

NEPP ETW 2019

Model-Based Radiation Assurance for Satellites with Commercial Parts A. Witulski, B. Sierawski, R. Austin, G. Karsai, N. Mahadevan, R. Reed, R. Schrimpf

Vanderbilt University

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CRÈME: Cosmic Ray Effects on Micro-Electronics Code GSN: Goal Structuring Notation JWST: James Webb Space Telescope MBMA: Model-Based Mission Assurance MBE: Model-Based Engineering MOSFET: Metal Oxide Field Effect Transistor MRQW: Microelectronics Reliability & Qualification Workshop NASA: National Aeronautics and Space Administration R&M: Reliability & Maintainabiltiy R-GENTIC: Radiation GuidelinEsfor Notional Threat Identification and Classification RESIM Radiation Effect System Impact Modeling RHA: Radiation Hardness Assurance SEAM: System Engineering and Assurance Modeling SEB: Single Event Burnout SiC: Silicon Carbide STD: Standard SysML: System Modeling Language

Radiation Assurance Approaches for Space Systems

Conventional:

- Widespread use of radiationhardened components
- Deep knowledge of components
- Several heavy-ion beam test campaigns
- Informed use of physics-based radiation modeling tools
- Relatively high budget and longterm development schedule
- Formal documentation of test procedures and results

"New, Commercial Space"

- Widespread, if not 100% use of COTS parts
- Little insight into components
- Minimal testing, possibly only proton testing of sub-systems
- Little use of radiation modeling tools
- Low budget, accelerated development schedule
- Little formal documentation or evidence of radiation behavior

Radiation Assurance for Space Systems

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What can we do early in the development of the project, other than formal modeling or ion-beam testing, to "buy down" risk of radiation-related failures?

Useful radiation reliability assurance platform characteristics:

- Model-based approach=digital representation of objects
- Tolerant of uncertainty, various levels of model fidelity
- Flexible as new info/design changes become available
- Qualitative arguments about why the system will work
- Quantitative estimates for reliability and location of weak links
- Systematically covers known faults (not ad hoc)

System Engineering and Assurance Modeling (SEAM) Platform

- Web-browser based
- Can access as guest or create account
- Creates system model diagrams and argument for radiation assurance case
- Maintained by Vanderbilt University
- Contains examples and tutorial information

https://modelbasedassurance.org/

GSN Assurance Models

SEAM supports the Goal Structuring Notations (GSN) standard to build assurance case models. SEAM uses hierarchical models, as well as cross-referencing to manage complexity in GSN models. Additionally, SEAM allows linking assurance cases to system models to provide context to the assurance case argument.

Integrated Models

SEAMS allows context specification through crossreferencing of modeling entities across the models. Functional models are cross-referenced in the system fault propagation models to capture the impact (function loss or degradation) of and response (mitigation function) to failure effects. Sub-system models that implement specific functions are cross-referenced in functional models. Subsystem and functional models are cross-referenced in

System Models

SEAM supports a subset of block diagram models in the SysML modeling standard. These include functional (hierarchical requirement) models and architecture design with block diagram models.

NASA R&M Hierarchy

NASA's Reliability and Maintainability Standard serves as a template to build radiation hardness assurance cases for using COTS systems in space missions. SEAMs provides template models of the R&M hierarchy to kick-start the assurance case development.

Examples

A set of examples is available including:

Fault Models

SEAM extends the internal block diagram models to allow specification of discrete fault propagation to capture the faults and their anomalous effects within a block (subsystem) and their propagation across the system through subsystem interfaces.

Collaborate

Collaborate with your colleagues by simultaneously working on the same project. SEAM uses the WebGME modeling framework that works just like Google Docs; it updates and shows all changes to each user concurrently. And you never lose work because the models are stored in a database in the cloud.

Overall System Reliability Characterization Flow

Systems Engineering Assurance and Modeling (SEAM)

Program History

• FY16: Started as collaboration of NASA OSMA, HQ, NEPP

- Work on Goal Structuring Notation Safety Cases
- Single events on SRAM CubeSat application
- FY17: collaboration of NASA OSMA, HQ, NEPP
	- Added SysML and Bayesian Nets (BN) to platform
	- JPL sponsors application to C&DH board
- FY18: NASA OSMA, HQ, NEPP, JPL
	- Coverage Checks, Start work on Requirements, Compatibility with Magic Draw, Fault Trees
- FY19: NASA OSMA, HQ, NEPP, JPL
	- Requirements, Fault Trees
	- Initial import of radiation modeling tools
	- Application of SEAM to development lifecycle

Radiation Reliability Assessment of CubeSat SRAM Experiment Board

- **Assessment completed on REM**
	- 28nm SRAM SEU experiment
- **Reasons for integrated modeling**
	- 1. Use commercial off-theshelf (COTS) parts
	- 2. System mitigation of SEL
	- 3. System mitigation of SEFI on microcontroller Courtesy of AMSAT

Functional Model: Count Upsets in SRAM

Functional models associate functions with components

Architectural Model of REM Board

Component Fault Propagation Model

 \bullet \star \leq Block >> **LinearRegulator** Vout F 0.006 Reciet F ighCurrent HighCurrent **High Current** werDisconnect omerDieconnec **Power Disconnect** OffSignal On/Of Degraded Operation Vronal WrongResistance $\mathsf E$ **Resistance Incorrect Output Voltage Low Output Voltage**

Fault Propagation Models show how fault effects originate in components and propagate from the component through the structure of the system

Modelbasedassurance.org

Component Fault Propagation Model: Fault

TID, SEE Low Output Voltage

HighCurrent

OffSignal

On/Ofi

Resistance

 \bullet \star \leq Block >> **LinearRegulator** Vout F Fault Propagation $0_b/0_f$ Reciet Models show how fault effects originate in $F)$ **lighCurrent** components and propagate from the **High Current** werDisconnect component through **OMAR (Dienonnen** the structure of the **Power Disconnect** system **TID** Degraded Operation **Originating** ext Output Voltage Έ fault:

Component Fault Propagation Model: Anomaly

 \bullet \star \leq Block >> **LinearRegulator** Vout F $0_b/0_f$ Reciet $F)$ **lighCurrent** HighCurrent **ligh Curren** werDisconnect Anomaly: Effect of a OffSignal FaultOn/Ofi TIN Degraded Operation Mong\ WrongResistance Έ **Incorrect Output Voltage Resistance Low Output Voltage**

Fault Propagation Models show how fault effects originate in components and propagate from the component through the structure of the system

Component Fault Propagation Model: Port

 \bullet \star \leq Block >> **LinearRegulator** Vout F 0.006 Reciet Ĉ, Port: $\left(5\right)$ Passes anomalies to other components **High Current** HighCurrent werDisconnect **OMAR (Dienonned Power Disconnect** OffSignal On/Ofi Degraded Operatio[®] ifro n a t WrongResistance E **Incorrect Output Voltage Resistance**

Low Output Voltage

Fault Propagation Models show how fault effects originate in components and propagate from the component through the structure of the system

Colors/Shapes Denote Function

[1] GSN Community Standard Version 1 2011 environment and requirements

Goal=Claim **Strategy**=Inference **Solution**=Evidence **Context**=Background **Justification**=Rationale **Assumption**=Unsubstantiated Claim

Benefits of GSN

Makes assumptions explicit Connects assurance case to models of system Shows how argument is supported by evidence Context shows spacecraft

GSN Assurance REM SEU Experiment Board

- Top Goal states overall objective
- Mission constraints can be radiation environment, performance requirements, cost constraints, etc.
- Top-level goals and strategies track NASA R&M template

Mission Assurance over the Development Lifecycle

- Create radiation assurance case early in the development cycle-find radiation problems earlier
- "Time-Varying" Radiation Assurance Case
- *R. A. Austin*, R. D. Schrimpf, A. F. Witulski, N. Mahadevan, G. Karsai, B. D. Sierawski, and R. A. Reed, "Capturing and Modeling Radiation Hardness Assurance throughout the Project Lifecycle," 27th Annual Single Events Symposium, La Jolla, CA, 2019.
- Interaction of requirements, component knowledge, and system design information

The Parts Engineer
 Vanderbilt Engineering

- **Starting point: Single-event Burnout Requirement**
- **End work product: The approved part list**
- **Information needed: Mission orbit and lifetime (can change), parts currently in the system (can change), how the parts are used in the system (can change)**
	- How can I keep up to date with system changes?
	- How can I capture my analysis?

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Requirement

Pre-A \overline{R} ϵ \mathbf{D} F F Δ Project Concept Concept & **Preliminary Design Final Design & Operations &** System Assembly, Closeout Life-Cycle Technology & Technology **Studies** Fabrication Integration & Test, Sustainment Phases Development Launch & Checkout Completion

Requirement Defined

 Id : RAD1

less than 1%

Text:

• **Beginning of Phase B: GSN template for part assurance**

- Generic goals generated from part assurance templates
- Framework for planning RHA activities

shall be less than 1%

<<Requirement>> **Ref - SEB Requirement** Goal **Part survives SEB** The probability of failure from SEB shall be **Strategy Determine part** susceptibility to SEB • **Requirement: The probability of failure from SEB Strategy** • Estimate environment • Perform radiation Goal test **Probability of failure from** • Calculate probability SEB is less than 1% of failure

Requirement

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Requirement

 \overline{R} C \mathbf{D} F Pre-A \mathbf{A} F Project Concept Concept & **Preliminary Design Final Design & System Assembly, Operations &** Closeout Life-Cycle Technology **Studies** & Technology Fabrication Integration & Test, Sustainment Phases Launch & Checkout Development Completion <<Requirement>> **Strategy Ref - Parametric Requirement** • Estimate Id : RAD3 environment • Perform radiation Text: test The operating voltage • Calculate failure for the part shall be 600 V probability or greater **Ref - Goal** Goal Goal **Calculate probability of Perform radiation test Estimate environment** failure \overline{c} <<Requirement>> **Ref - SEB Test Requirement** Id: RAD2 **Solution Solution Environment description Results of test** Text: **Heavy ion testing** shall be performed to an LET of 37 MeV-cm²/mg

- **Information about system needed in order to perform test:**
	- Mission length, orbit, and shielding \rightarrow Inputs to environment tool
	- Part use in system \rightarrow Inputs to determine parametric failure levels
	- Outputs from environment tool and part failure analysis \rightarrow Inputs for radiation test

Requirement

Requirement

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tool and part failure **Cumulative SPE:** \overline{c} <<Requirement>> $C = 99%$ GEO **SEB Test Requirement** tool and part failure LEO RAD₂ **Solution** analysis \rightarrow Inputs for **Results of test** $\frac{9}{5}$ 10⁻⁵ radiation test **Heavy ion testing** 10^{-7} be performed to an 10° 10^{-1} $10⁰$ $10¹$ 10^2 of 37 MeV-cm²/mg LET (MeV-cm²/mg)

Requirement

Project

Phases

Life-Cycle

perform test:

radiation test

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Requirement

Project

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Life-Cycle

perform test:

radiation test

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Requirement

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Today's Example: Single Event Burnout Requirement *Vanderbilt Engineering* Pre-A B C D E F \mathbf{A} Project Concept & **Preliminary Design Final Design & System Assembly, Operations &** Concept Closeout Life-Cycle Technology & Technology Integration & Test, **Studies** Fabrication Sustainment Phases Launch & Checkout Development Completion Reliability Predicted• **Requirement: Mission shall meet a reliability level** O O Goal • **End of Phase C Calculate probability of** - Probability calculation failure - Assuming nothing changed about the system from Phase B Ö **Solution Probability of failure**

Today's Example: Single Event Burnout Requirement *Vanderbilt Engineering* Pre-A B C D E F \mathbf{A} Project Concept & **Preliminary Design Final Design & Operations &** Concept System Assembly, Closeout Life-Cycle Technology & Technology Integration & Test, **Studies** Fabrication Sustainment Phases Launch & Checkout Development Completion Reliability Predicted• **Requirement: Mission shall meet a reliability level** O O Goal • **End of Phase C Calculate probability of** - Probability calculation failure - Assuming nothing changed about the system from Phase B \rightarrow 1100 V H _{R50} V 0.8 \leftrightarrow 650 V • **Reliability calculation attached to solution** \triangle 600 V Reliability
Reliability
0.4 200 400 600 800 1000 Aluminum Shield Thickness (mils)

- **MBMAis a function of time**
	- Captures the evolution of mission assurance as the system is developed
- **MBMAenables concurrent engineering of reliability and design engineering**
	- Argument structure show how a requirement is verified and how it is derived
- **MBMAenables intelligent mission-specific requirements**
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Fault Tree Generation Capability Added to SEAM

- **Fault tree captures logical relationships between events**
- **Inputs are probabilities of events**
- **System information in SEAM SysML model can be used to generate fault trees for various system functions**
- **Fault tree structure can be exported in standard format to other reliability tools**

Example: Fault Tree for Temperature Control Loop of a Command and Data-Handling Board

Vanderbilt Engineering

Component failure modes

- Promote visibility and adoption of SEAM, e.g., University Nanosat program at AFRL, S3VI at NASA, AAQ at Auburn, NASA MBx community
- Lower the barriers to learning and using SEAM-identify required prior knowledge and skills and make that information explicit
- Develop more libraries and templates of common spacecraft components, functions, assurance arguments

Bibliography

Systems Engineering Model-Based Assurance (SEAM)

- R. Austin, "A Radiation-Reliability Assurance Case Using Goal Structuring Notation for a CubeSat Experiment," M.S. Thesis, Vanderbilt University, 2016.
- Evans, J. Cornford, S., Feather, M. (2016). "Model based mission assurance: NASA's assurance future," Reliability and Maintainability Symposium, p. 1-7. RAMS. 2016.
- Sanford Friedenthal, Alan Moore, Rick Steiner, "OMG SysML™ Tutorial," [www.omgsysml.org/INCOSE-OMGSysML-Tutorial-Final-090901.pdf,](http://www.omgsysml.org/INCOSE-OMGSysML-Tutorial-Final-090901.pdf) INCOSE, 2009.
- A. Witulski, R. Austin, G. Karsai, N. Mahadevan, B. Sierawski, R. Schrimpf, R. Reed, "Reliability Assurance of CubeSats using Bayesian Nets and Radiation-Induced Fault Propagation Models," NEPP Electronic Technology Workshop (ETW), 2017, nepp.nasa.gov/workshops/etw2017/talks.cfm.
- GSN Community Standard Version 2, Assurance Case Working Group (ACWG), SCSC-141B, Jan. 2018.
- J. W. Evans, F. Groen, L. Wang, R. Austin, A. Witulski, N. Mahadevan, S. L. Cornford, M. S. Feather and N. Lindsey, "Towards a Framework for Reliability and Safety Analysis of Complex Space Missions" Session 269-NDA-06, 2017 AIAA SciTech Conference, Grapevine, Texas, January 11, 2017.

Bibliography

- *Vanderbilt Engineering* A. Witulski, B. Sierawski, R. Austin, G. Karsai, N. Mahadevan, R. Reed, R. Schrimpf, K. LaBel, J. Evans, P. Adell, "Model-Based Assurance for Satellites with Commercial Parts in Radiation Environments," Paper SSC18-WKV-04, AIAA Small Satellite Conference, Ogden, Utah, August 2018, available online in Small Sat archive.
- B. Sierawski, R. Austin, A. Witulski, N. Mahadevan, G. Karsai, R. Schrimpf, R. Reed, "Model-Based Mission Assurance," 27th Annual Single Event Effects (SEE) Symposium, May 21-24, 2018, San Diego, CA.
- R. Austin*,* N. Mahadevan, J. Evans, A. Witulski, "Radiation Assurance of CubeSat Payloads Using Bayesian Networks and Fault Models," 64th IEEE Annual Reliability and Maintainability Symposium, Reno, NV, January 22-25, 2018.

Radiation Effect System Impact Modeling (RESIM) (Mentor Questa Flow)

- A. F. Witulski, N. Mahadevan, Jeff Kauppila, Gabor Karsai, Philippe Adell, Harald Schone, Ronald D. Schrimpf, "Simulation of Transistor-Level Radiation Effects On Board-Level Performance Parameters," IEEE Radiation Effects on Components and Systems, (RADECS), Sept. 2018.
- A. F. Witulski, N. Mahadevan, Jeff Kauppila, Gabor Karsai, Philippe Adell, Harald Schone, Ronald D. Schrimpf, A. Privat, and H. Barnaby, "Simulation of Transistor-Level Radiation Effects On System-Level Performance Parameters," Accepted for publication in the IEEE Transactions on Nuclear Science**.** Available on IEEE Xplore Early Access