^{239,235}$U, $^{210}$Po, etc.)

- Direct ionization characterized by stopping power, $dE/dx$

High-energy neutrons (>1 MeV)

- $n + ^{28}$Si reaction showing some of the reaction pathways and associated threshold energies

- Not covering effects due to low-energy/thermal neutrons, which can be an issue for technologies that contain $^{10}$B

Energy Deposition in Silicon

What Are Single-Event Effects (SEE)?

• A single-event effect is a disturbance to the normal operation of a circuit caused by the passage of a single ion (e.g., alpha particle or neutron inelastic reaction product) through or near a sensitive node in a circuit

• SEEs can be either destructive or non-destructive

Several Representative SEE Types

<table>
<thead>
<tr>
<th>Non-Destructive</th>
<th>Destructive</th>
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<tr>
<td>Single-Event Upset (SEU)</td>
<td>Single-Event Latchup (SEL)</td>
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After S. Buchner, SERESSA 2011 Course, Toulouse, France
• Knowledge (via validated simulation results and/or experimental measurements) of the SEE event rate at the component level and/or the realized fault probability at the (sub-)system level is essential
Current Focus Areas for COTS
Electronics in Reliable Systems
Important Distinction Between Aerospace & Automotive

• Spacecraft and payloads are still largely custom-built
• Touch labor and significant testing for validation
• Traditionally, little to no economy of scale

Image Credit: NASA
Important Distinction Between Aerospace & Automotive

→ What are COTS parts?

• Space users’ perspective
  • Parts designed for applications where the specifications, materials, etc. are established solely by the manufacturer/vendor pursuant to market forces
  • Parts not explicitly designed for space applications
    • May have additional requirements imposed by users or external organizations
  • Automotive-grade parts are a type of COTS hardware, but fall into a unique category

Image Credit: NASA

Xilinx Virtex-7 FPGA prepared for radiation testing
Road Vehicle Functional Safety – Radiation Perspective

- SEE shows up as **random hardware failures**
  - Stochastic failure that can occur during the lifetime of a component
- SEE follows a probability distribution that may or may not be known
  - Constant with time, state-dependent, etc.
- Can impact both availability and reliability
ISO 26262 Automotive Safety Integrity Levels (ASIL)


<table>
<thead>
<tr>
<th>Level</th>
<th>Associated Severity Class</th>
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<tbody>
<tr>
<td>ASIL A</td>
<td>No injuries</td>
</tr>
<tr>
<td>ASIL B</td>
<td>Light and moderate injuries</td>
</tr>
<tr>
<td>ASIL C</td>
<td>Severe and life-threatening injuries (survival probable)</td>
</tr>
<tr>
<td>ASIL D</td>
<td>Life-threatening injuries (survival uncertain), fatal injuries</td>
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Functional Safety Analysis Implications for Radiation Effects

• Produces a range of implications for component-level radiation response knowledge, efficacy of validation practices, and ultimate system visibility


<table>
<thead>
<tr>
<th>ASIL</th>
<th>Failure Rate</th>
<th>Single Point Failure Metric (SPFM)</th>
<th>Latent Failure Metric (LFM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>&lt; 1000 FIT</td>
<td>Not relevant</td>
<td>Not relevant</td>
</tr>
<tr>
<td>B</td>
<td>&lt; 100 FIT</td>
<td>≥ 90%</td>
<td>≥ 60%</td>
</tr>
<tr>
<td>C</td>
<td>&lt; 100 FIT</td>
<td>≥ 97%</td>
<td>≥ 80%</td>
</tr>
<tr>
<td>D</td>
<td>&lt; 10 FIT</td>
<td>≥ 99%</td>
<td>≥ 90%</td>
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1 FIT = 1 failure in $10^9$ device-hours
Current Hardware Assurance Focus Areas

- Spans both component- and packaging-levels
  - Workmanship and board-level issues are separate; still critical

- Power device technologies (e.g., GaN, Si, and SiC)
- Memories – volatile and non-volatile
- FPGAs, GPUs, Processors, and SoCs / SoMs / SiPs
- Packaging – 2.5D/3D, new substrates, Ag/Cu bond wire
- Characterization, Guideline, and Knowledge Objectives
- Model-based mission assurance (MBMA)
Observed Trends and Challenges

Current and emerging programs continue to pose new technological challenges – size, weight, and power (SWaP)

Finite budgets and truncated schedules force designers and management to push technologies to their physical limits

Budget and schedule pressures challenge how technologies and products are verified

Need a clear understanding of the different verification processes to ensure proper verification of the technology

Capabilities, advantages, and limitations of the testing and inspection performed at each level are different, and the risk incurred by omitting verification steps depends on the level of integration as well as the application, (radiation) environment, and lifetime

Future Needs for COTS Electronics in Reliable Systems
Climbing the Autonomy Ladder

- Climbing to Level 3+ requires massive computing power and levels of real-time ADAS integration that will necessitate a shift in testing and verification methodologies.
- What will “adequate” state space coverage look like for a system guaranteed to experience random failures from radiation events?
Adapting to the COTS Assembly

• Increasing the integration level of fundamental elements may speed technology insertion and adaptability
  • Confounds current evaluation approaches
• Physics of failure requires deep insight – not always available
• Given a modular architecture, what will happen if hardware is intentionally refreshed periodically?
  • Adapt to security risks & customer demands
  • Mitigate impact of process defect ceiling constraints
  • How will this impact the supply chain and functional safety verification processes?

Set of NanoRacks CubeSats is photographed by an Expedition 38 crew member after the deployment by the NanoRacks Launcher attached to the end of the Japanese robotic arm
Radiation Engineering & Testing Infrastructure

- Even with sophisticated modeling, radiation testing remains essential to characterize, qualify, and validate

- Radiation testing facilities are often unique and the required engineering expertise is highly-specialized and takes time to develop

- NASEM report provides:
  - Background on space environment and its effects on electronics
  - Current state of single-event effects hardness assurance and infrastructure
  - Future infrastructure needs and a path forward

*Testing at the Speed of Light* – The State of U.S. Electronic Parts Radiation Testing Infrastructure

Committee on Space Radiation Effects Testing Infrastructure for the U.S. Space Program
National Materials and Manufacturing Board
Division on Engineering and Physical Sciences

The National Academies Press
Washington, DC
www.nap.edu

Additional Thoughts for Consideration

  - Analyzes the social side of technological risk
  - Examines complex vs. linear interactions and tight vs. loose coupling
  - Argues that conventional engineering approaches to ensuring safety fail because systems complexity makes failure inevitable
    - Pessimistic view, but worth considering

  - Presents a multi-stage framework for establishing accurate use conditions inputs for product reliability modeling
  - Discusses knowledge-based qualification of integrated circuit products, which includes predicting product failure in the field over time for failure mechanisms
Partnering is Critical for Success

- Radiation effects is one of the most challenging areas for reliable system design
  - Cross-cutting, multi-disciplinary
- NASA partners with:
  - Academia
  - Industry
  - International
  - Other government agencies
- Encourage expansion internal to and external from automotive electronics community
Summary

• Space radiation, and modulation due to space weather, affects the terrestrial radiation environment (e.g., neutrons et al.) -- alpha particles are an additional environment

• SEE are initiated by the ground-level radiation environment and can produce failures that propagate through systems

• Performance requirements in combination with size, weight, power, and cost constraints will challenge verification methodologies, including potential radiation testing

• Adapting radiation engineering processes at the assembly level will be a paradigm-shifting challenge

• Partnering and knowledge sharing is always beneficial and will become essential to meeting and overcoming challenges
International Space Station is seen in this twenty-second exposure as it flies over the Washington National Cathedral, 29-Nov-2017.

Image credit: NASA