System-level uncertainty quantification using mixed-signal models

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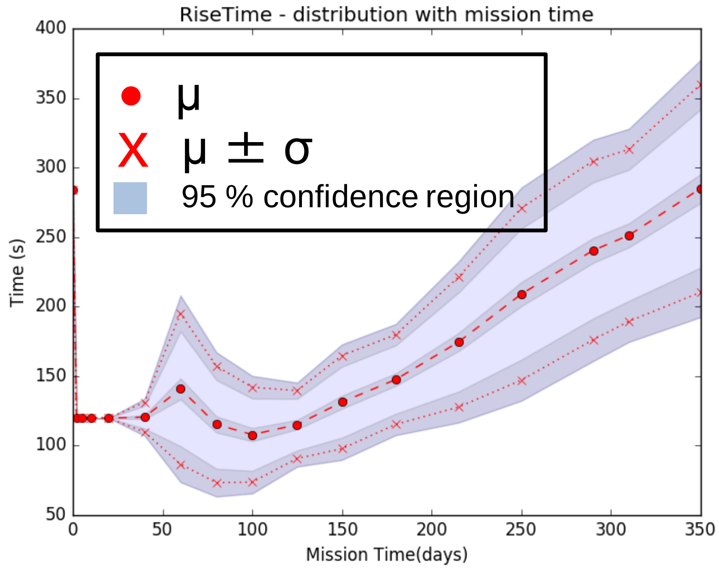
Ionizing Dose System Modeling Project Motivation

- **Total Ionizing Dose (TID) causes performance degradation at component level, parameters that characterize mission performance are at the system level**
- **Commercial-off-the-shelf (COTS) parts:**
  - Desirable from cost, performance point of view
  - Not controlled by fab for radiation impacts
  - High variability part-to-part in radiation response
- **Need multi-scale simulation with estimation of parameter degradation for analog, digital, mixed-signal, power parts**
- **Goal: Estimation of variation of *system-level key performance indicators (KPIs)* as a function of TID.**

Ionizing Dose System Modeling Project Approach

- **Need a flexible approach that is scalable for system-level complexity**
- **Perform behavioral modeling at the functional level**
  - Note: Physics-based modeling at transistor level is not scalable
  - Model electrical behaviors of components used in system on the ‘macro’-level
  - Incorporate radiation variation into parameters of the behavioral model
  - Parameter variation with TID can be estimated based on testing or operational data, behavior of similar parts



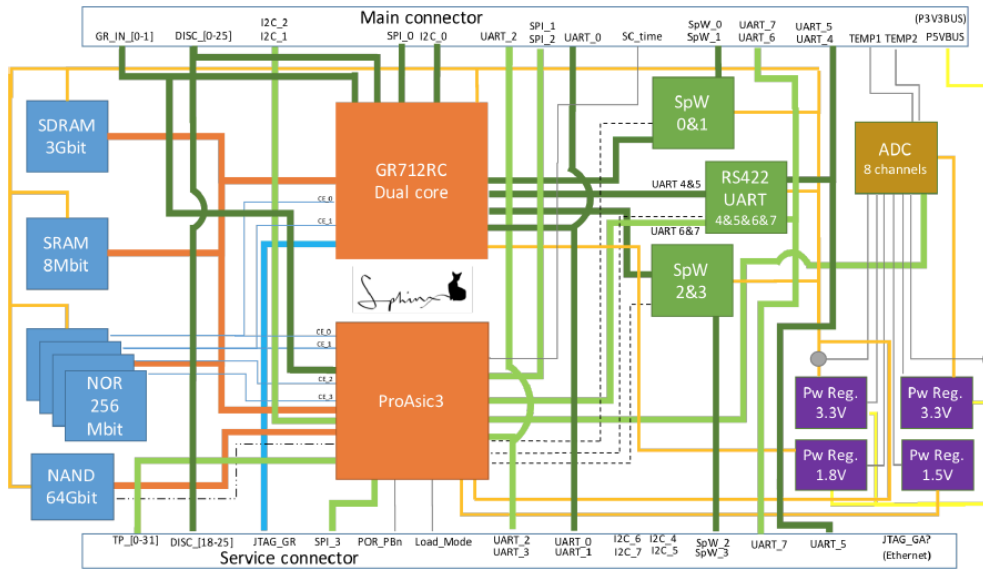
System KPI vs Mission Time

Overview of REMIX Modeling Flow

1. Select a specific system function that uses TID-sensitive components
2. Select the KPI(s) for the system function to be characterized
3. Build an approximate model for the system function
4. Simulate the system to determine the KPI(s) as function of specific values for electrical parameters P and a specific value of TID.
5. Determine the relevant statistical TID environment for the mission
6. Use a smart sampler (e.g. SNL/Dakota) to compute KPI(s) over a range of TID and P, drawn from distributions
7. The variation of TID with mission time enables calculation of reliability metrics of system margin-to-failure and time-to-failure

1. Select a system function that involves TID-sensitive components

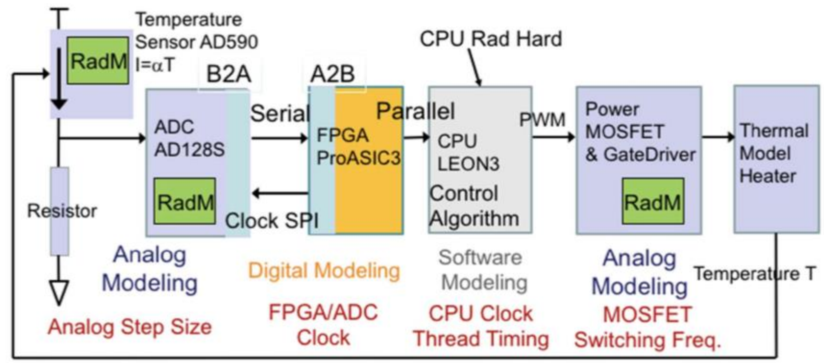
Sphinx board



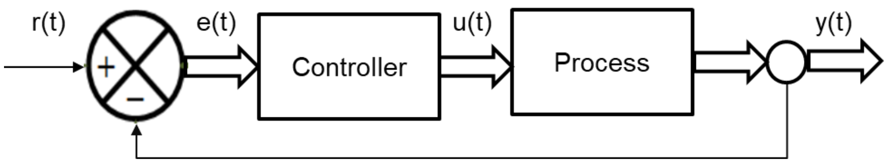
Sphinx C&DH System Functions: Communications, data management, system diagnostics, time keeping, temperature regulation…

Example: Controlled Heating of Spacecraft before Activation

- Closed loop temperature control system implemented on Sphinx C&DH Board
- KPI measures the response to control loop step change in temperature.
- Behavioral models of subsystems and components
- Radiation-aware functional models for analog, digital, and mixed signal parts

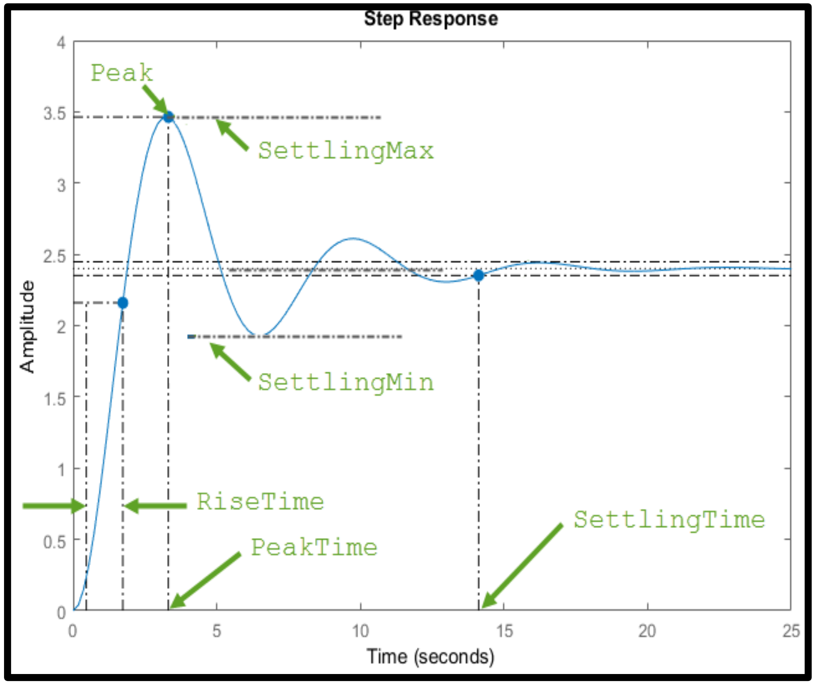


2. Choose key performance indicators (KPI-s) for the system function



Signals:
- r(t): reference signal, desired temperature
- e(t): error signal: difference between desired and measured temperature
- u(t): control signal: power to the heater
- y(t): process signal: measured temperature

Example KPIs:
- SettlingMax: maximum value reached by y(t) before settling to the desired steady-state value
- SettlingTime: time taken for reaching the steady-state value and stabilizing within X% of it



Source : https://www.mathworks.com/

3. Build behavioral models for components that affect the KPIs

AD590 Temperature sensor datasheet:

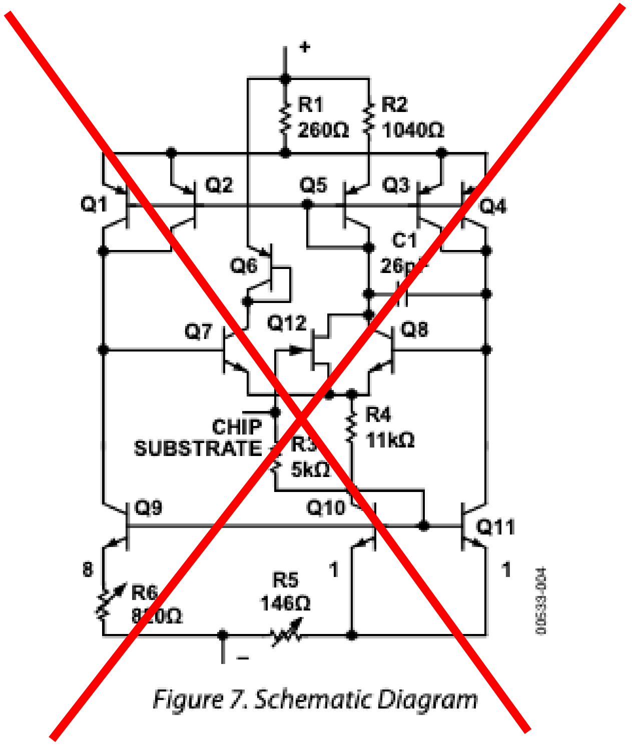


Figure 7. Schematic Diagram

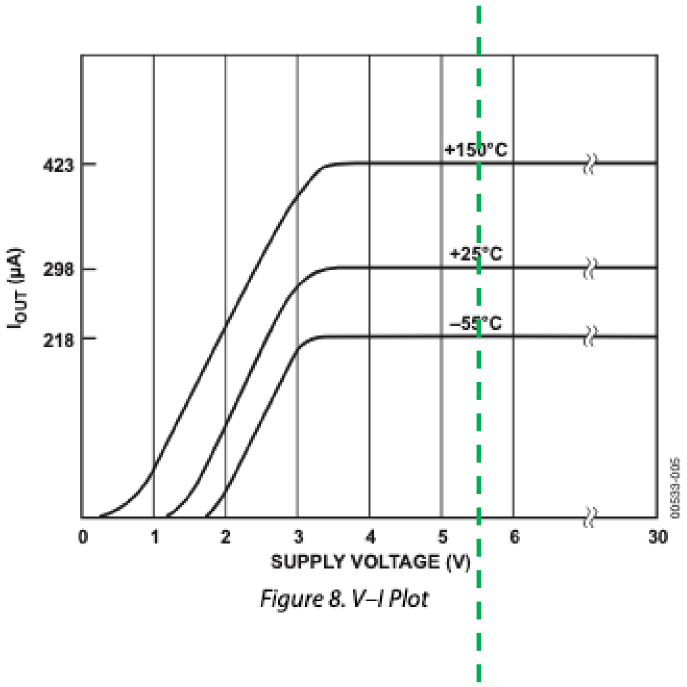


Figure 8. V–I Plot

Transistor Level: TOO COMPLEX

Behavioral Level: SUFFICIENT

AD590 Model

- Voltage = R*(K+M*Temperature +α*TID)
  - R = 2800 Ohms
  - K = 273.2e-6
  - M = 1e-6
  - α = 0.2e-6
- Parameter for AD590 part to part variability
  - Param1: Gaussian with μ=1, σ=0.05
- Updated equation with part-to-part variability
  - Voltage = Param1*R*(K+M*Temperature +α*TID)

ADC Model

ADC-Code = ADC_MAX * (Vin)/ (Vmax– Vmin) - α * TID * (Vin-Vmin)^2

- ADC_MAX, max code from ADC = 2^n – 1 (for a n-bit ADC), = 255 for n=8
- n = 8
- Vmax = 5, Vmin = 0
- α = (ADC_MAX/n)/ ((Vmax- Vmin) ^ 2*30)

Parameter for ADC model part to part variability

- Param2: Gaussian with μ=1, σ=0.05

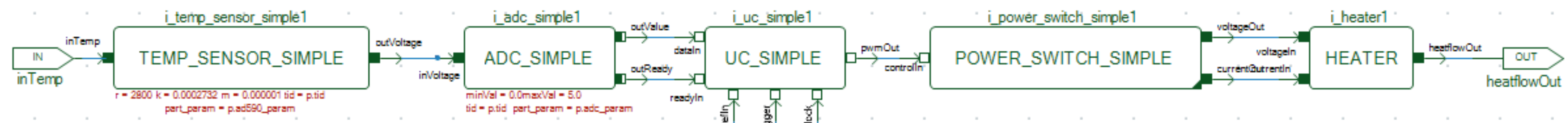
Updated equation with part-to-part variability

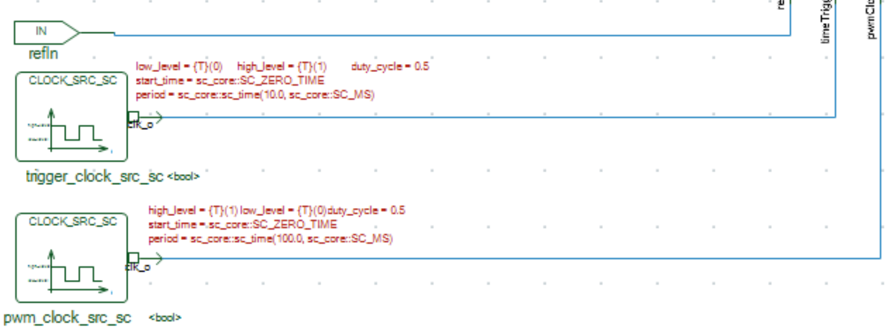
ADC-Code = ADC_MAX * (Vin-Vmin)/ (Vmax – Vmin)

- Param2*α * TID * (Vin-Vmin)^2

Composed System Model

SystemC/AMS model constructed from components using the COSIDE mixed-signal modeling tool





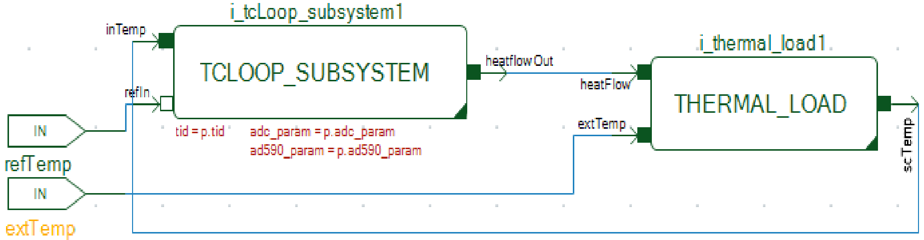
Block	Model	Type
TEMP_ SENSOR	AD590 model	SystemC/AMS.TDF
ADC	ADC model	SystemC/AMS.TDF
UC	(1) control algorithm (code) running on the microcontroller, (2) PWM signal generation logic	SystemC
POWER_SWITCH	Ideal model of a switch controlling power to the heating element	SystemC/AMS.TDF
HEATER	Heating element	SystemC/AMS.ELN

Radiation sensitive components:

- TEMP_SENSOR
- ADC

4. Simulate system function

For simulation a ‘testbench’ is needed that includes the system model, as well as the model of the system’s environment.



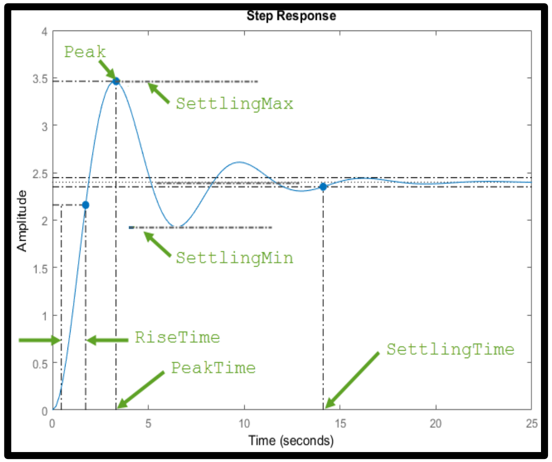
Block	Model	Type
TC_LOOP	System model	SystemC/AMS
THERMAL_LOAD	Spacecraft thermal mass	SystemC/AMS.ELN

Inputs:

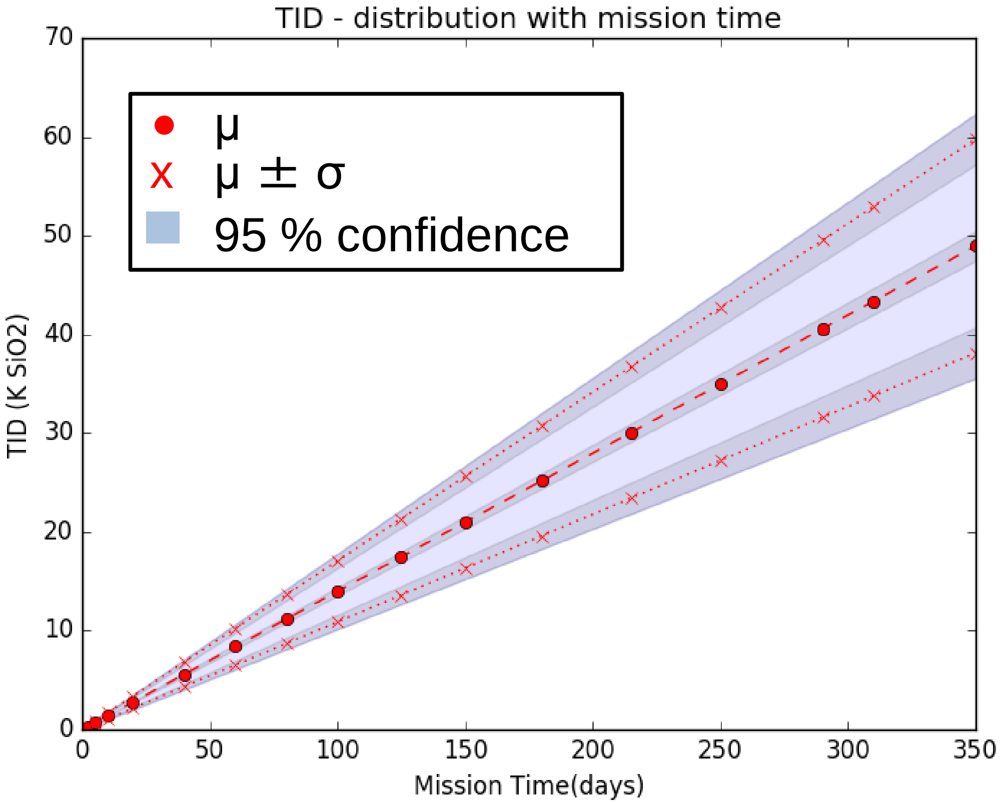
- refTemp: reference temperature (step change)
- extTemp: ambient temperature

Response:

- scTemp: spacecraft temperature

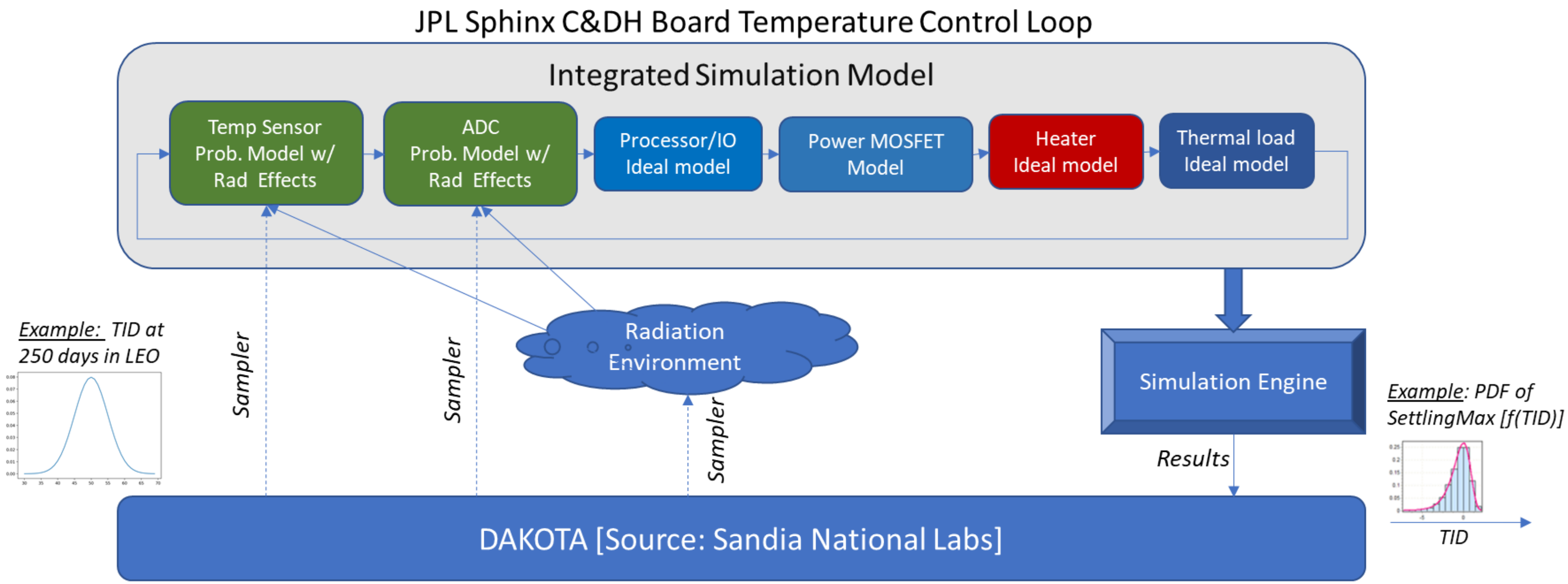


5. Determine TID environment



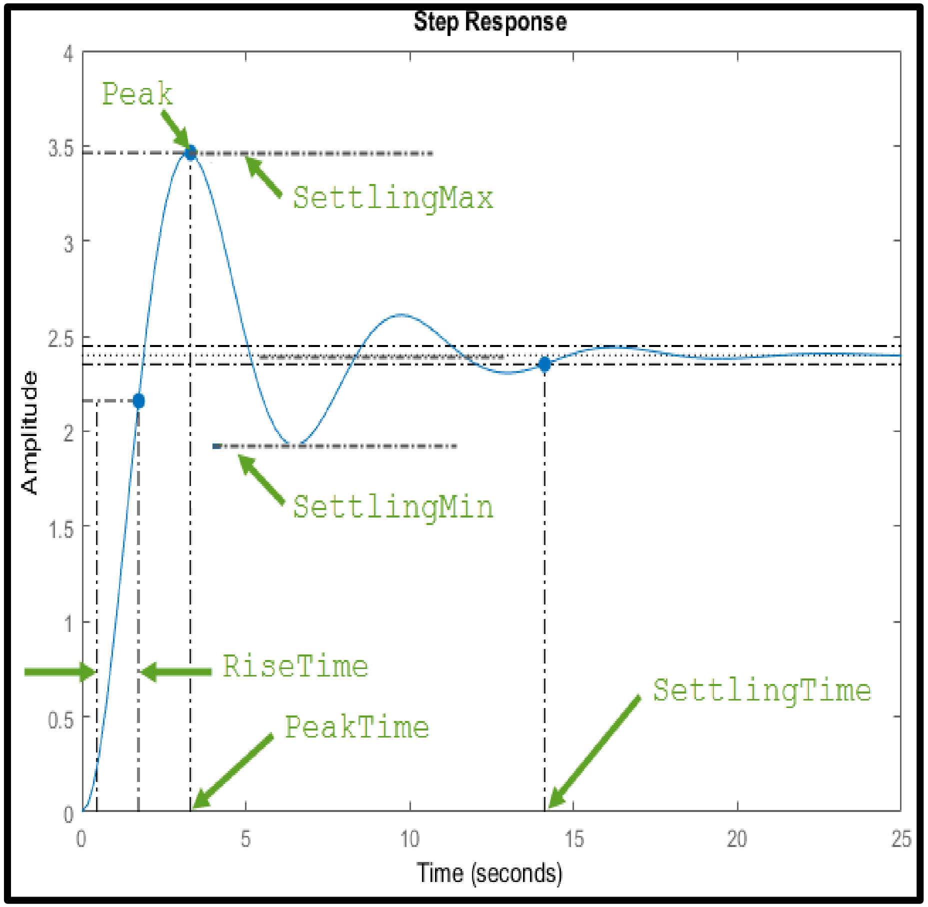
- TID environment uncertainty modeled as a Gaussian with increasing standard deviation with mission time
  - TID rate: Gaussian with μ=0.14 σ=0.03
- Determined based on operational data or models
- Can be time varying
- Plot is an ensemble of 350 PDFs, one for each mission day

6. Use a smart sampler to compute KPI(s) over a range of TID and P, drawn from distributions



The Sandia DAKOTA UQ platform samples the probabilistic models using intelligent sampling algorithms and runs simulations for the sample points. The collected simulation results are samples from a probability distribution, that represents the system's performance as a function of the radiation environment.

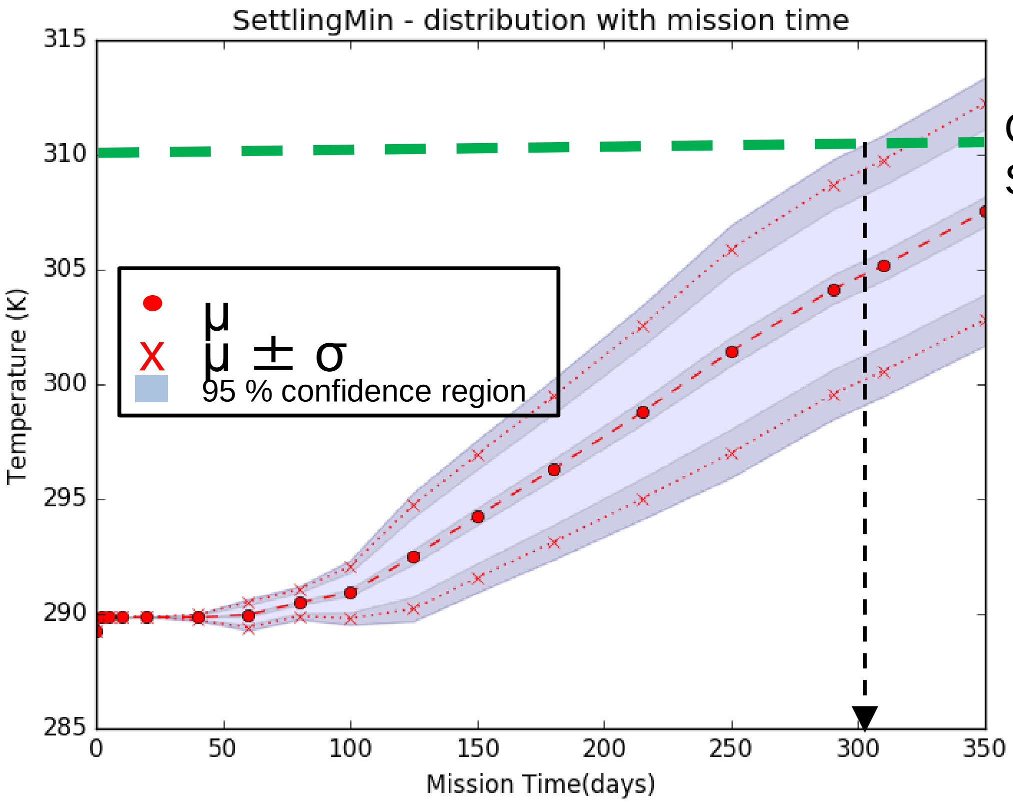
Recap: Key Performance Indicators (KPIs)



- **RiseTime** — Time it takes for the response to rise from 10% to 90% of the steady-state response.
- **SettlingTime** — Time it takes for the error between the response $y(t)$ and the steady-state response y_{final} to fall to within 2% of y_{final}.
- **SettlingMin** — Minimum value of $y(t)$ once the response has risen.
- **SettlingMax** — Maximum value of $y(t)$ once the response has risen.
- **Overshoot** — Percentage overshoot, relative to y_{final}.
- **Undershoot** — Percentage undershoot.
- **Peak** — Peak absolute value of $y(t)$
- **PeakTime** — Time at which the peak value occurs.

Source : https://www.mathworks.com/help/control/ref/stepinfo.html

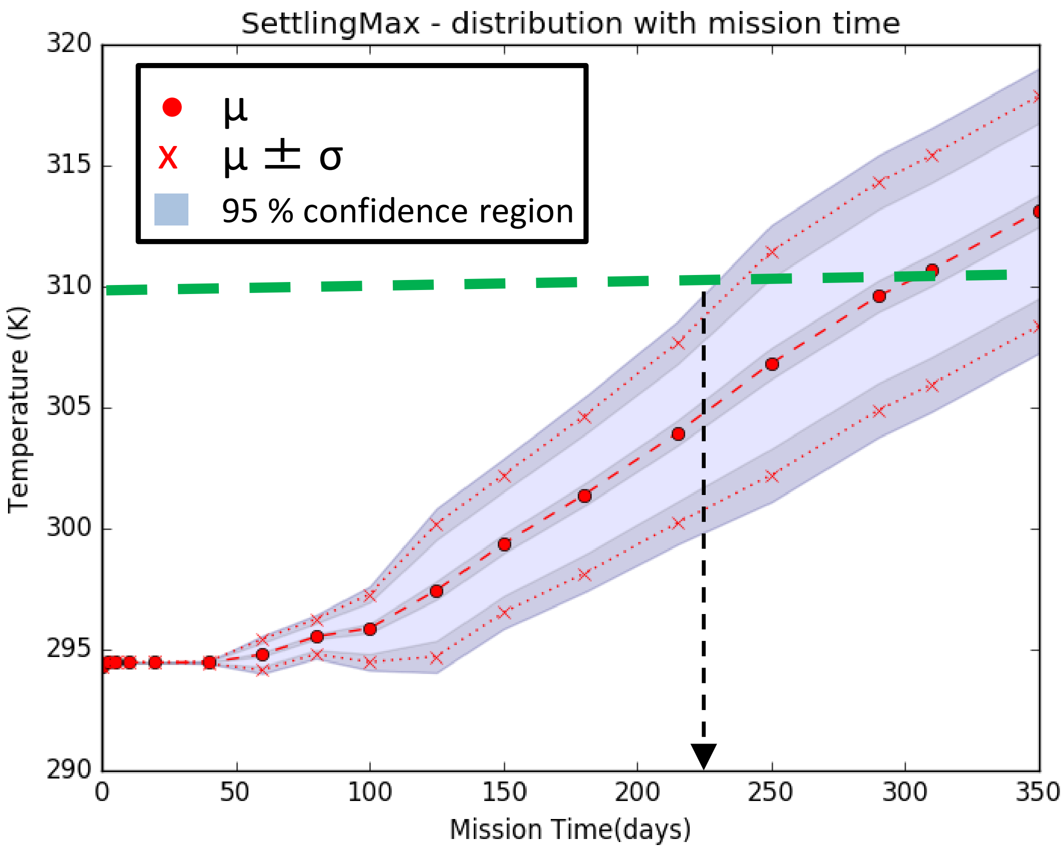
Results:
Settling Min: mean and std-dev with time



Operational Limits/ Requirement Specification (here Temp <= 310 K)

- Operation out of Spec. possible around Day 303

Results:
Settling Max: mean and std-dev with time

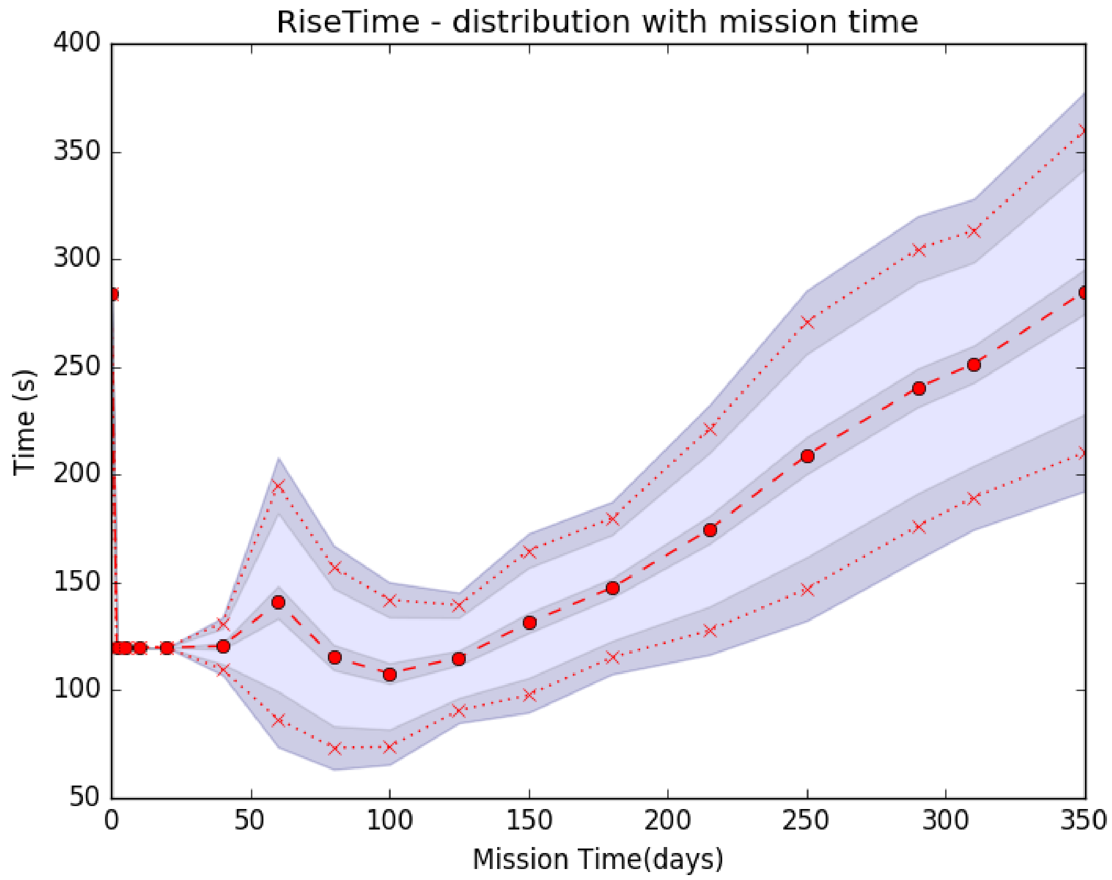


Operational Limits/ Requirement Specification (here Temp <= 310 K)

Operation out of Spec. possible around Day 225

Different functions may have parametric failures at different times in the same dose environment.

Results:
Rise time: mean and std-dev with time



Observations

- System KPI CDFs (at different mission times), allow for computing probability that the KPI remains within operational requirements.

- Example: Assume requirements state that maximum permissible temperature is not to exceed 310K.

- Probability of Failure (mission time = 350 days)

$$P_f = 1 - Prob(SettlingMax <= 310, mission\text{-}time = 350\ days) = 0.56$$

Conclusions

- Multi-scale mixed-signal simulation of electronic systems can predict impact of component-level TID degradation on system function KPIs
  - Behavioral models for standard components – transfer functions
  - Radiation-effected parameters are sampled from distributions
  - Mixed-signal models can use the actual control algorithm code
- ”Smart” Monte Carlo sampling and simulation can give probabilistic estimates of environmental impacts on system KPI-s as a function of elapsed mission time
- Different system functions experience different impacts of TID; they may fail at different doses
- Probability of a specific KPI failure at specific mission time can be calculated