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Overview of Model-Based System Assurance for Spacecraft with Commercial Parts

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Acronyms and Abreviations

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COTS: Commercial Off the Shelf components
CRÈME: Cosmic Ray Effects on Micro-Electronics Code
GSN: Goal Structuring Notation
MBMA: Model-Based Mission Assurance
MBSE: Model-Based System Engineering
MRQW: Microelectronics Reliability & Qualification Workshop
NASA: National Aeronautics and Space Administration
R&M: Reliability & Maintainabilty
R-GENTIC: Radiation Guideline for 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
SEL: Single Event Latchup
STD: Standard
SysML: System Modeling Language

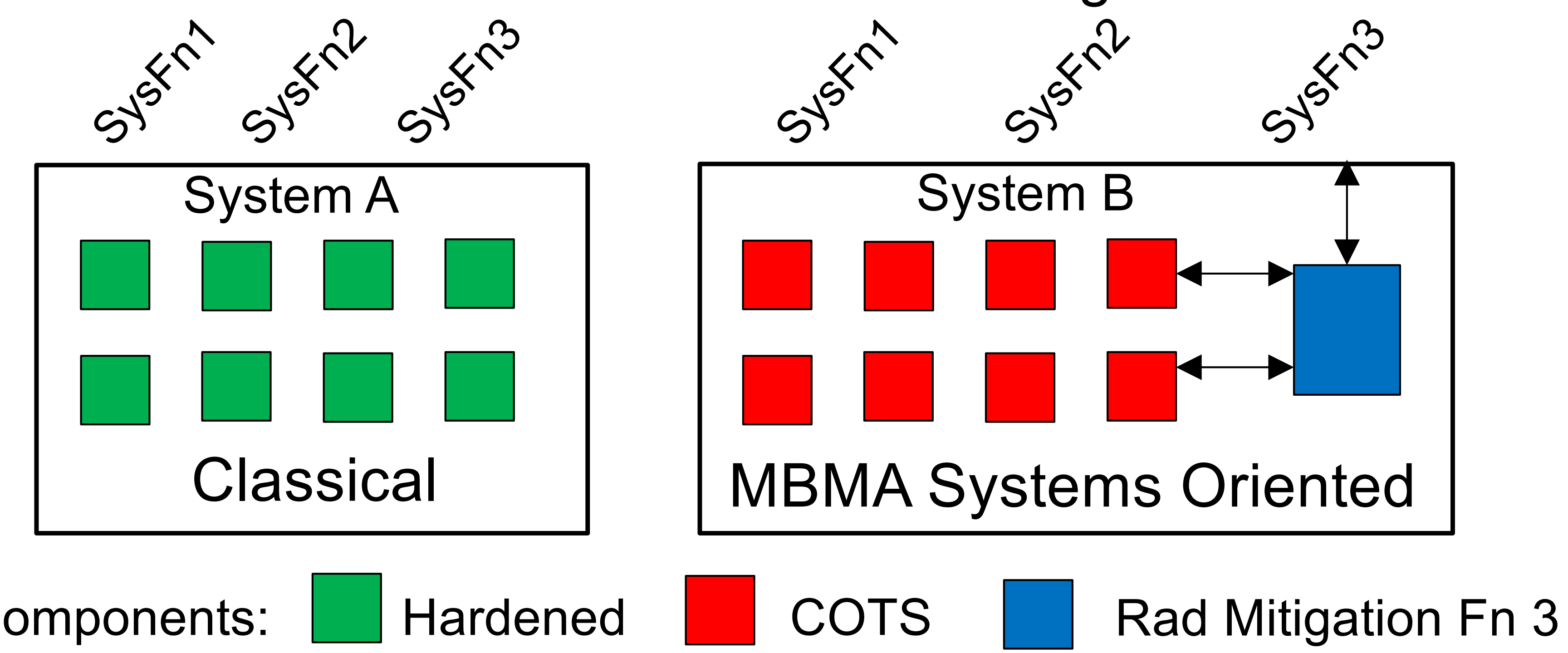
Classical and Systems-Oriented Radiation Analysis

If Parts Rad-Hard,

⇨ System Rad Hard

If System Rad-Tolerant,

⇨ Part params allowed to vary, or mitigation is added



Radiation Assurance Approaches for Space Systems

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Classical Radiation Analysis:
- Widespread use of radiation-hardened components
- Deep knowledge of components
- Several heavy-ion beam test campaigns
- Informed use of physics-based radiation modeling tools
- Relatively high budget and long-term development schedule
- Formal documentation of test procedures and results

"New, Commercial Space"
- Widespread, if not 100% use of Commercial (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

Class A ⟵⟶ Class D

Pros and Cons of Radiation Assurance Approaches

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Classical Radiation Analysis:
- Rock-solid hardness
- Justifiable by testing/analysis
- Extensive knowledge base
- Don't need to estimate part lifetimes or degradation
- Testing expensive, time-consuming
- Must be repeated if parts change
- Over-subscribed beam facilities
- Rad-hard parts expensive, long lead times, lag commercial performance curve

Model-Based Systems Approach
- Enables use of COTS parts
- Can be started early in design cycle, then iterated
- Easily changed
- Gives estimate of part degradation, impact on system
- Requires knowledge of system
- Inadequate modeling info available
- Difficult to model system in detail
- Requires learning of tools

Class A ⟷ Class D

Two System Radiation Characterization Flows

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Rad Effects System-Impact Modeling (RESIM)

Questa, Coside
- Quantitative
- Based on rad data
- Mixed Signal Sim
- Functional models

System Waveforms
- Electrical +Rad sims
- Timing diagrams
- Probability distributions

Physical Modeling

Systems Engineering Assurance Modeling (SEAM)

SysML: Diagramatic
- System Architecture
- Part rad faults
- System functions
- Specifications

GSN: Text Based
- Specifications
- Environment info
- Goal/Strategy/Evidence
- Assurance Argument

Bayesian Nets
- Identify a function
- Create BN graph
- Export to BN Tool

Fault Trees
- Tied to system functions
- Create FT structure
- Export to FT Eval tools

Logical Modeling

SEAM Systems Engineering Assurance Modeling

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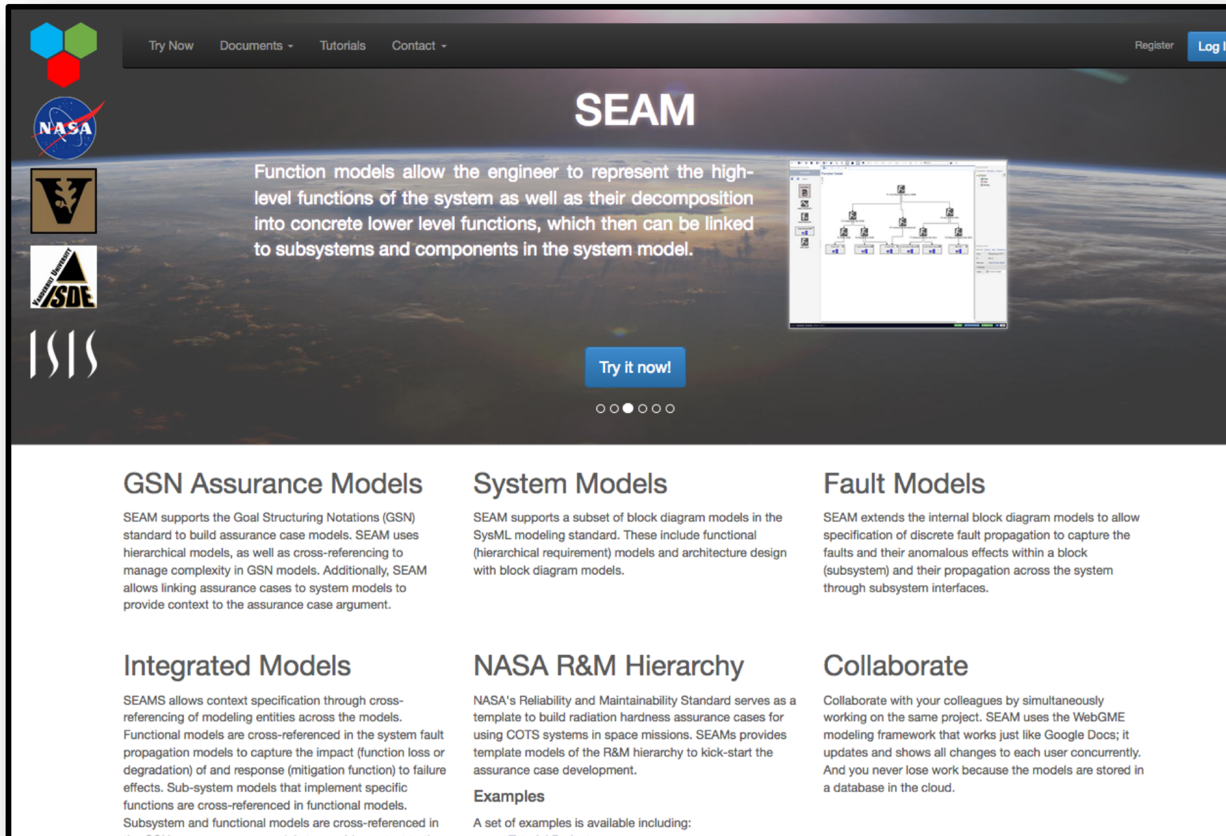
- Dedicated software platform
- Access as guest or create account
- Maintained by Vanderbilt University
- Contains examples and tutorial information
- Diagrams in following presentations



https://modelbasedassurance.org

RESIM Radiation Effects Systems-Impact Modeling

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- Software Modeling Flow that can be implemented on several platforms
- Requires modeling of several kinds of blocks: analog, digital, mixed, power, software
- All models simulated on same time base
- Physical or math-based modeling
- Quantitative system impacts of rad effects

Behavioral Models for Subsystems

Radiation models for parameters of Behavioral Models

Vary radiation parameters to obtain variation is system outputs

Reference:
A. F. Witulski, et al, “Simulation of Transistor-Level Radiation Effects On System-Level Performance Parameters,” IEEE Transactions on Nuclear Science, July 2019, Volume: 66, Issue: 7, pp. 1634-1641.

SEAM: Characteristics of Logical Modeling

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Logical Models:

- Description-Based, not equation-based
    - Relates system functions to components
    - Describes system architecture
    - Describes fault origination in a component and how it propagates through a system
- Especially useful in early stages of a design
- Does not require detailed component knowledge
- Intermediate stage between physical models and reliability models

RESIM: Characteristics of a Physical Model

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Physical Modeling:

- Equation or algorithm based
- System modeling requires many kinds of models
  - Analog-continuous differential equations
  - Digital: combinational and sequential logic
  - Software and algorithms (e.g. ECC)
  - Other physical domains (mechanical, optical, etc.)
  - Interfaces between domains (binary-digital-analog)
- Questa can run many kinds of models together, all on the same simulation time steps.
- Use for quantitative estimation of radiation degradation

Structural Components of SEAM

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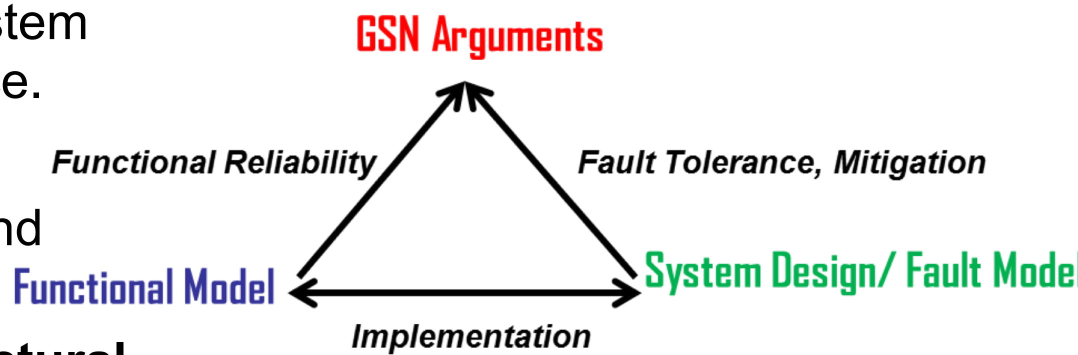
- **Three structural components in SEAM**
  - Goal: Describe system structure and make logical argument for system radiation hardness or tolerance.
- **Functional Model (SysML)**
  - Connects System functions and components
- **Fault propagation and Architectural Models:**
  - Captures relationships between part failure modes and cascading effects
- **Goal Structuring Notation:**
  - Visual representation of assurance argument



Structural Components of SEAM

Reliability Components of SEAM

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- **Three structural components in SEAM**
  - Goal: Describe system structure and make logical argument for system radiation hardness or tolerance.
- **Functional Model (SysML)**
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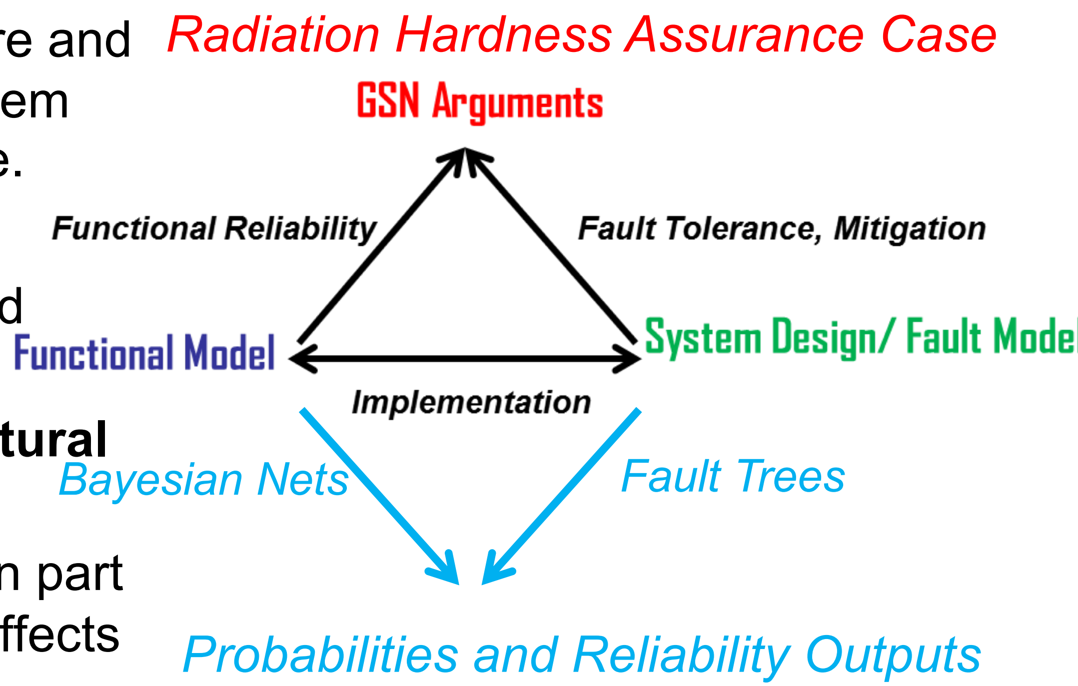

SEAM/SysML: Fault Propagation Through Ports

Example: Block Diagram/Architectural Model of Circuit Board

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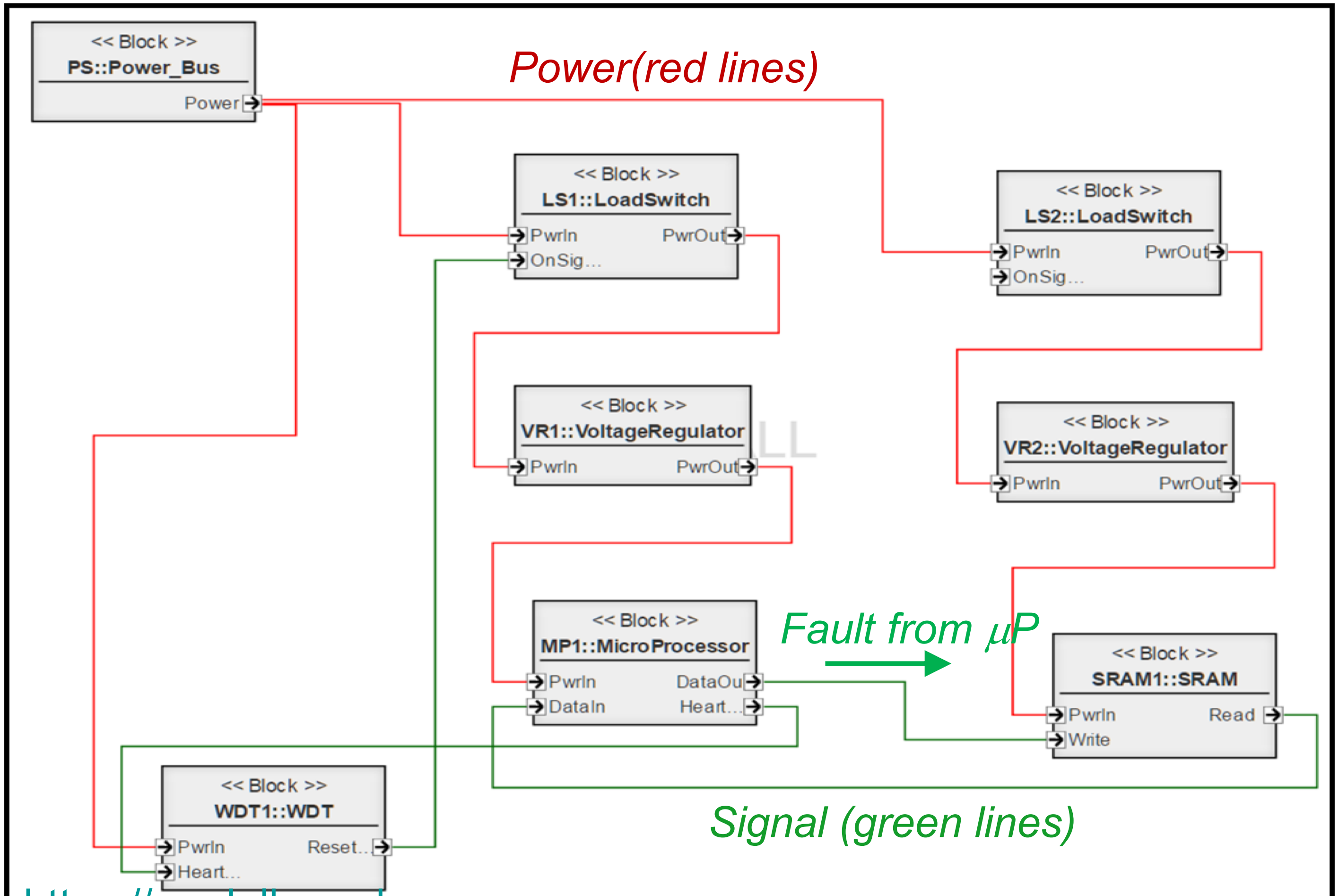

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Architectural Models capture the structure and interconnection of the system and fault propagation

SEAM/SysML: Functional Decomposition Model
Example: Cubesat Experiment Board: Count Upsets in SRAM

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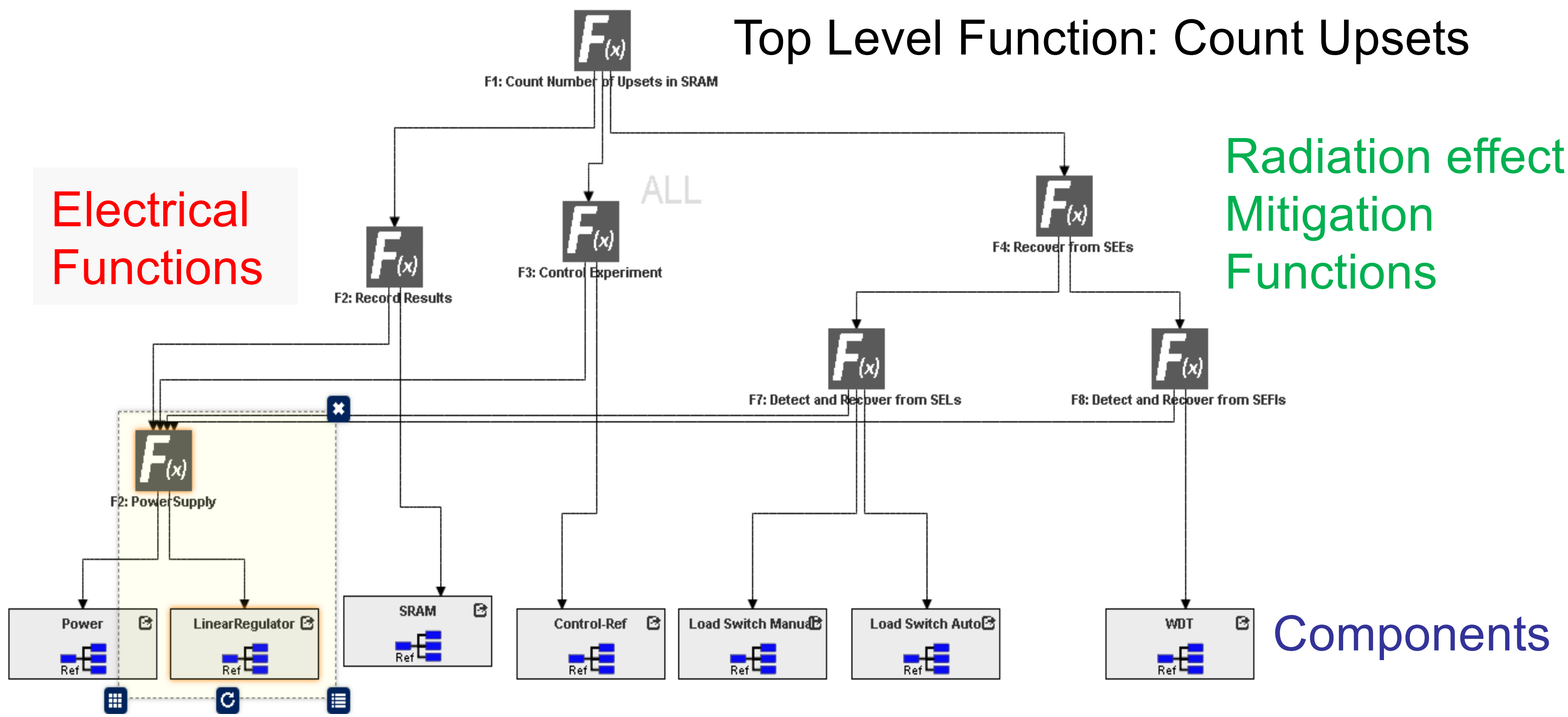

Functional Decomposition associates functions with component blocks

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SEAM Example: Internal Fault Diagrams
Thermal Control Loop – System Model

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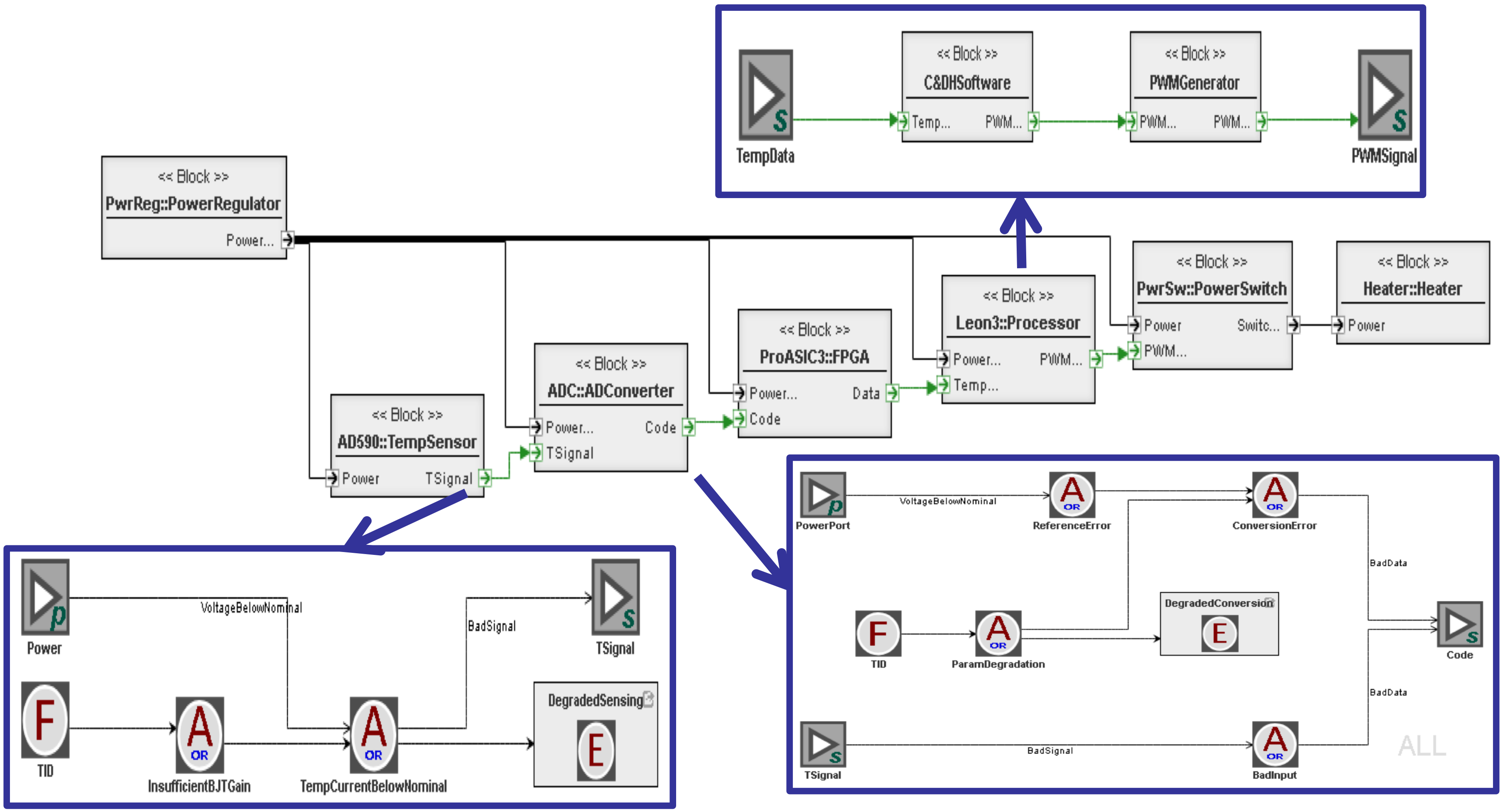
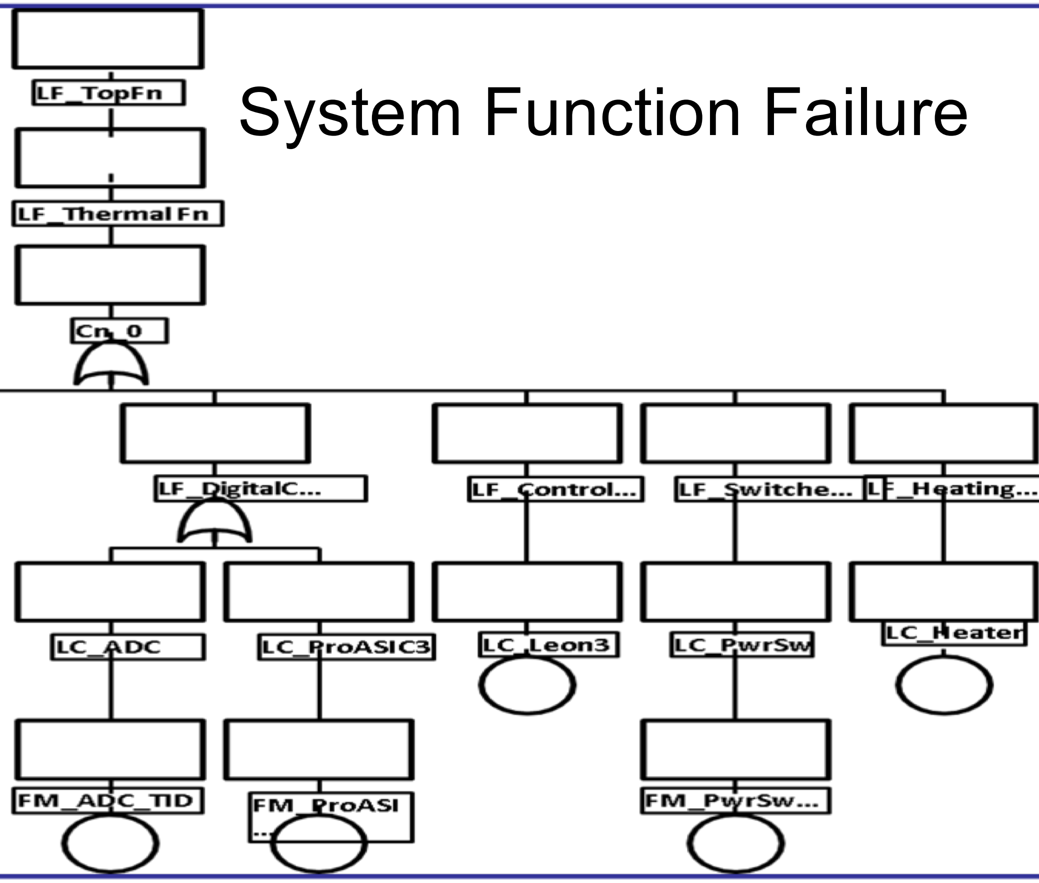


SEAM Example: Assembling FT Topology
Thermal control loop – Generated Fault Tree

Generated from Functional & Architectural Model in SEAM

System Function Failure



Component failure modes

RESIM Example: Radiation Impact on System or Circuit Board-Level Variables

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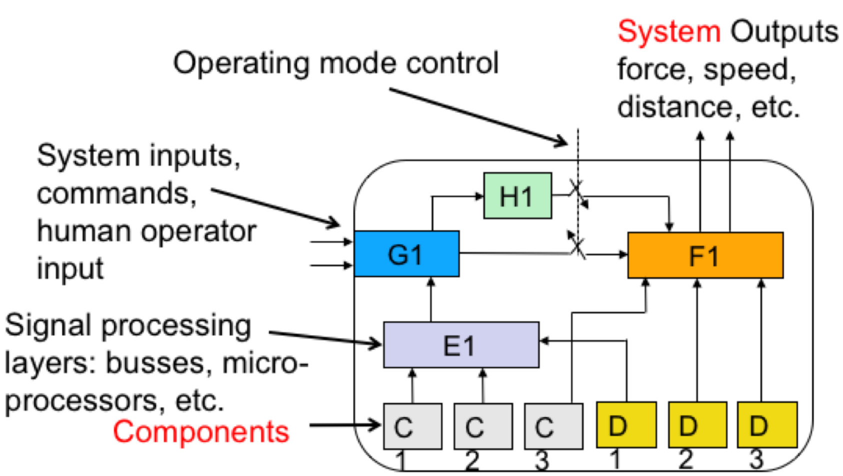
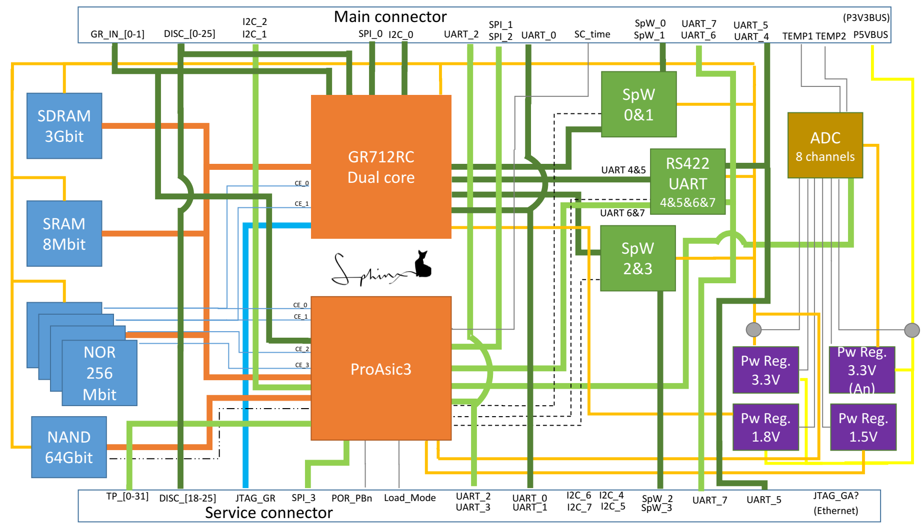
One System, Many Components



One System, Many Functions



Radiation effect at component level
Variable of interest at System level

Demonstration vehicle is the JPL Sphinx C&DH board flight computer

Modeling Thermal Regulation Loop Sphinx Board

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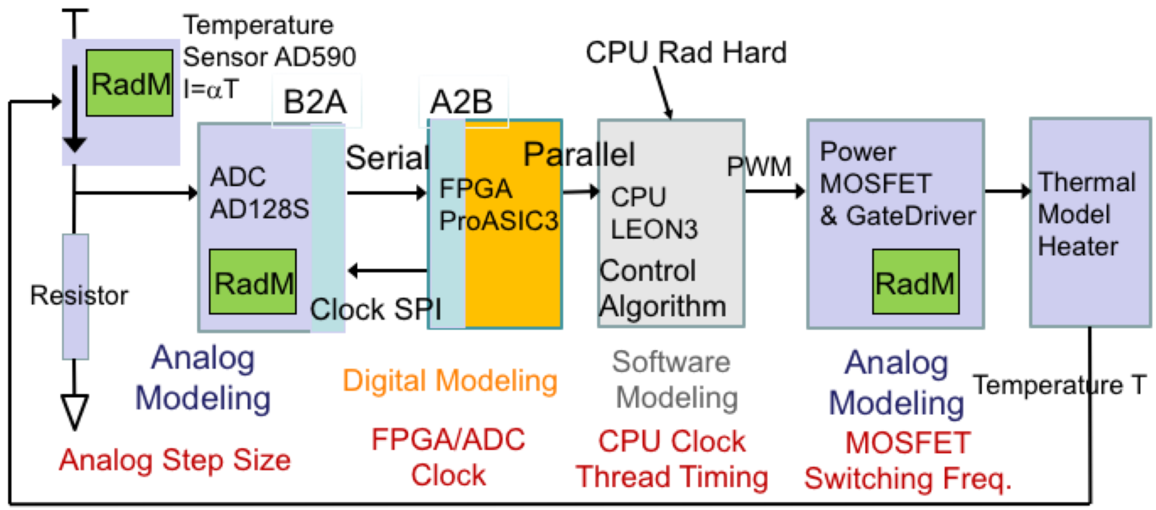
- Want deterministic model of system
- Find right level of abstraction
- Model subsystems or components with behavioral models
- Incorporate radiation models into the behavioral models
- Need different kinds of functional models for digital, analog, mixed-signal parts

- We chose the temperature loop regulation function of C&DH board



Thermal Loop Example: Behavioral Radiation Models Functional Models of Components

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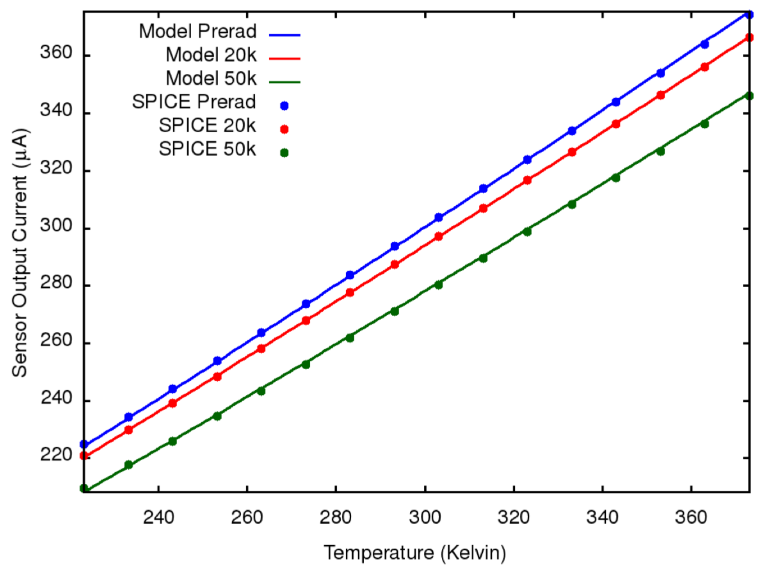
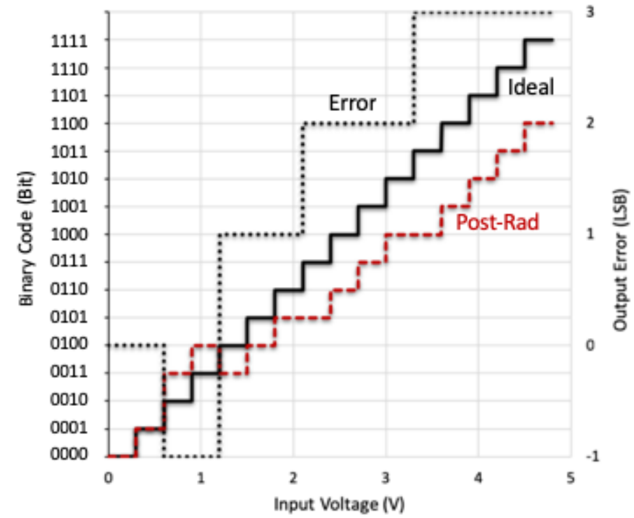


Analog functional model of AD590 temperature sensor



Mixed-signal functional of A/D converter in Verilog AMS

Thermal Loop Example: -Final Result
Simulation and measurement of temp. step and regulation

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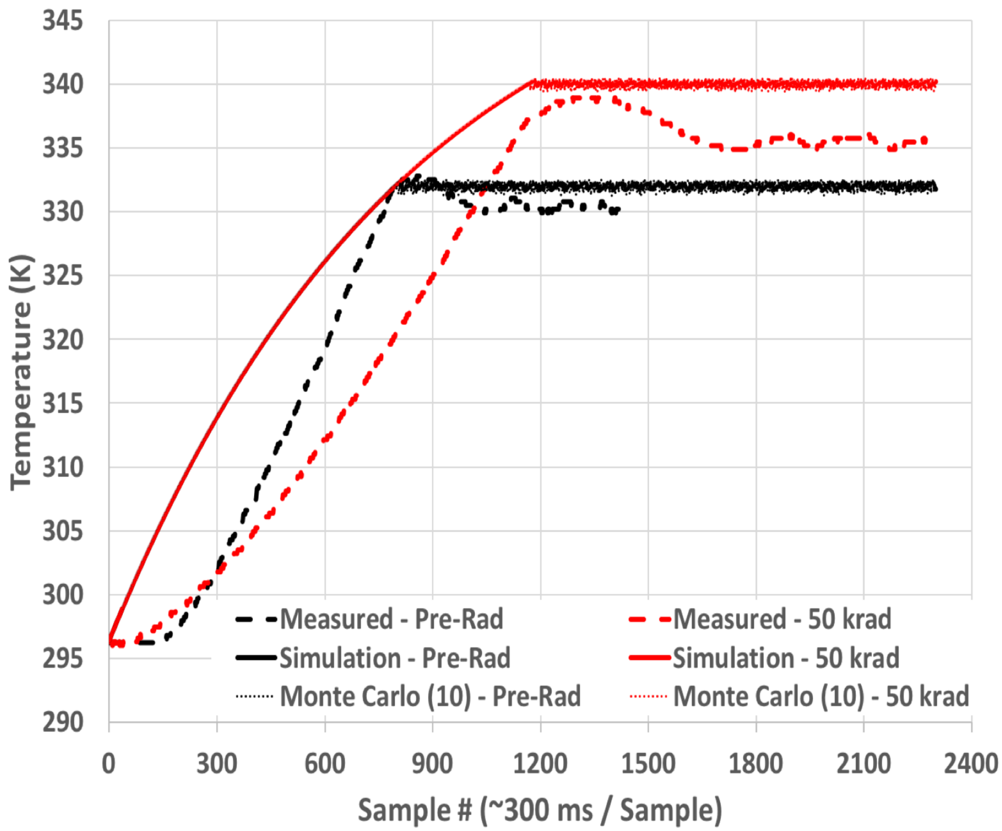
- Comparison of RESIM simulation flow to simulation
- Relates system performance (temperature regulation) to TID degradation of parts



NEPP Project: Model Based Mission Assurance for Spacecraft Reliability

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NEPP NASA Electronic Parts and Packaging Program

Program History

- FY16: Started as collaboration of NASA OSMA, HQ, NEPP
  - Work on Goal Structuring Notation Safety Cases
- FY17: collaboration of NASA OSMA, HQ, NEPP, JPL
  - Added SysML and Bayesian Nets (BN) to platform
- FY18: NASA OSMA, HQ, NEPP, JPL
  - Coverage Checks, Requirements, Compatibility Magic Draw, Fault Trees
- FY19: NASA OSMA, HQ, NEPP, JPL
  - Import of radiation modeling tools, Application of SEAM to development lifecycle, User interface
- FY 20: NASA NEPP
  - Interface with R-Gentic, Tutorials, Templates, Risk Quantification

Overview of ADC Modeling Task in JPL Concurrent Qualification Program

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- Make it easy for new users to start models in SEAM
  - Interface with R-Gentic mission planning tool
  - Use output of R-Gentic to generate templates of part times used in mission
- Use SEAM to facilitate Quantification of Risk
  - Risk is probability of event times consequence
  - Use SEAM tools to locate and define failure modes
  - Find a model for comparing consequence of various kinds of risk
    - Terrestrial Testing
    - On-orbit data

STTR Phase I : Testing of COTS Systems in Space Radiation Environments

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- NASA STTR 2019 Phase I Solicitation from Langley Research Center
- T6.05 Testing of COTS Systems in Space Radiation Environments

RFP: Investigate the feasibility of COTS electronics for *High Performance Computing (HPC)* in *space environments which are already heavily shielded*. It seeks strategies *based on a complete system analysis of HPC COTS* that include, but not limited only to, *failure modes* to mitigate radiation induced impacts to potential HPC systems in those highly shielded space environments.

STTR Phase I : Testing of COTS Systems in Space Radiation Environments

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ALPHACORE
Robust High Performance Microelectronics

Alphacore. Inc.

Vanderbilt

Small Business

Research Partner

Alphacore Inc. (Phoenix AZ)

- Radiation Hardened by Design (RHBD) approach
- Integrated Circuits specifically designed for Space, Medical, Homeland Security, Scientific Experiment, and Defense applications that operate in hazardous high-radiation environments

Institute for Space and Defense Electronics (Vanderbilt)

- Engineers, faculty members, graduate students
- Research expertise in radiation transport, IC and device radiation hardening, system impacts of radiation, and radiation testing.

Identifying Faults in COTS Systems in Shielded Env.

- Use Beagle Bone Black Open-source single-board computer as a COTS demonstration system
- Use SEAM to identify the most significant and likely faults for a highly-shielded environment in space
- Estimate probabilities of faults
- Design assembly-language level routines to exercise the components most likely to fail
- Test the routines in situ in a proton beam to find most sensitive areas of processor and most common fault behaviors
- Look for low cost mitigation solutions

JPL Program on Concurrent Qualification

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- Collaboration on SEAM/RESIM since 2017
- New 3-year program on Model-Based Concurrent Qualification with VU and UCLA
  - First year in FY2020
  - Aim to make radiation modeling and prediction more systematic, iterative, and practical for early use in flight development programs
- Vanderbilt provides modeling for system impacts of radiation with SEAM and Quest flows
- UCLA incorporates SEAM/Questa information into overall subsystem reliability assessment using their HCLA tool.

Overview of ADC Modeling Task in JPL Concurrent Qualification Program

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- Big Picture: Intentd make decisions involving radiation impacts on system early in design cycle,
  - Update as more information becomes available.
  - Also need some idea of how certain/uncertain the answers are: Uncertainty Quantification
- Can use system tools like Mentor Questa (or Coside or Saber) to bring together many kinds of models
- For this simulation plan to be useful, we need a large repository of rad-aware models for designers to use
- Start with ADC models-take an architectural approach
- Incorporate TID degradation inside model
- Find quick, low cost way to validate models

Outline of Presentations

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Topic	Presenter	Modeling Tool	Comment
SEAM Interface	K. Ryder	SEAM	R-Gentic Interface
Risk Quantification	R. Austin	SEAM	Cube Sat Example
COTS Computing	M. Reaz	SEAM	Highly Shielded Environments
A-D Converters	M. Rony	RESIM/Questa	Example of Behavioral Modeling

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- 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)

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