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Model-Based Mission Assurance of Radiation Effects on Electronic Systems

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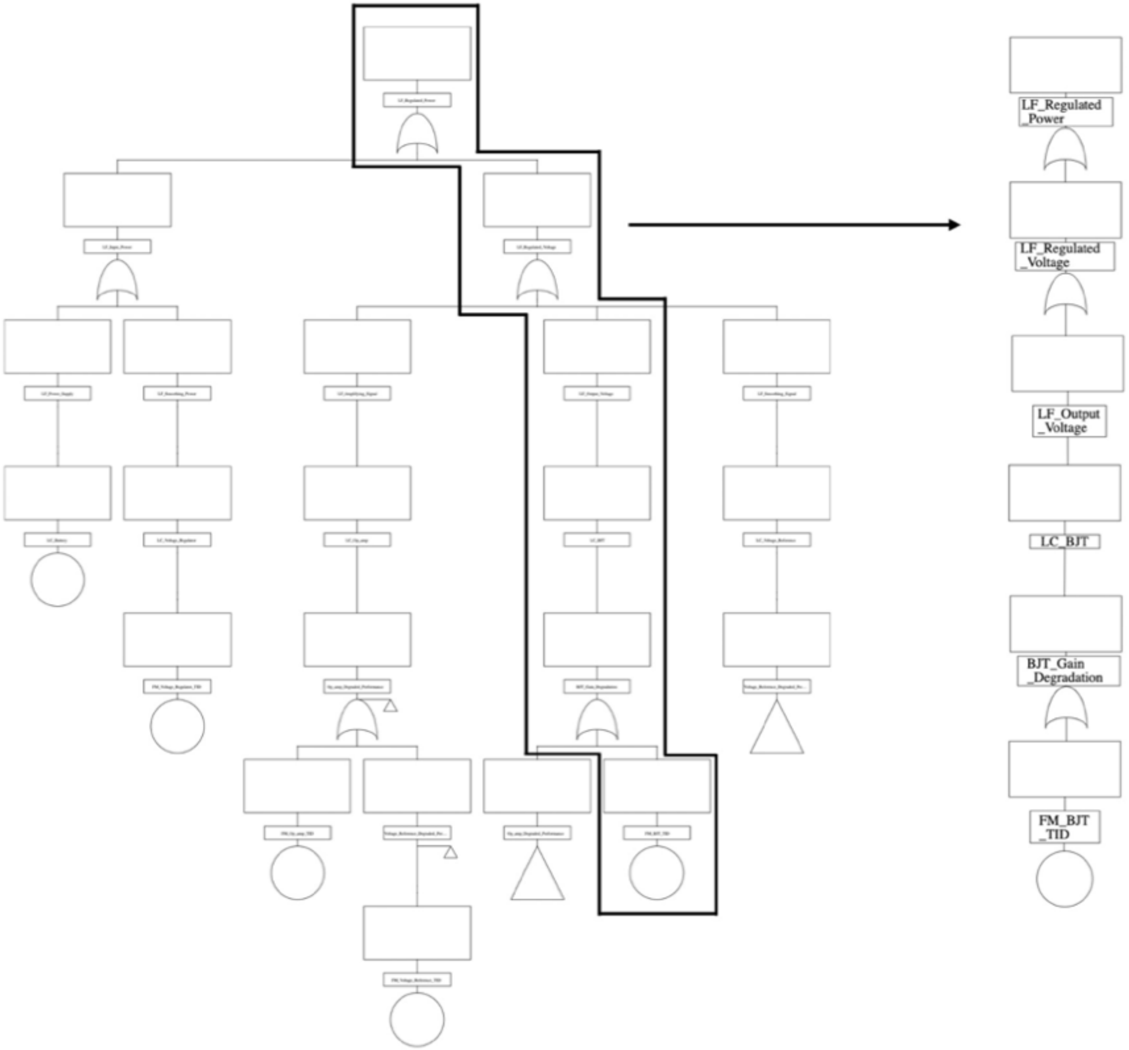
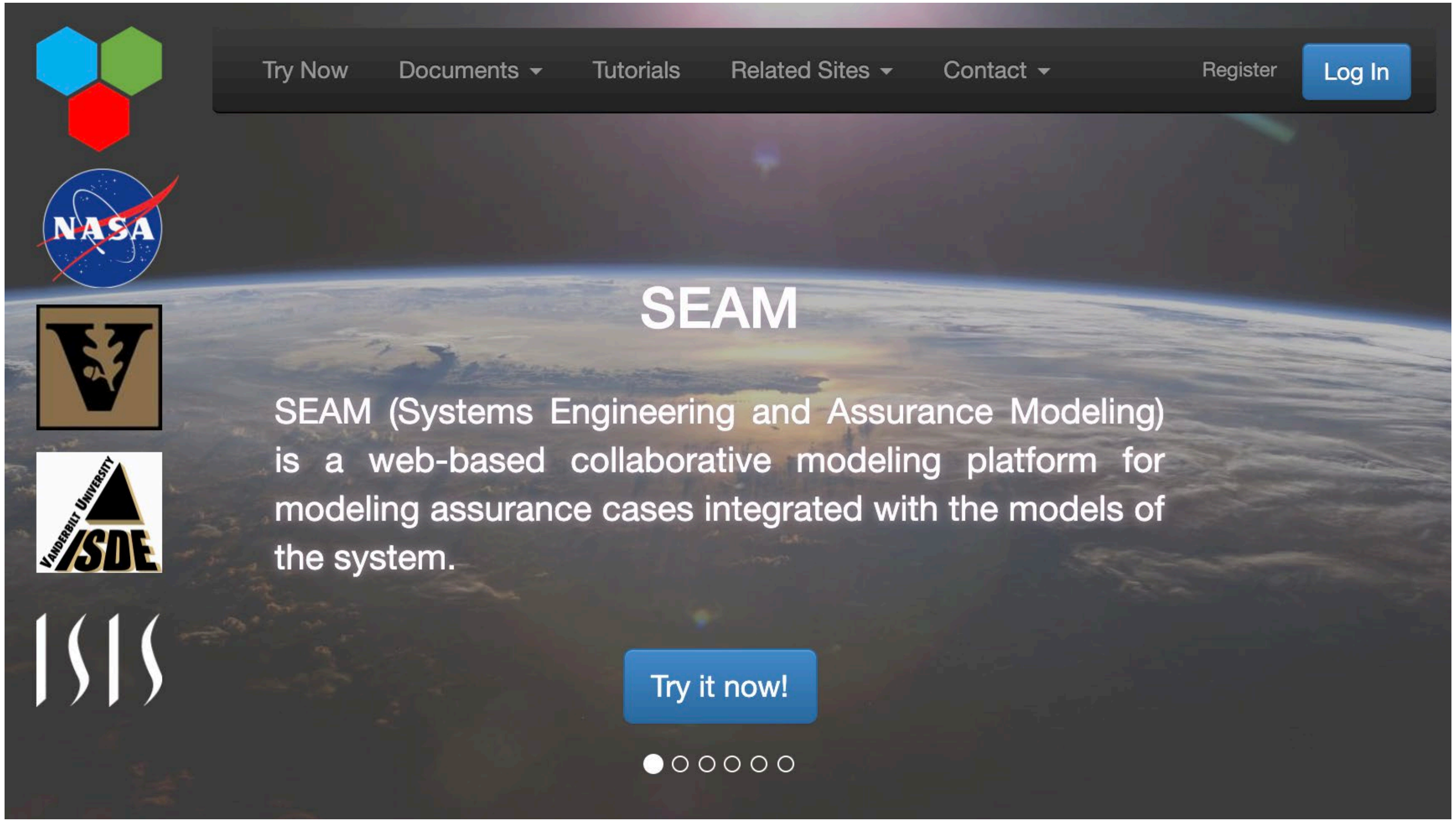
Outline of Discussion

Purpose of Work



- COTS parts often used because:
  - Tend to be several tech generations ahead of rad-qualified counterparts
  - More affordable
- Model-based mission assurance can allow engineers to track failure nodes introduced by COTS parts on space systems
- Example ➡ Fault tree on the left is generated by SEAM from a functional decomposition model of a linear voltage regulator
  - Arrow points to a branch showing TID impact on the regulator's internal BJT

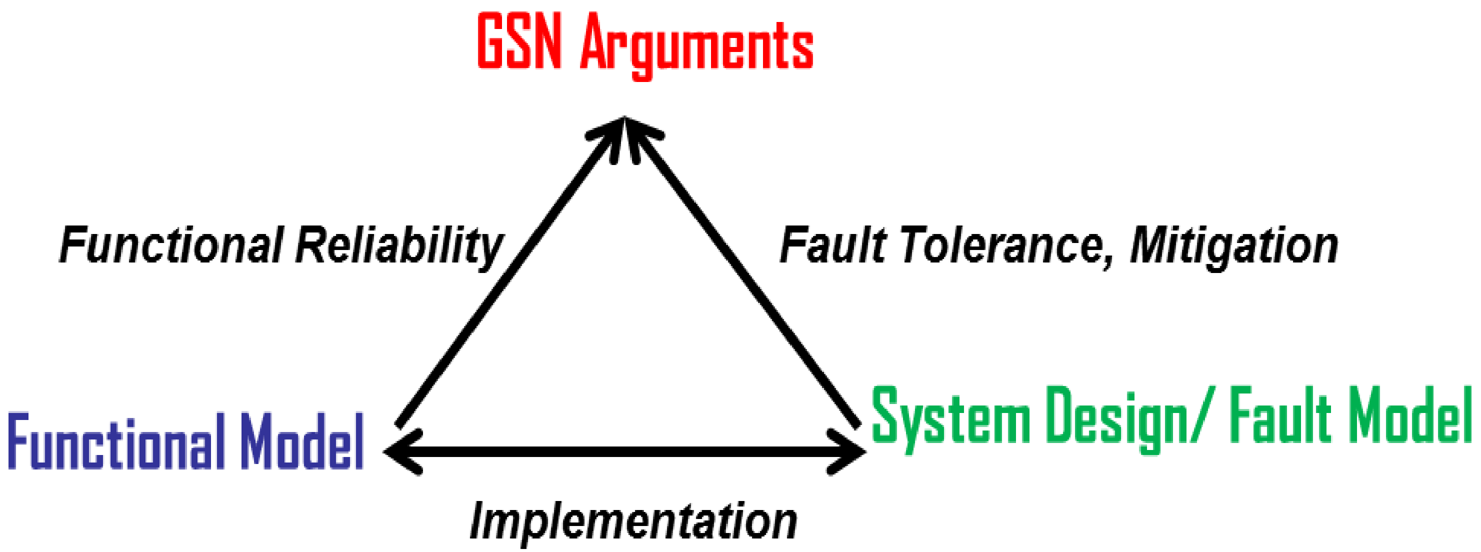
What is SEAM?



https://modelbasedassurance.org/

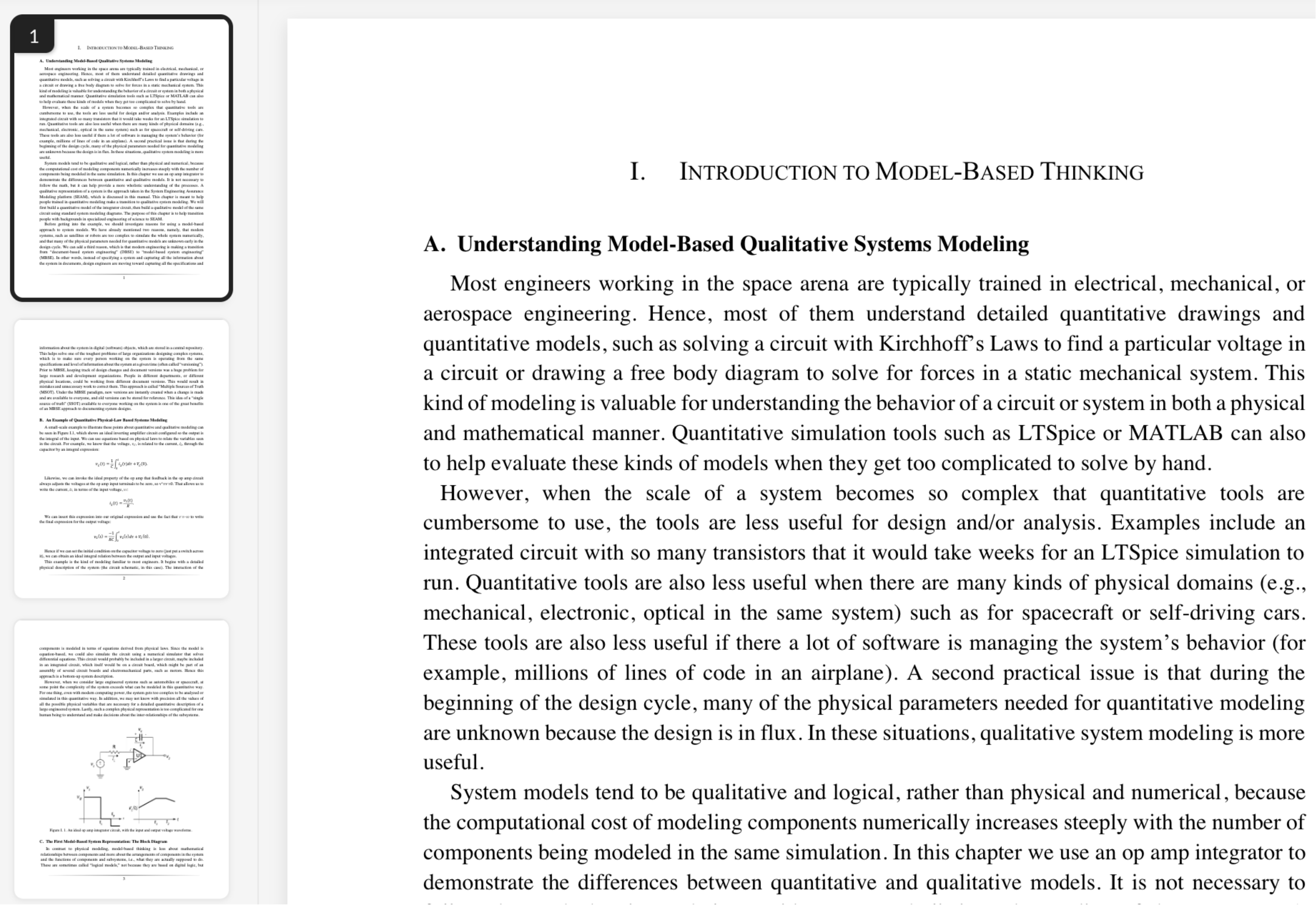
- Platform used to evaluate a spacecraft system
- Especially useful for small satellite applications with short development timeframes and significant utilization of COTS components
- Free registration
- User site-based installations available

SEAM: Systems Engineering and Assurance Modeling



- SEAM uses Systems Modeling Language (SysML) internal block diagrams
- SEAM enables a systematic assessment of the radiation performance of a spacecraft in situations where intensive radiation testing campaigns, or extensive physical knowledge of the electronic components are not available

SEAM Manual Documentation



I. Introduction to Model-Based Thinking

A. Understanding Model-Based Qualitative Systems Modeling

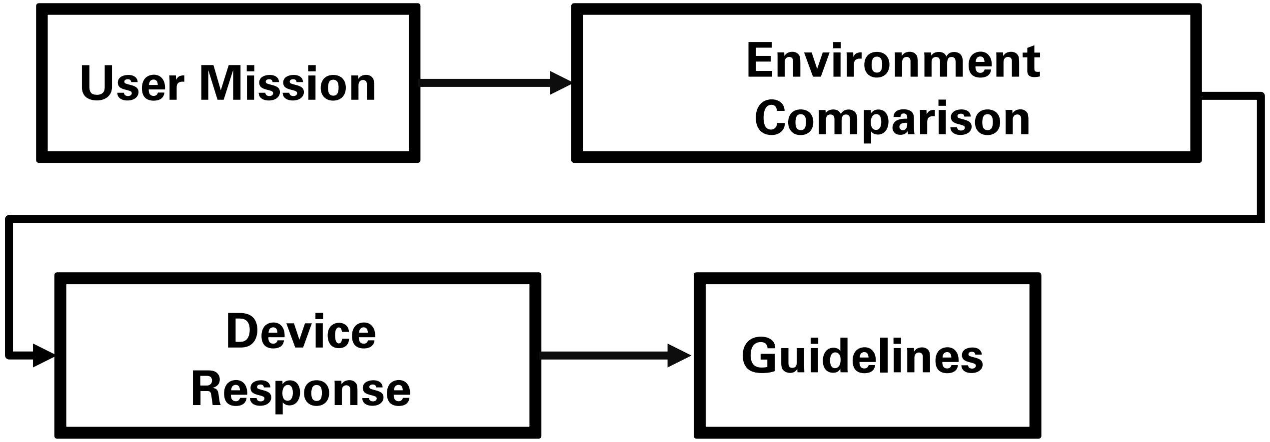
Most engineers working in the space arena are typically trained in electrical, mechanical, or aerospace engineering. Hence, most of them understand detailed quantitative drawings and quantitative models, such as solving a circuit with Kirchhoff's Laws to find a particular voltage in a circuit or drawing a free body diagram to solve for forces in a static mechanical system. This kind of modeling is valuable for understanding the behavior of a circuit or system in both a physical and mathematical manner. Quantitative simulation tools such as LTSpice or MATLAB can also to help evaluate these kinds of models when they get too complicated to solve by hand.

However, when the scale of a system becomes so complex that quantitative tools are cumbersome to use, the tools are less useful for design and/or analysis. Examples include an integrated circuit with so many transistors that it would take weeks for an LTSpice simulation to run. Quantitative tools are also less useful when there are many kinds of physical domains (e.g., mechanical, electronic, optical in the same system) such as for spacecraft or self-driving cars. These tools are also less useful if there a lot of software is managing the system's behavior (for example, millions of lines of code in an airplane). A second practical issue is that during the beginning of the design cycle, many of the physical parameters needed for quantitative modeling are unknown because the design is in flux. In these situations, qualitative system modeling is more useful.

System models tend to be qualitative and logical, rather than physical and numerical, because the computational cost of modeling components numerically increases steeply with the number of components being modeled in the same simulation. In this chapter we use an op amp integrator to demonstrate the differences between quantitative and qualitative models. It is not necessary to

- We are completing a manual for the SEAM platform.
  - A key activity to improve adoption of the SEAM platform, both for new users and for documentation of what SEAM accomplishes.
  - All chapters are completed, and it is currently in review.
- Published here: https://seam.pages.isis.vanderbilt.edu/seamdoc/docs/

What is RGENTIC?

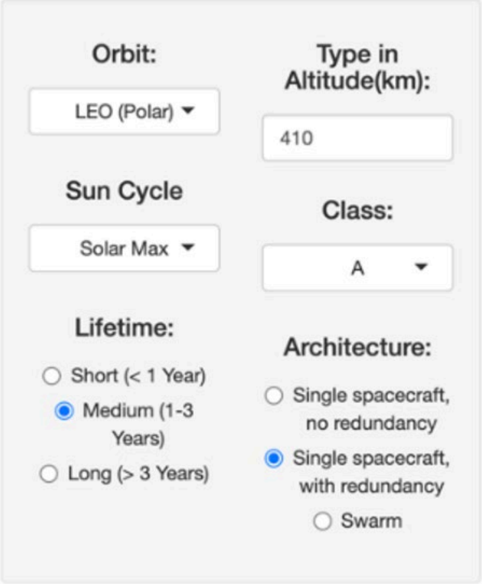


- RGENTIC stands for Radiation GuidelinEs for Notional Threat Identification and Classification
- Developed by NASA Goddard Space Flight Center (GSFC)
- Associates user's EEE components to potential rad-hard risks based on user-inputted mission environment.
- Provides guidance on assessing rad-hardness of EEE components

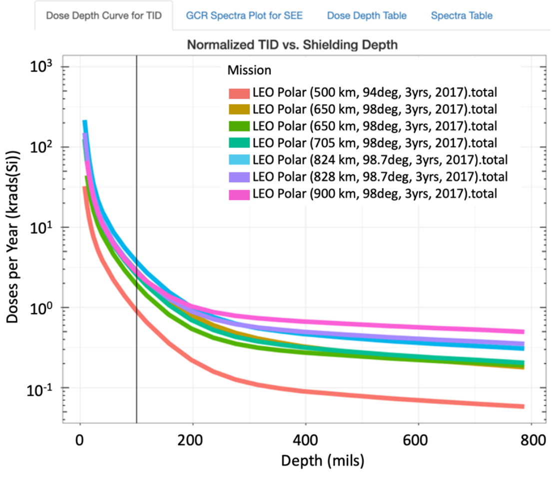
https://vanguard.isde.vanderbilt.edu/RGentic/

RGENTIC's Capability

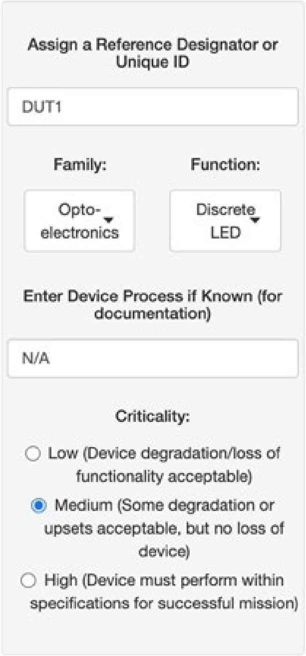
User Mission



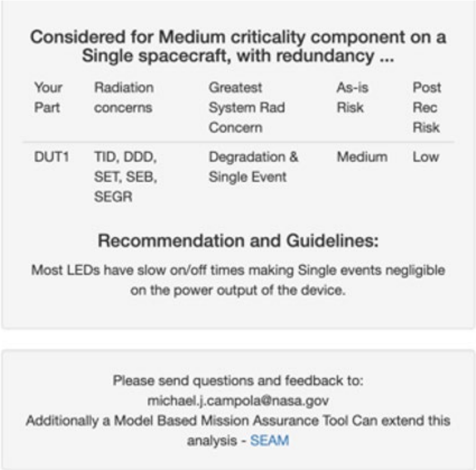
Environment Comparison



Device Response



Guidelines



Porting RGENTIC to SEAM

RGENTIC

Creates a part list associating components with rad risks based on user-specific environment

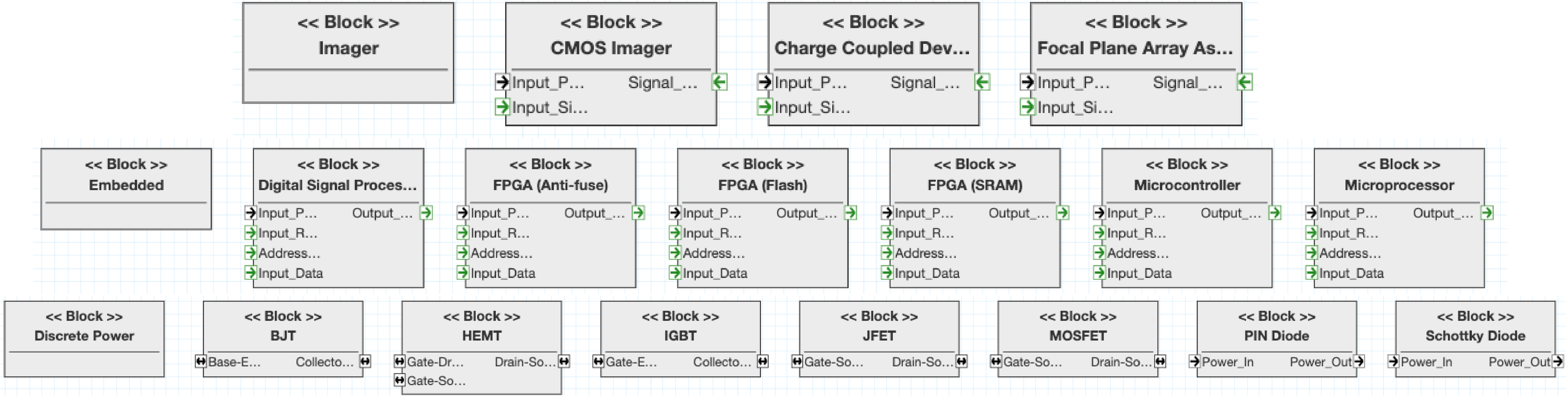
→

SEAM

Creates a canvas with corresponding fault models for user to interconnect

- RGENTIC's output is being integrated as an input into SEAM
  - Lowers the barrier-to-entry for using SEAM
  - SEAM has fault propagation models for each of the EEE part-type families RGENTIC
  - List of parts from RGENTIC triggers selection of equivalent fault propagation templates in SEAM upon upload

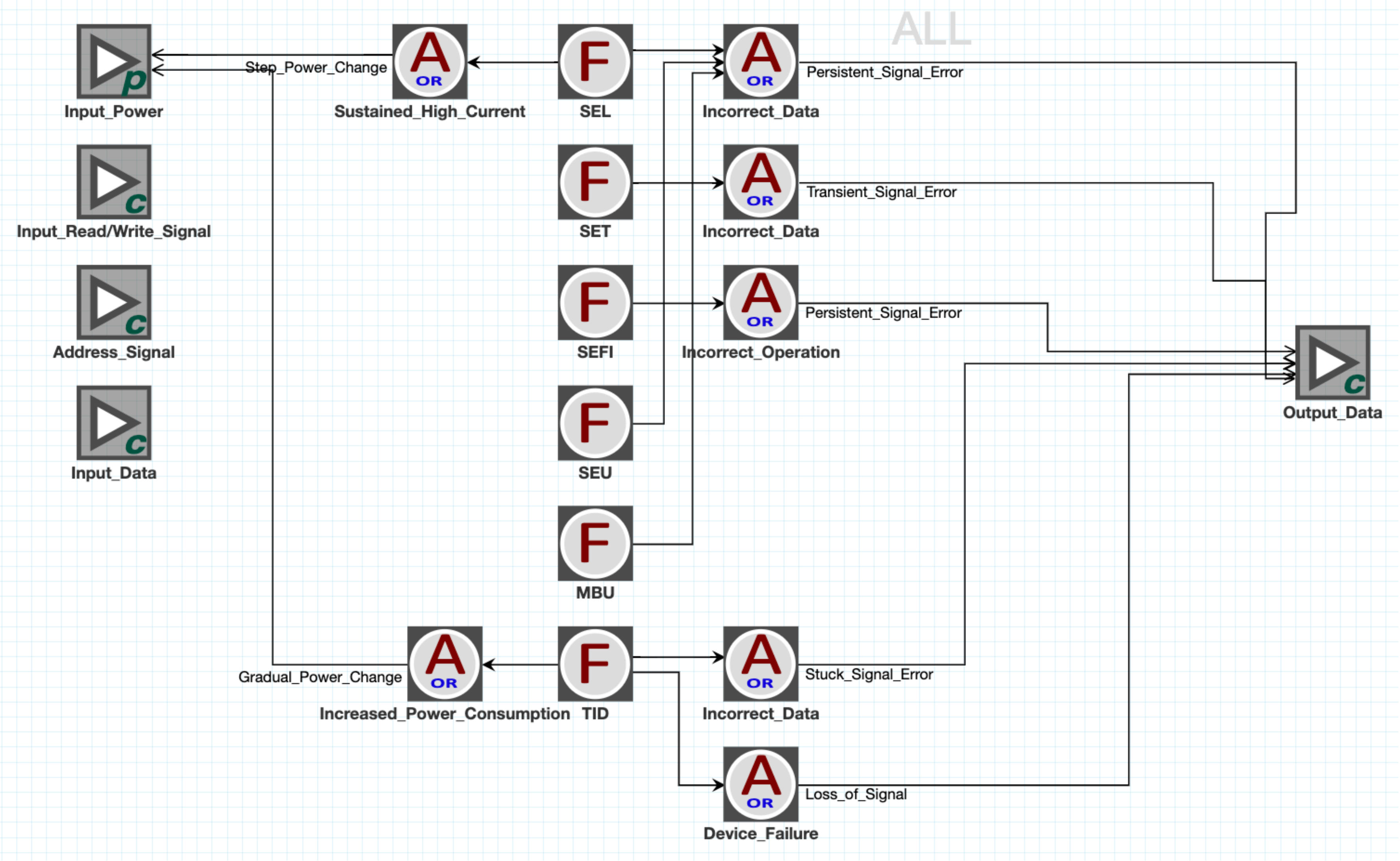
Selected Models from SEAM Part-Type Library



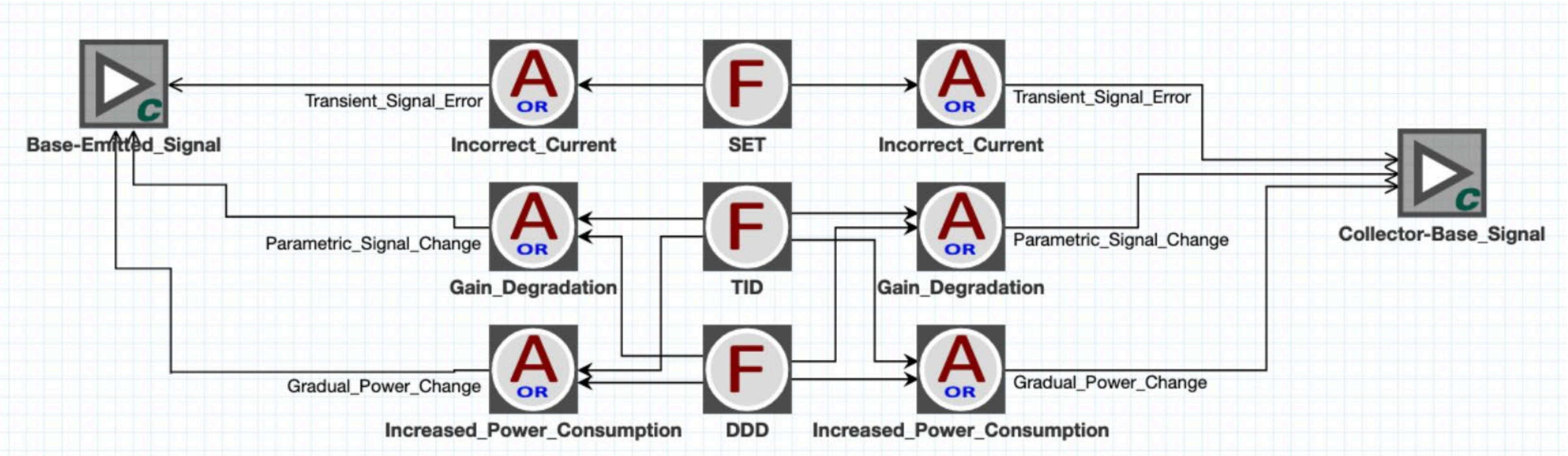
- The full library of Fault Models is available on the SEAM site
- Fault models for devices incorporate:
  - Expert knowledge about the rad vulnerabilities of part-types based on literature searches
  - Experiences and analysis by the Vanderbilt research groups
  - Inputs from NASA NEPP

SEAM Output-based on Part-Type Templates Outputted from RGENTIC

- SEAM model of Digital Signal Processor shown in the editor canvas.
- SEAM allows users to create project libraries for both components and failure labels.



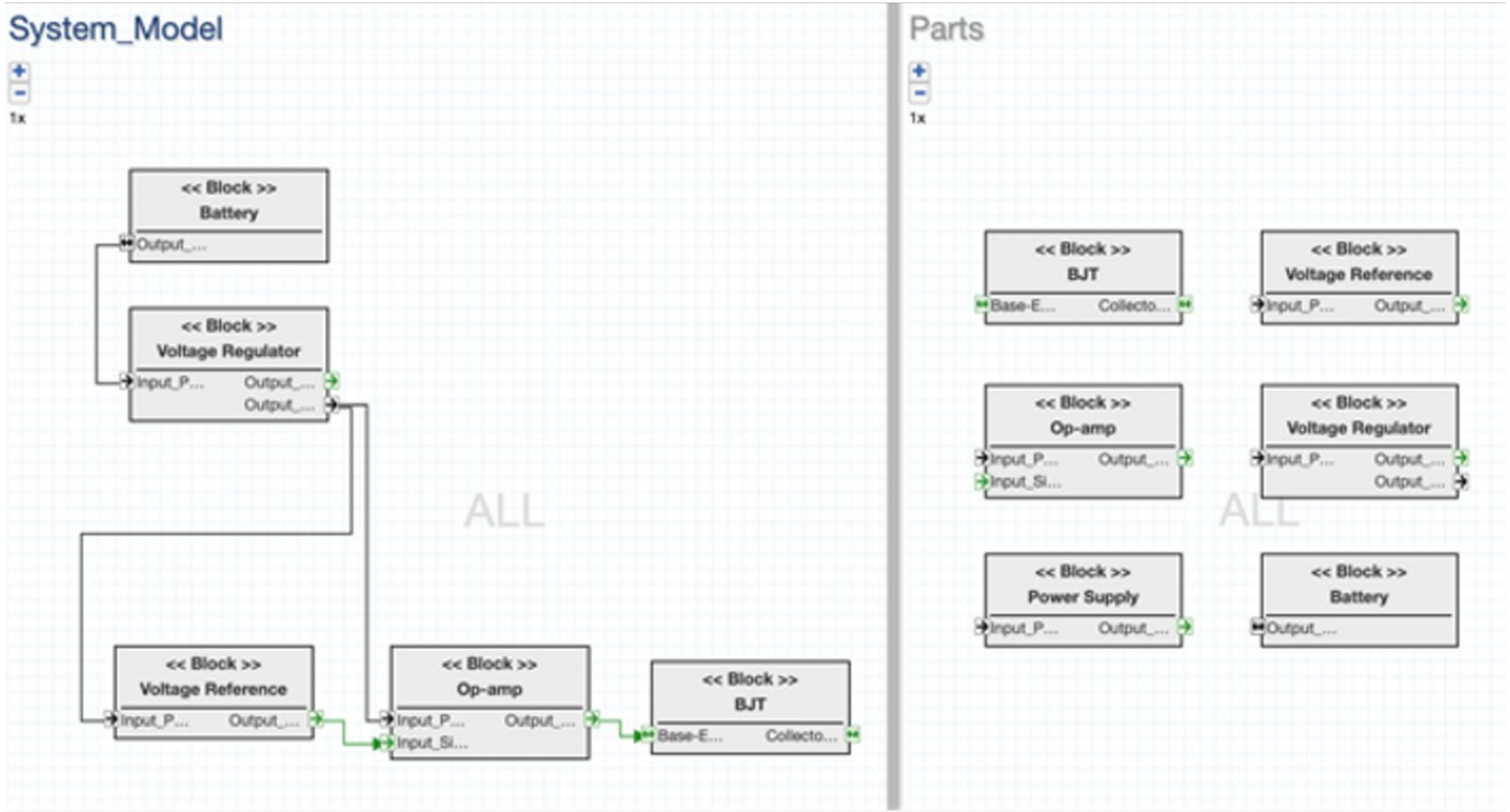
Incorporating Composite Ports for Part Templates in SEAM



BJT part type with composite ports for the 'Base-Embedded Signal' and the 'Collector-Base_Signal' blocks

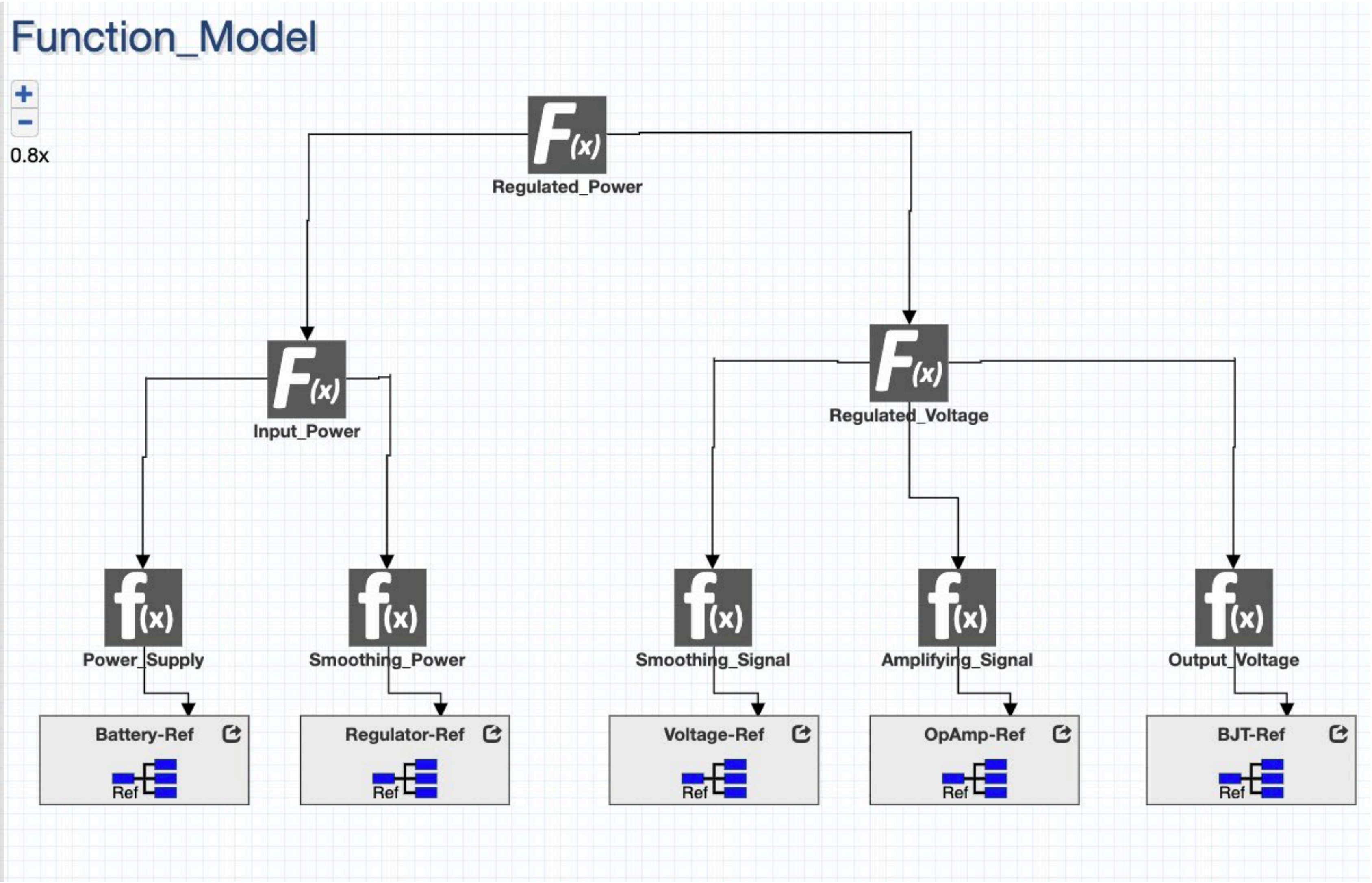
- Composite ports in SEAM allow for a port to be expressed as both a signal port and a power port so that a failure can propagate between devices.
- User evaluates whether a failure effect in one part will result in a relevant failure effect in surrounding parts
- If a failure effect is not relevant to the mission, the user can delete it from the fault diagram.
  - Each template model is annotated with additional explanations and reviewed and signed off by Vanderbilt graduate students and faculty.

Example 1: Linear Voltage Regulator

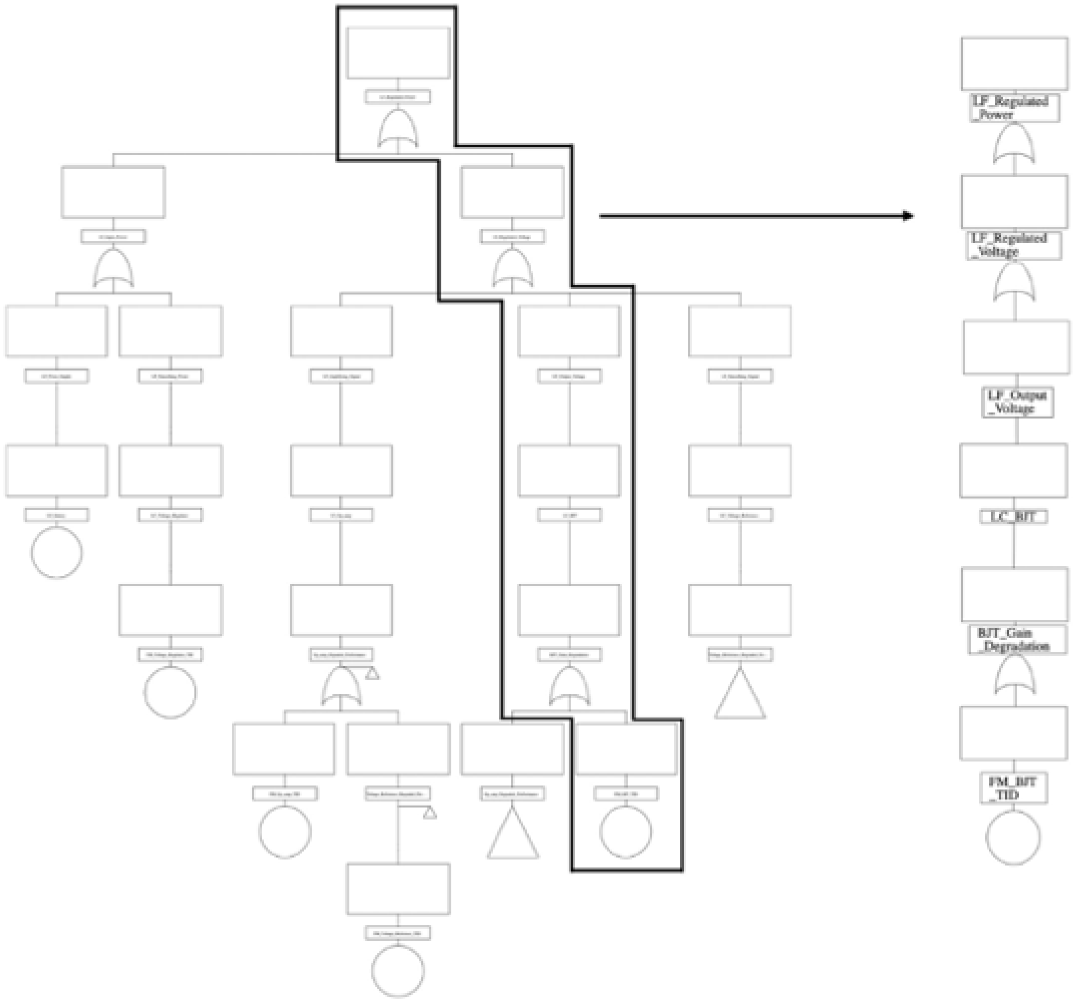


SEAM system model (left) and parts library (right) for the linear voltage regulator

Linear Voltage Regulator: Fault Decomposition Model



Fault Tree Analysis of the Linear Voltage Regulator



Fault Tree

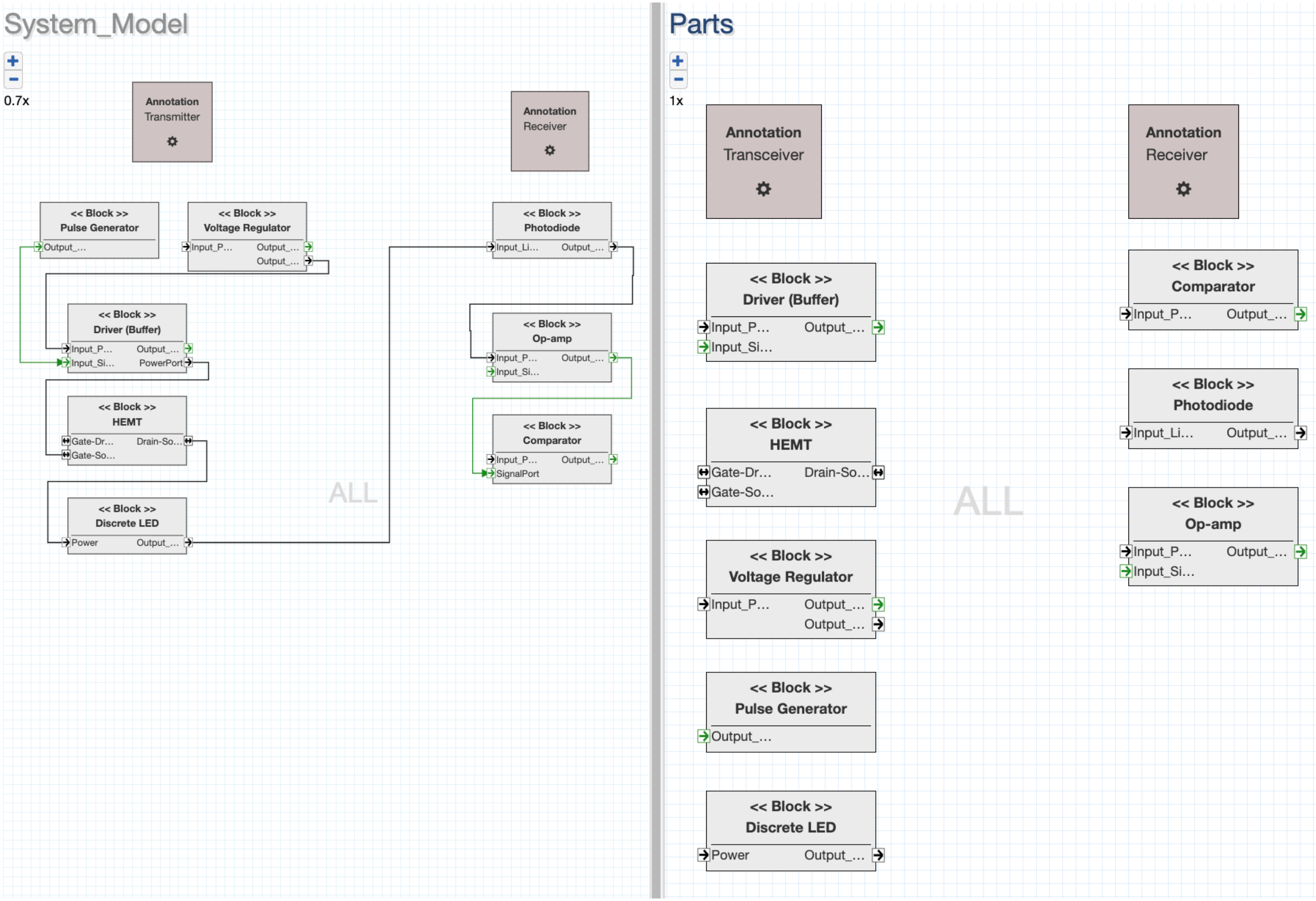
- Directed graphs with nodes representing failure probabilities and dependencies

Definitions

- ‘FM’ refers to ‘failure mode’
- ‘LC’ refers to ‘loss of component’
- ‘LF’ refers to ‘loss of function’

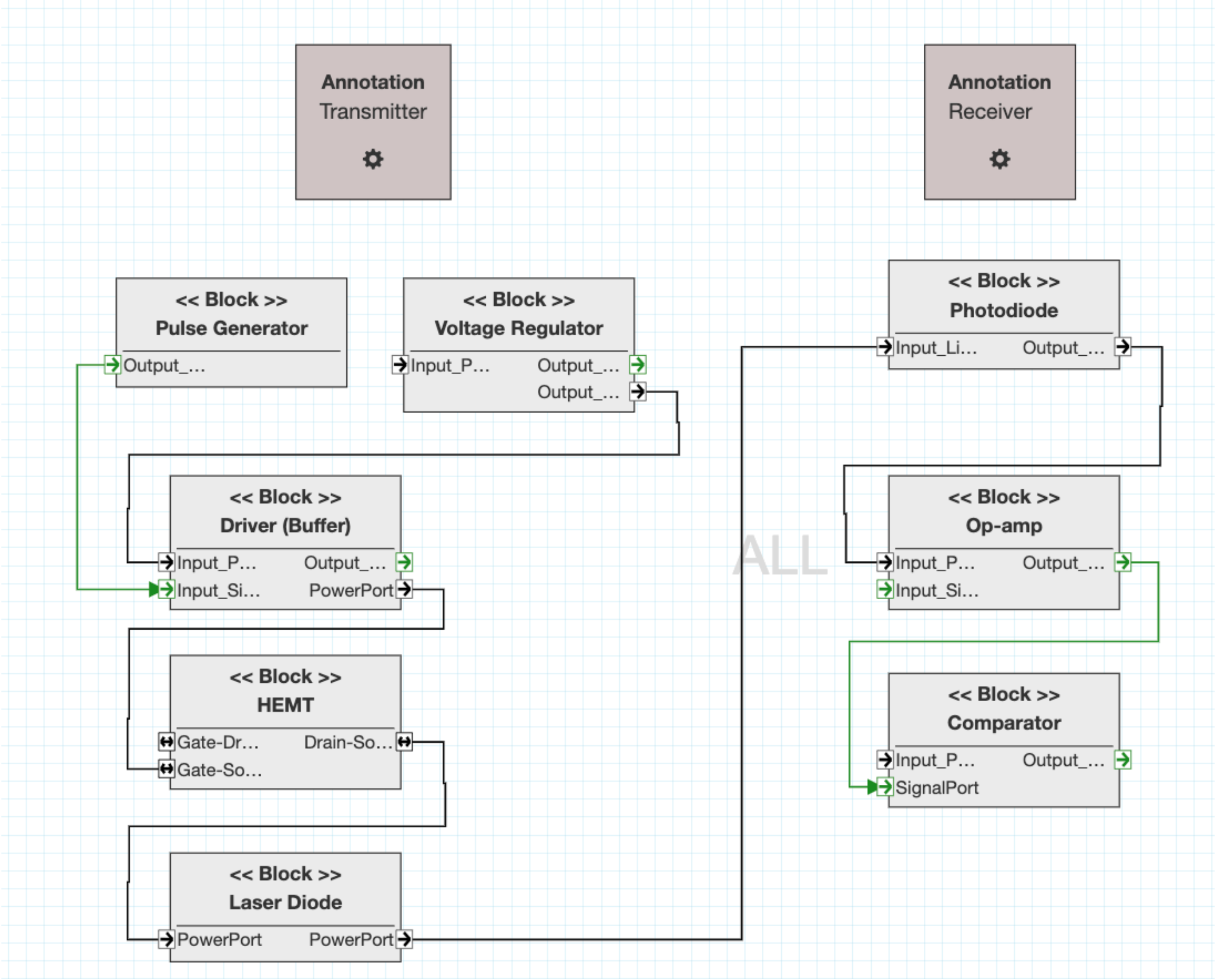
Fault tree generated from a functional decomposition model and system model of the linear voltage regulator in SEAM

Example 2: LiDAR Transmitter and Receiver

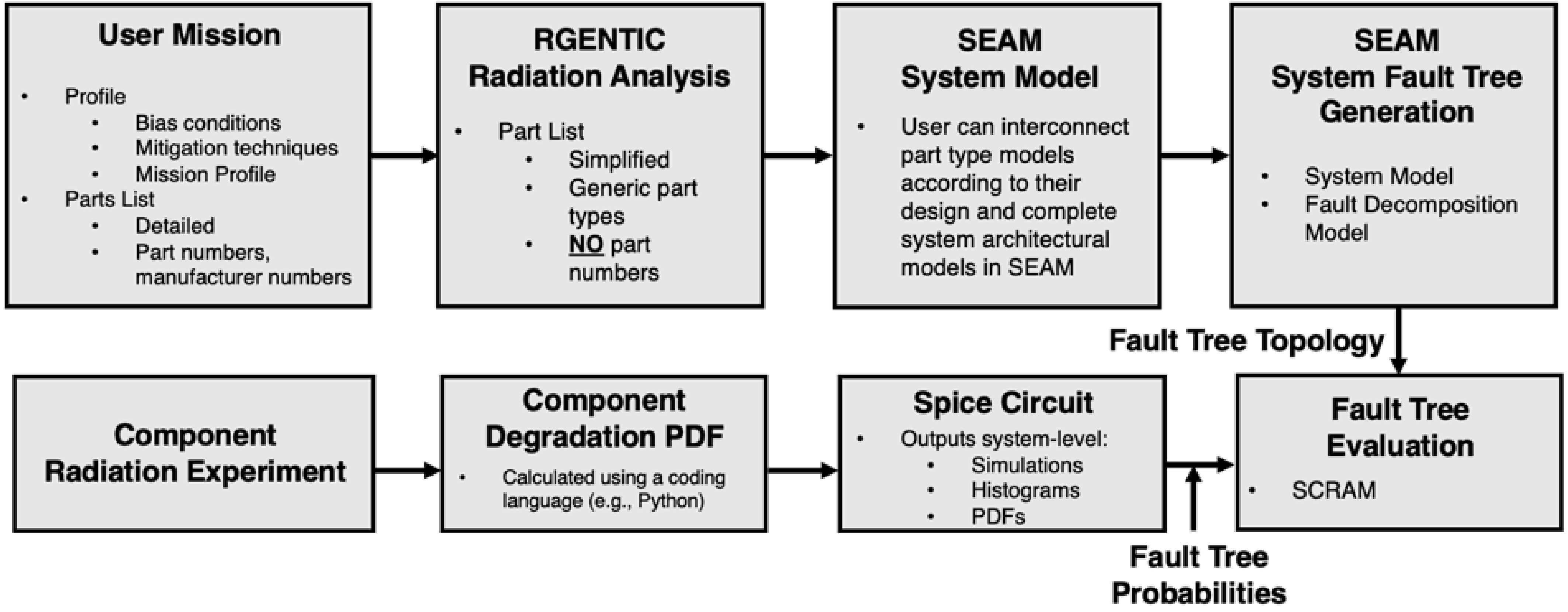


- LiDAR is a complex system that includes a transceiver and receiver
  - Transmitter incorporates a laser drive, which contains a GaN power device
  - Receiver incorporates a photodiode receiver

Example of a SEAM System Model: LiDAR System



Work Related to SEAM: Experimental Data and Probability Models



Process for correlating radiation datasets to system failure probabilities using Bayesian Analysis, LTspice, RGENTIC, SEAM, and Fault Trees

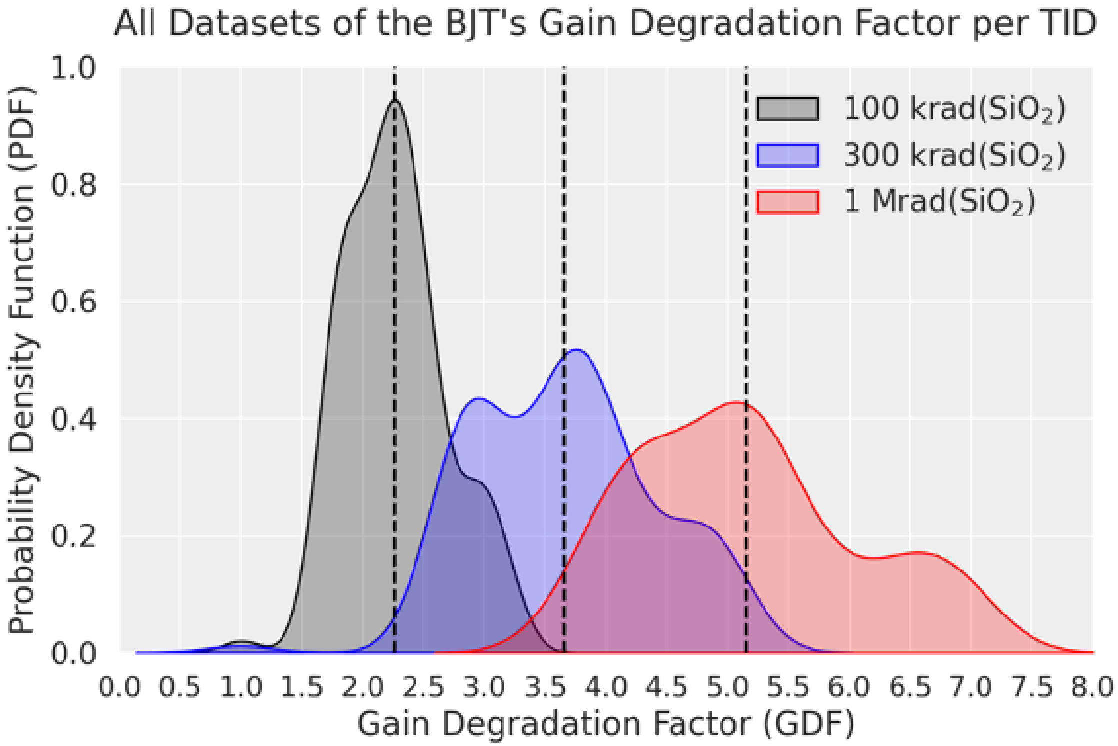
Bayesian Analysis and Reliability Statistics

$$P(A|B) = \frac{P(B|A) * P(A)}{P(B)}$$

$$Posterior = \frac{Likelihood * Prior}{Normalization}$$

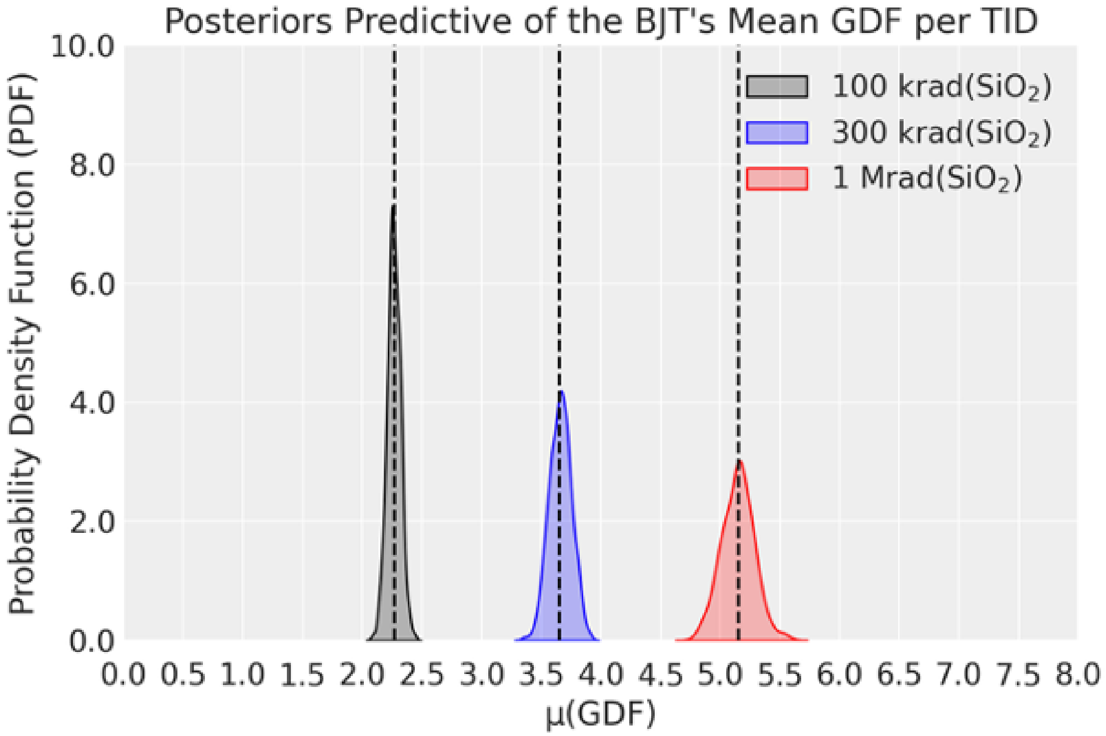
- Probability of an event's occurrence based on:
  - Initial knowledge of the event
  - Incrementally improving knowledge as more info of the event becomes available
- Defining eq. variables:
  - P(A) and P(B) - independent probabilities of event A and event B
  - P(A|B) - probability of A given B
  - P(B|A) - probability of B given A
- Most of the time, probabilities in fault trees represent expert knowledge, or "priors" in Bayesian language
- Can we use experiment evidence and simulation as additional evidence to refine our initial priors in reliability diagrams?

Raw Data vs. Posterior Predictive of Mean GDF



3 datasets of GDFs per TID.
Dashed black lines represent mean GDF at each TID

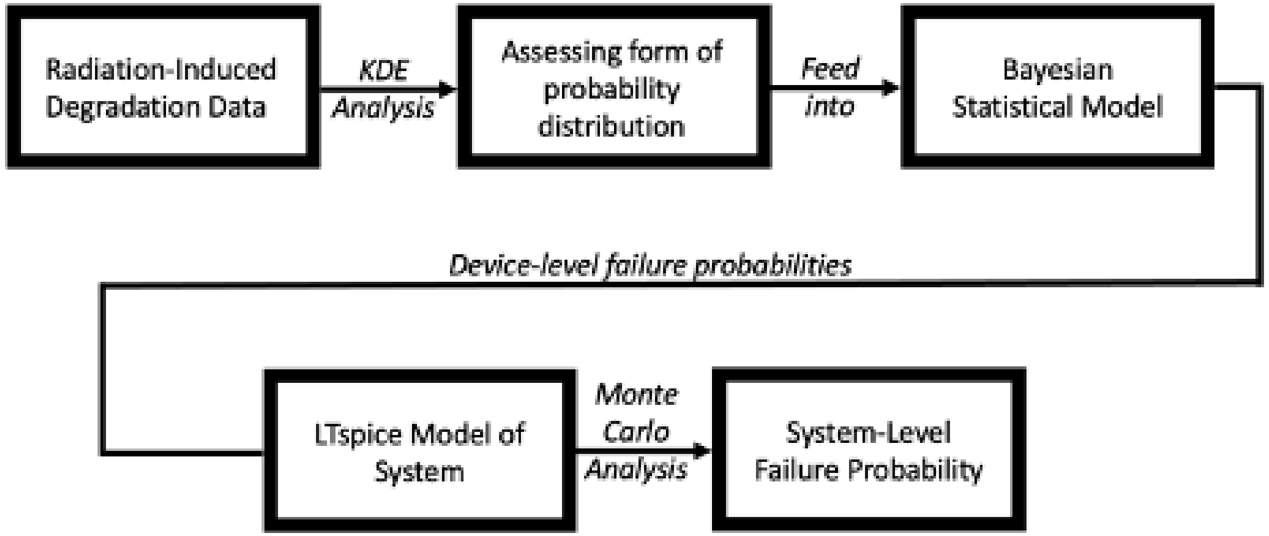
vs.



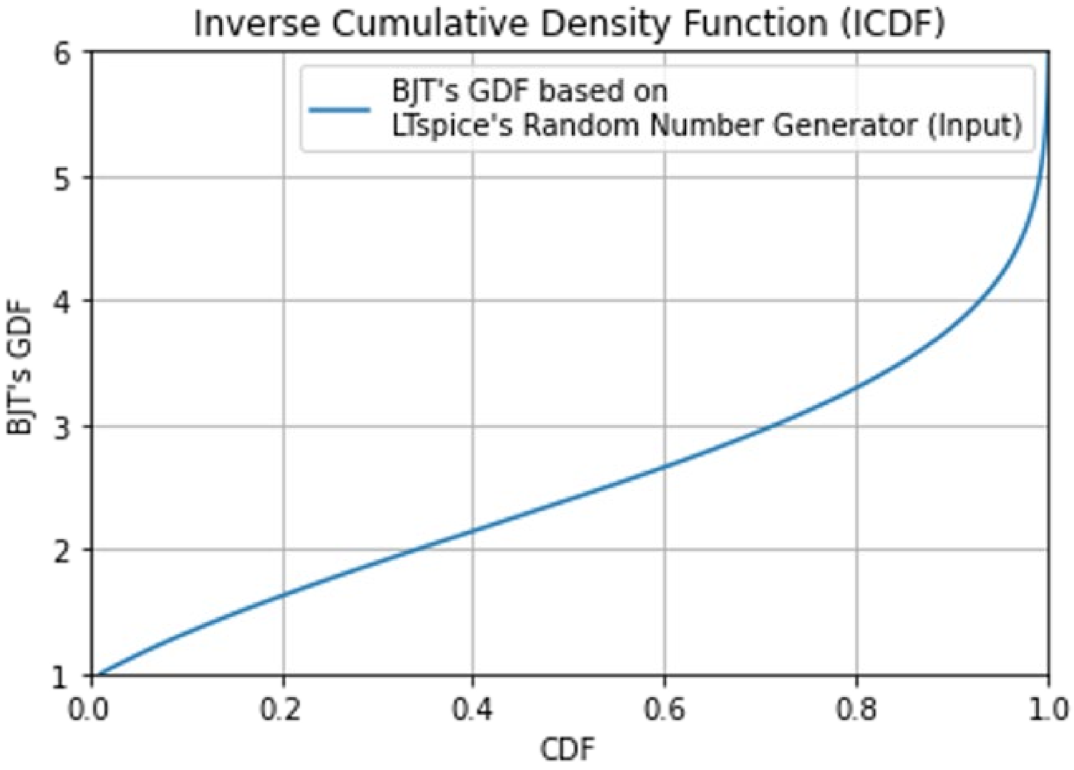
3 Bayesian-generated posteriors of mean GDF per TID, plotted as histograms

R. Ladbury and B. Triggs, "A Bayesian Approach for Total Ionizing Dose Hardness Assurance," IEEE Trans. Nucl. Sci., vol. 58, no. 6, pp. 3004–3010, Dec. 2011.

Monte Carlo Analysis in LTSpice
Gain Degradation Factor of a Linear Voltage Regulator's BJT



Workflow of the Methodology



Inverse Cumulative Density Function (ICDF)

Output From Incorporating Monte Carlo into LTspice

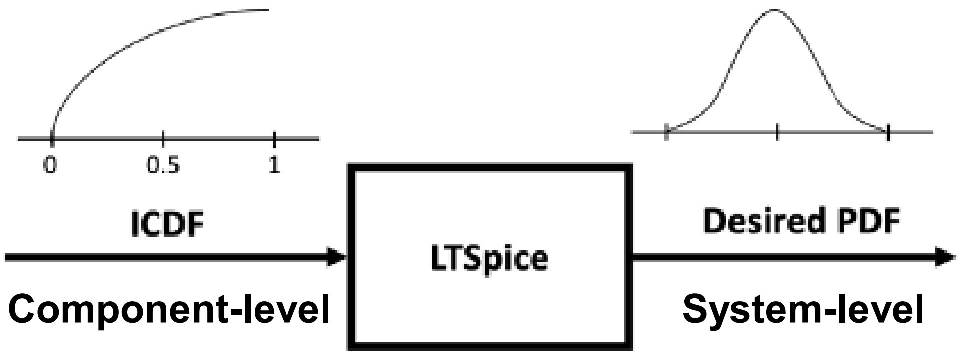
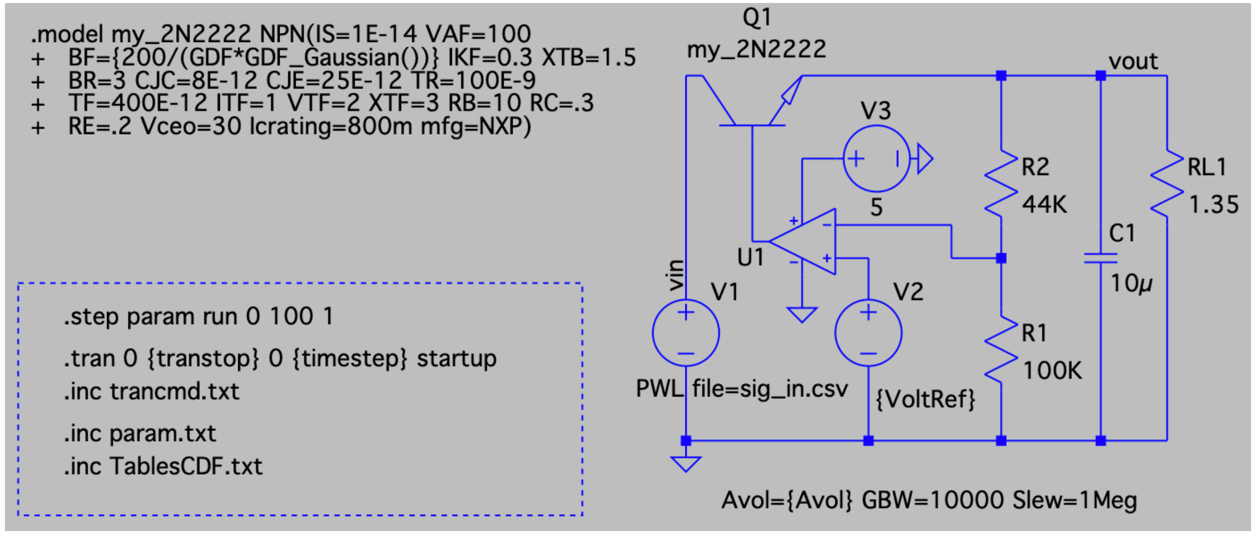
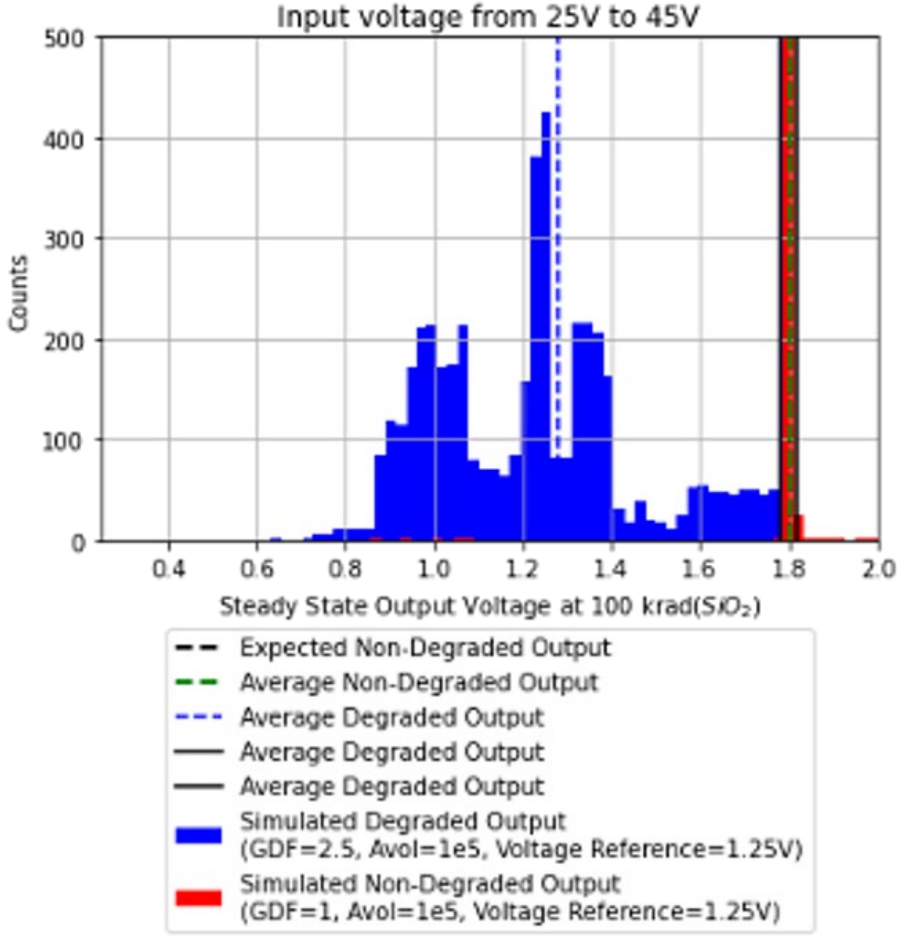


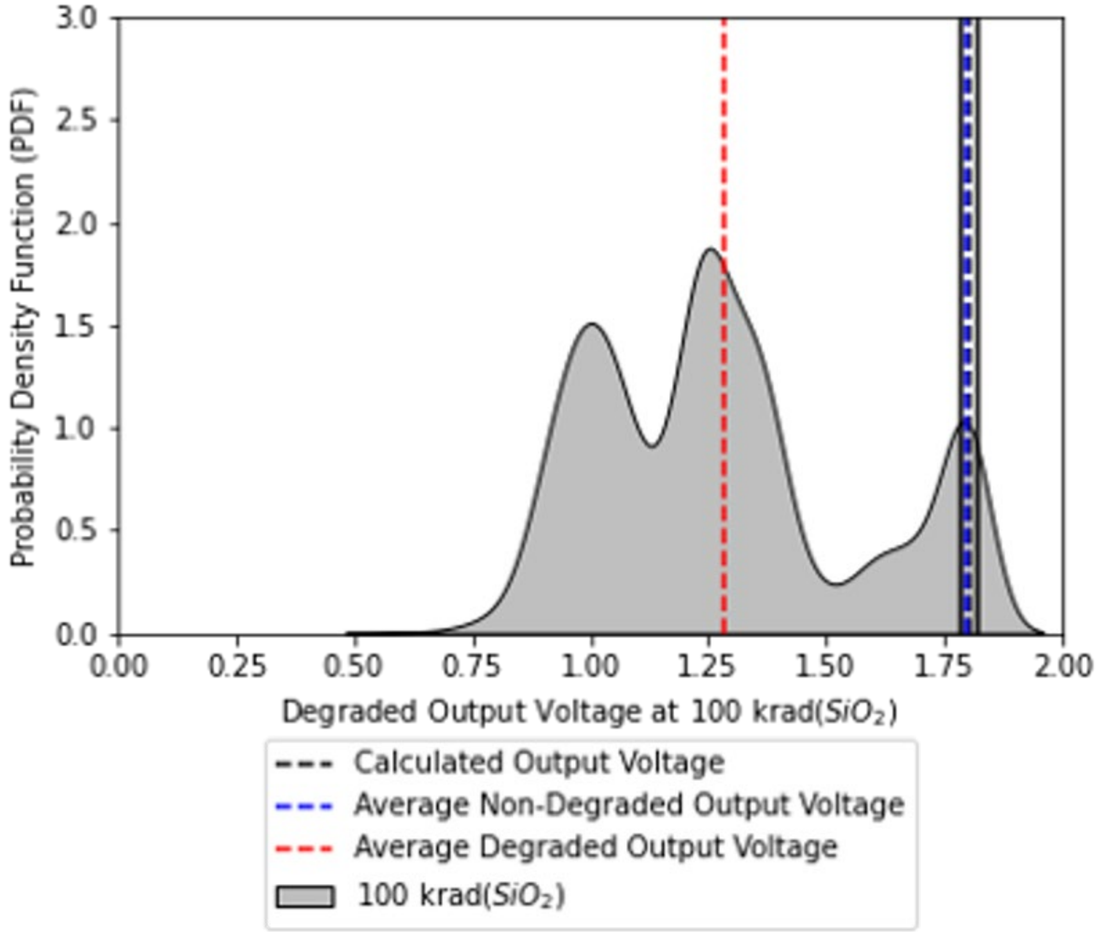
Image representing LTspice's PDF creation



- Avol = open-loop voltage gain (operates as voltage input/voltage output ratio)
- The expected output voltage from the op-amp is 1.8 V.

Converting LTspice's Figures of Merit into PDFs





Conclusions

- Combining RGENTIC and SEAM provides a user with an estimated rad vulnerability assessment for their system
- First version of the SEAM manual is complete.
- First version of EEE part fault model template library is complete-ready made fault modes for users to start modeling.
- We are working on improving user ease of model modification.
- We have versions of SEAM installed behind the firewall at two major agencies.
- We started a parallel effort to try to relate SEAM models to radiation experiment data, the first “systems” are a linear voltage regulator and a LiDAR.