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Methodology for Correlating Historical Degradation Data to Radiation-Induced Degradation System Effects in Small Satellites

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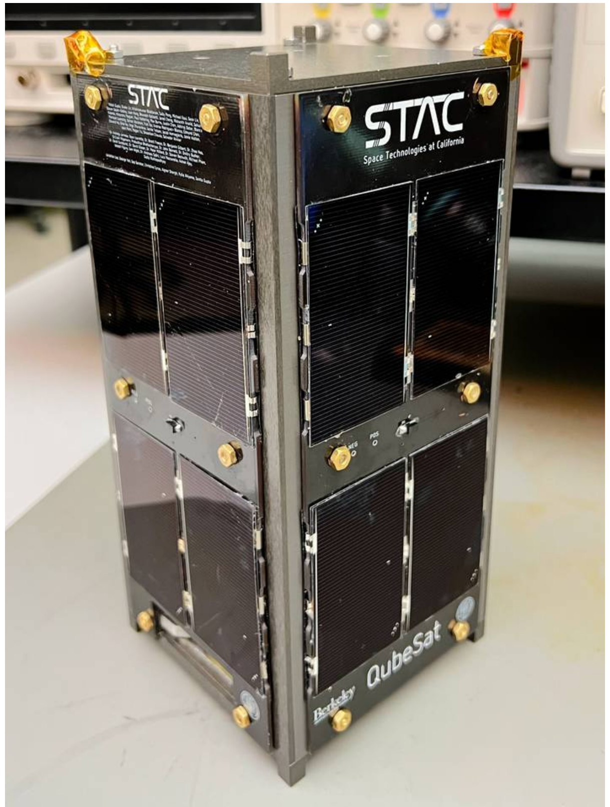
This work is sponsored by NEPP Grant and Cooperative Agreement Number 80NSSC20K0424

08/07/2022

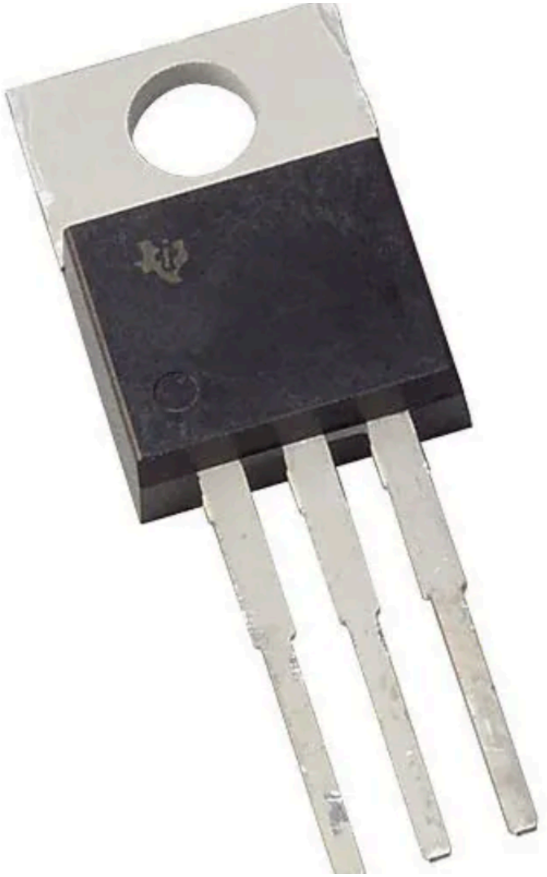
Introduction



QubeSat –
tech demonstration mission of quantum gyroscopes in space
University of California, Berkeley

- Important for an engineering team to have a general understanding of their system's failure probability
- Multiple rounds of radiation testing can be prohibitive due to test facilities' costs (costing >$1k per hour)
- We propose a method for deriving a preliminary system-level failure probability from component failure data.
  - Device-level failure probabilities from historical device data
  - Generates system-level failure probability through a Monte Carlo process

Background



Linear Voltage Regulator (LM317KCS)
Texas Instruments

- ***Objective***: Use Bayesian analysis to derive failure probabilities from radiation databases
- ***Purpose***: Useful for small satellite applications with short development timeframes and significant utilization of COTS components
- ***Case example***: A selected commercial BJT (2N2222) in a self-designed linear voltage regulator was found to have a high degradation probability

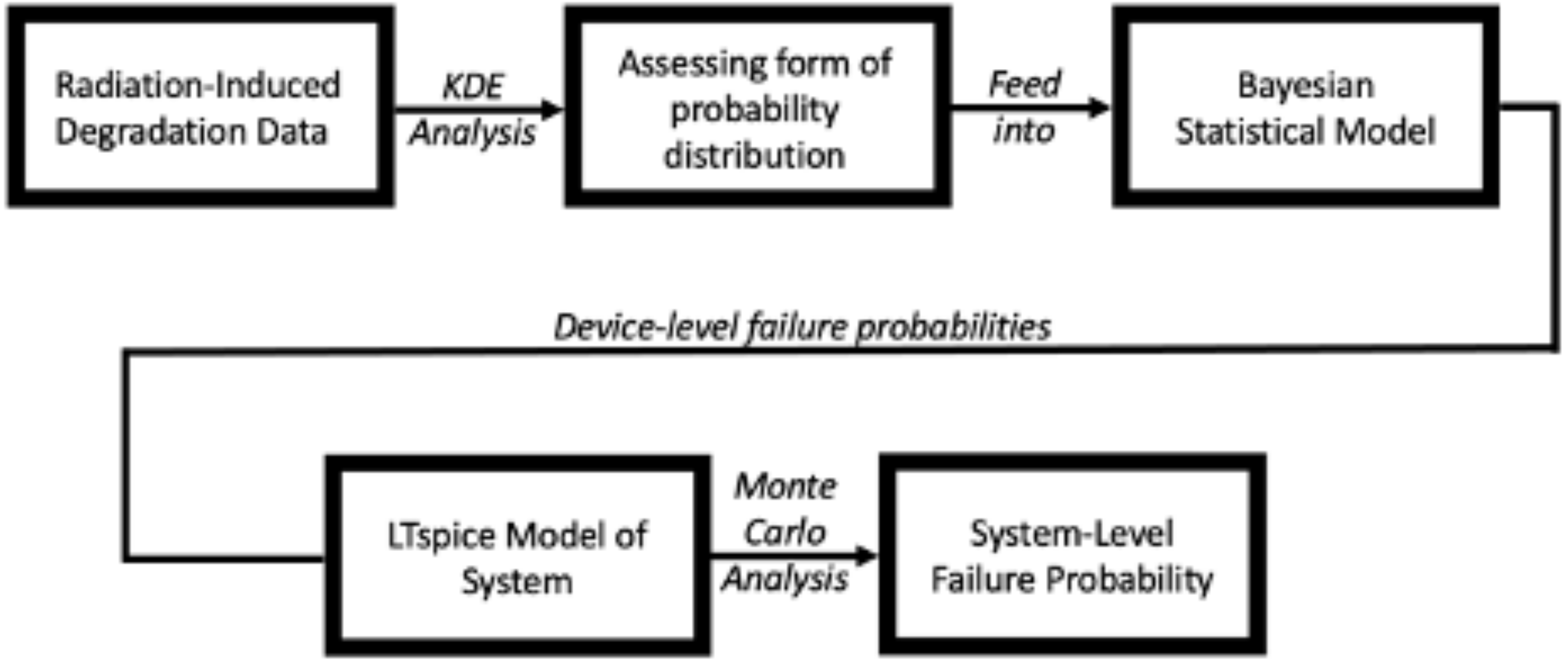
Methodology

For Extracting System-Level Probability from Component-Level Degradation

Device-level data fed into kernel density estimation, resulting in most likely distribution shape of the dataset

Device-level data feed into Bayesian statistical model

Existing radiation database



LTspice-simulated output of modeled linear voltage regulator run multiple times

System-level outputs are converted into a system-level failure probability

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Bayesian Analysis
For Estimation of Component-Level Probabilities

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

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

Kernel Density Estimation (KDE)

For Component Probability Distribution Extraction

$$\hat{f}(x) = \sum_{observations} K\left(\frac{x - observation}{bandwidth}\right)$$

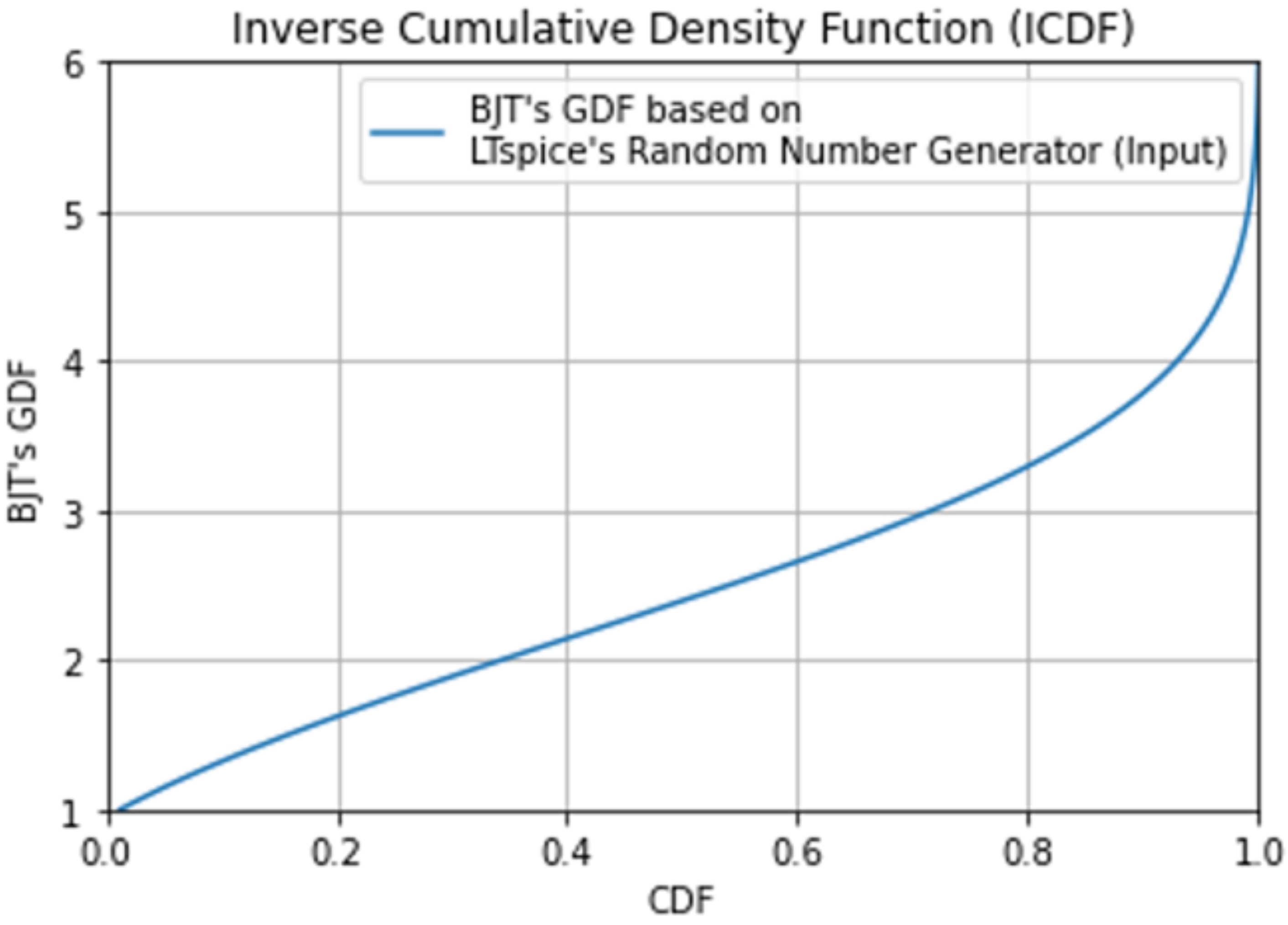
$$n^{\frac{-1}{(d+4)}}$$

$$p\left(x \middle| \mu, \sigma^2\right) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \#$$

$$p\left(x \middle| \mu, \sigma^2\right) \propto e^{-\frac{(x-\mu)^2}{2\sigma^2}} \#$$

Monte Carlo Method

For System Probability Distribution Extraction



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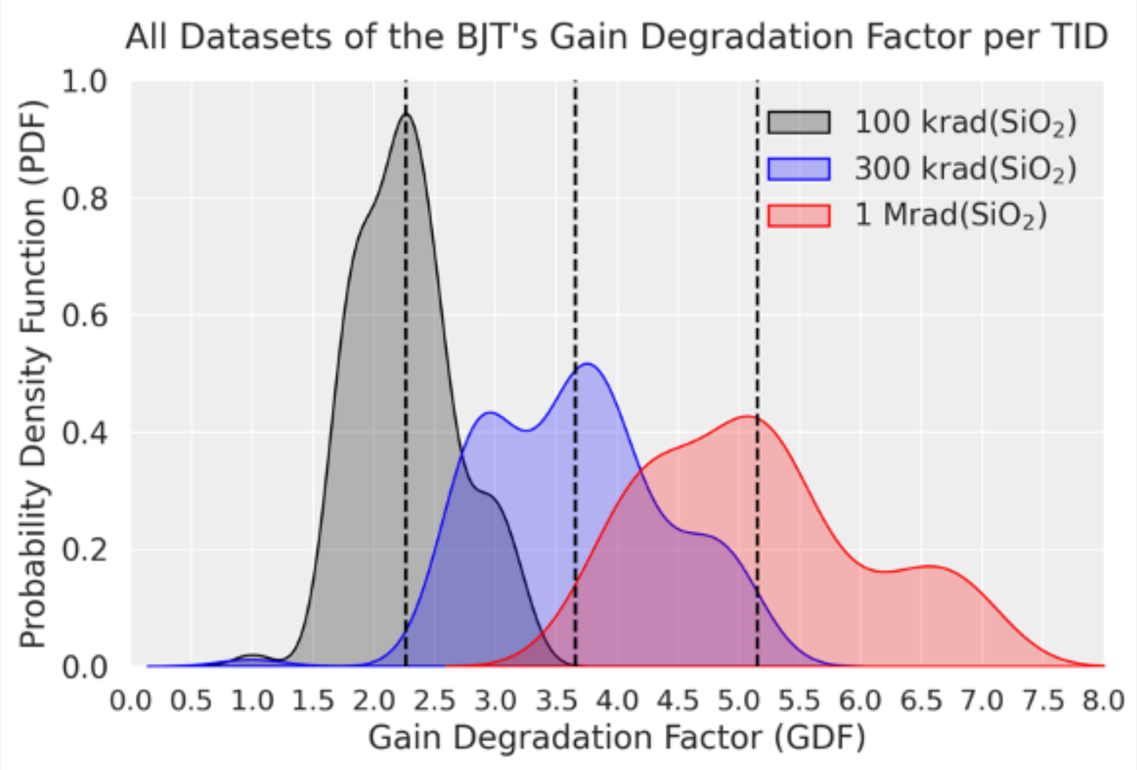
Experimental Radiation Database
2N2222



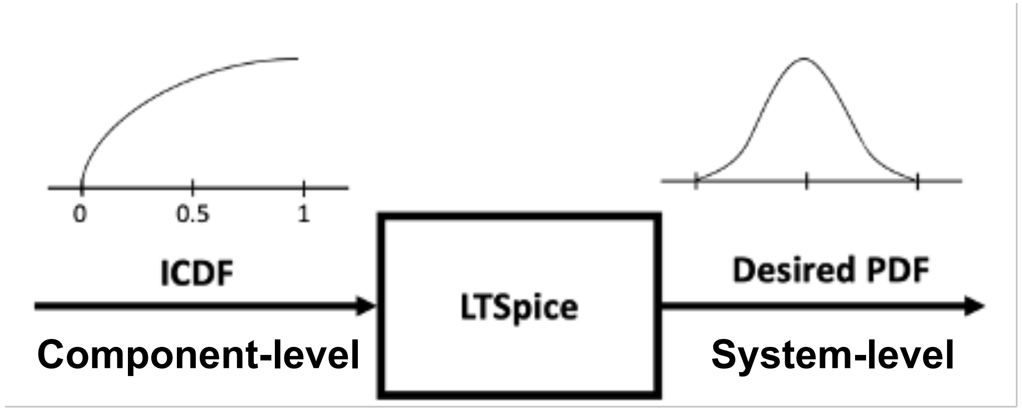
3 datasets of GDFs per TID
Dashed black lines represent mean GDF at each TID

- GDF = Gain Degradation Factor
  - Ratio of post-rad gain to pre-rad gain
- For 100 krad(SiO_2), the distribution is approximately Gaussian
- For 300 krad(SiO_2) and 1 Mrad(SiO_2), appears more like a multi-modal distribution
- We approximated the 100 krad(SiO_2) as a Gaussian

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.

Simulation Setup

Using LTspice for Monte Carlo Simulation of System of Degradation



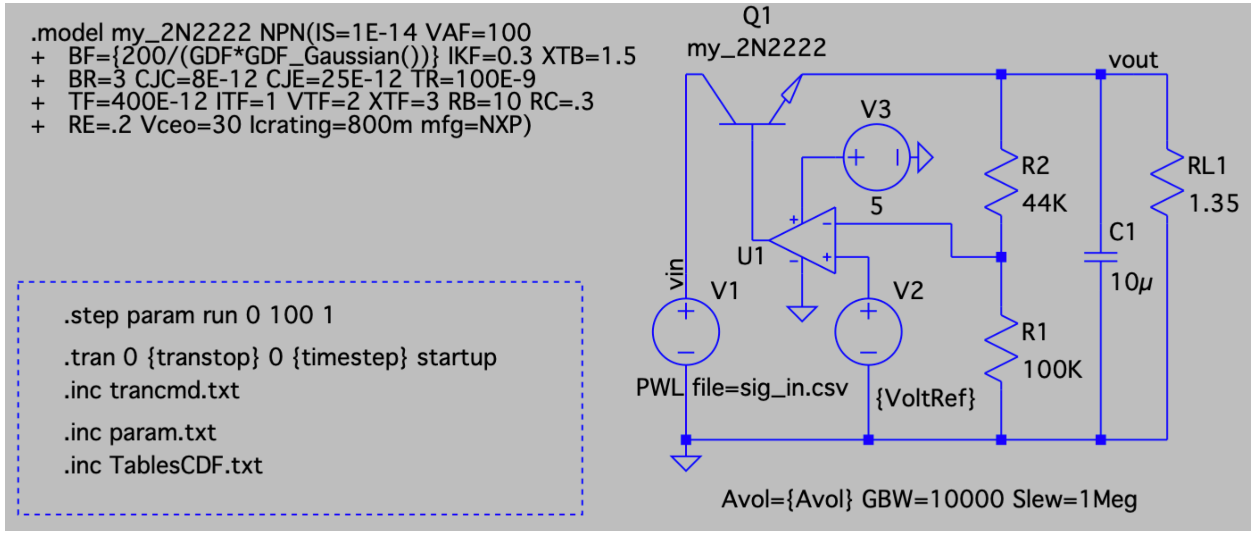


Figure represents random sampling of the ICDF of components with TID degradation using the Monte Carlo feature in LTspice to produce a PDF of system behavior at the output

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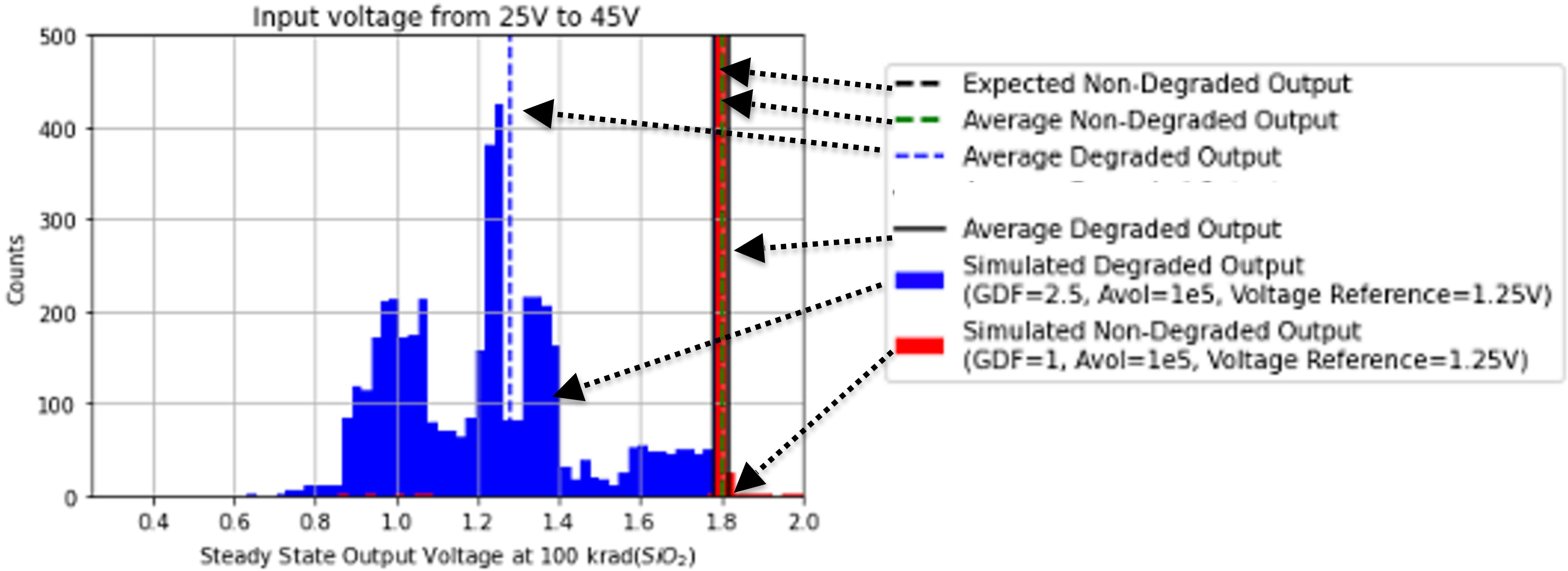
Simulation Results

Histogram of LTspice's Simulation Results



LTspice Regulator Output System Simulation Results
Band of Acceptable System Outcomes

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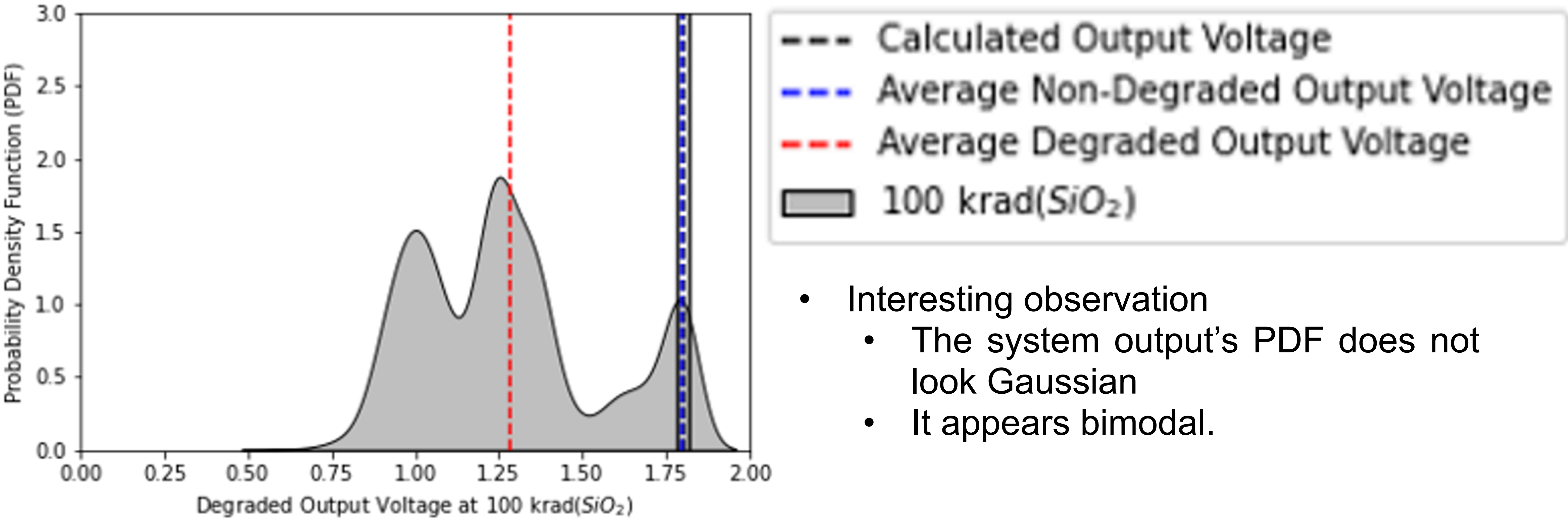
Distribution Obtained from KDE analysis of LTspice output histogram



- Interesting observation
  - The system output's PDF does not look Gaussian
  - It appears bimodal.

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Conclusions