FPGA SYSTEM ERROR RATE ANALYSIS FOR HARSH RADIATION ENVIRONMENTS

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Introduction

- FPGA computation capabilities
  - FPGAs are well-suited to remote-sensing, comms and other DSP applications often used in space
- Large percentage of FPGA space applications target LEO
  - LANL CFE, NASA GRACE, U. Southern Australia FedSat, NASA TACSAT-2, etc.
- We want to extend the reach of FPGAs to more interesting orbits
  - e.g. GPS, GEO, Molniya, Polar, etc.

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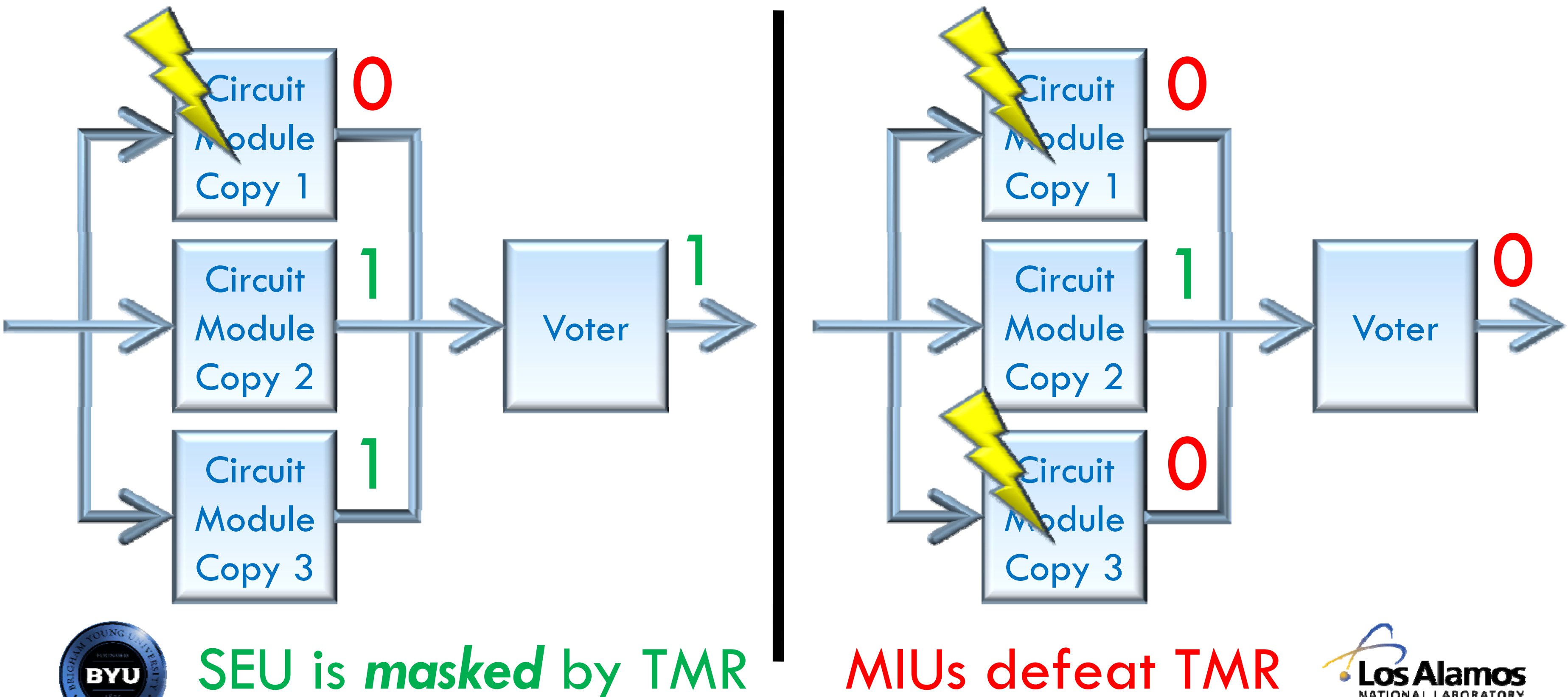
Background :: FPGA Radiation Effects

- Single Event Upsets (SEU)
  - Change of state in memory structure
  - A significant portion of SRAM-based FPGA memory cells are dedicated to the user's circuit design (configuration memory)
  - SEUs in the configuration memory can modify the actual operation of the circuit
- Mitigating FPGA Radiation Effects
  - Triple modular redundancy (TMR)
    - XTMR style of TMR with triplicated voters must be employed to eliminate all single points of failure
  - Scrubbing
    - Periodic or continuous refresh of configuration memory back to intended state
    - Prevents accumulation of upsets in configuration memory
    - Reduces probability of simultaneous upsets (i.e. multiple independent upsets, MIUs) in configuration memory

Background :: Mitigating FPGA Radiation Effects (cont.)

- Multiple independent upsets (MIUs) can defeat TMR and scrubbing



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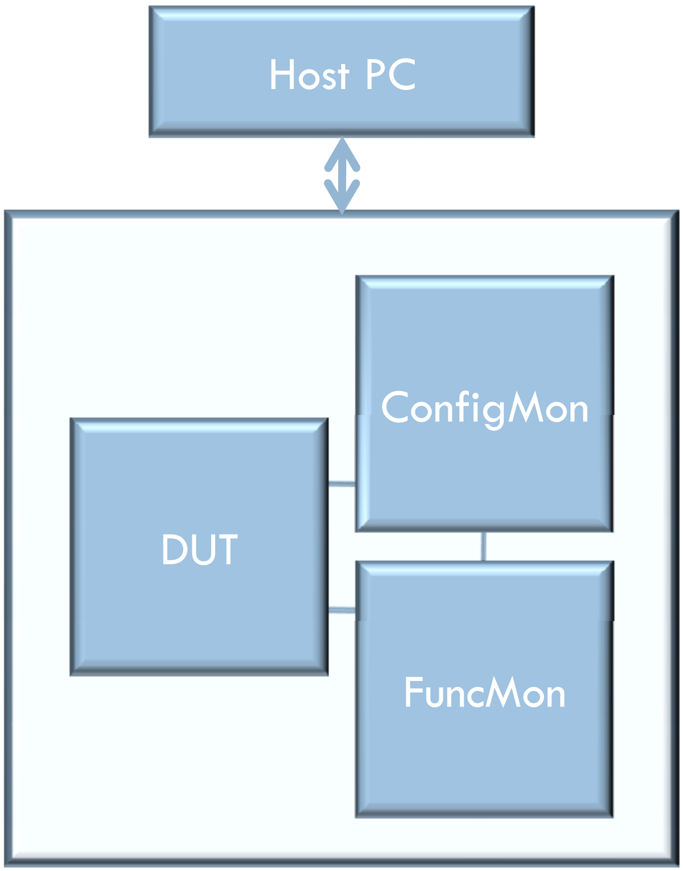
Background :: Harsh Radiation Environments

- Solar energetic particle (SEP) events (colloquially known as solar flares)
  - Harshest radiation environment in space Earth orbits (Tylka et al.)
  - SEU rate can increase orders of magnitude
  - Modeled in CREME96 by week-long event in October 1989
  - Primarily affect orbits further away from the Earth's magnetic field or at the poles (e.g. GPS, GEO, Molniya, Polar)
- An increase in SEU rate increases the likelihood of MIUs
- *The purpose of this work was to measure the probability of failure from MIUs during SEP events*

Testing Methodology :: Fault Injection

- DUT = Xilinx Virtex-4 XC4VSX55



Test Fixture

- Algorithm

```
do {
    o generate 'i' random bits
      to upset
    o inject 'i' upsets into
      bitstream
    o check for output error
    o fix upset bits
    o reset device
    o record data to output
      file
} while trials < 'm'
```

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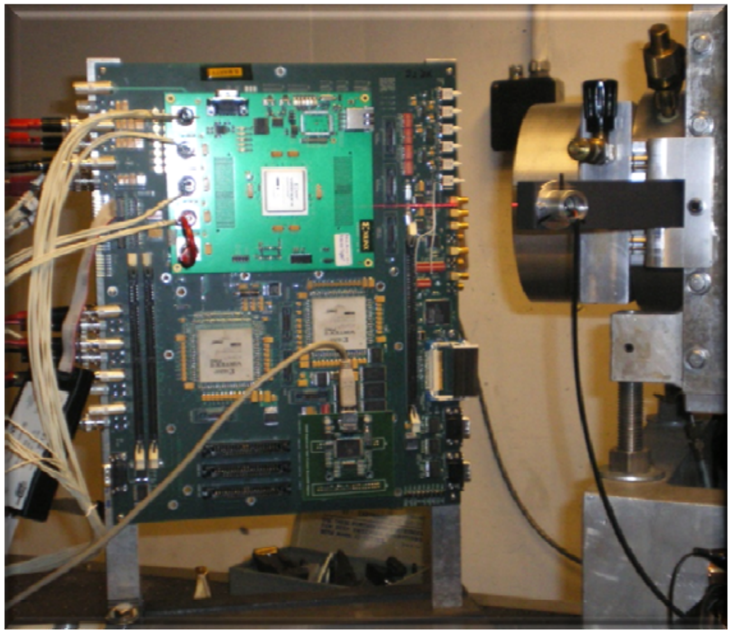
Testing Methodology :: Accelerator

- DUT = Xilinx Virtex-4 XC4VSX55
- Crocker Nuclear Laboratory, UC Davis
- 63 MeV Protons



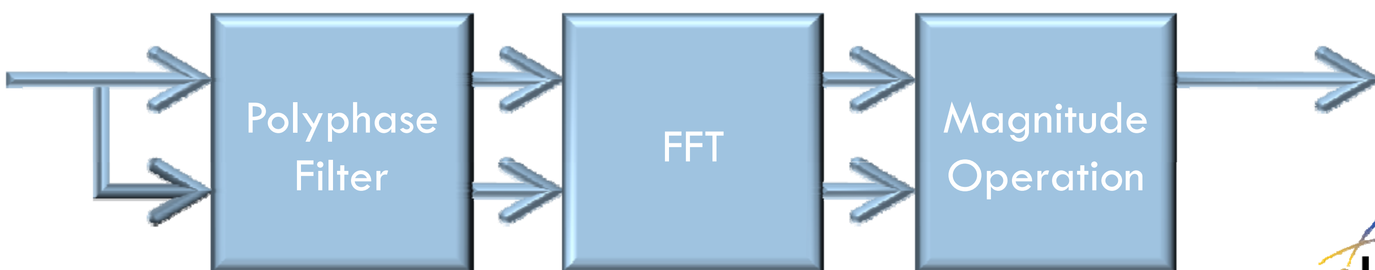
- Algorithm

```
do {
    o sleep for time 't'
    o get and fix upset frames
    o if upsets found
        o record upsets to file
        o check for output error
    o reset DUT
} while time < 'T'
```

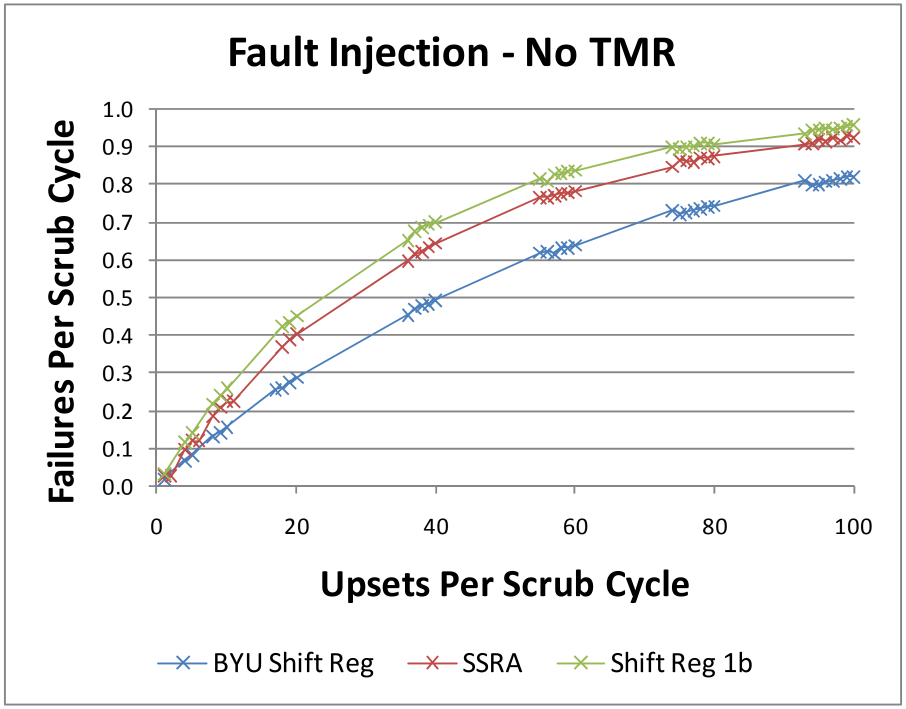
Results :: Example Circuits

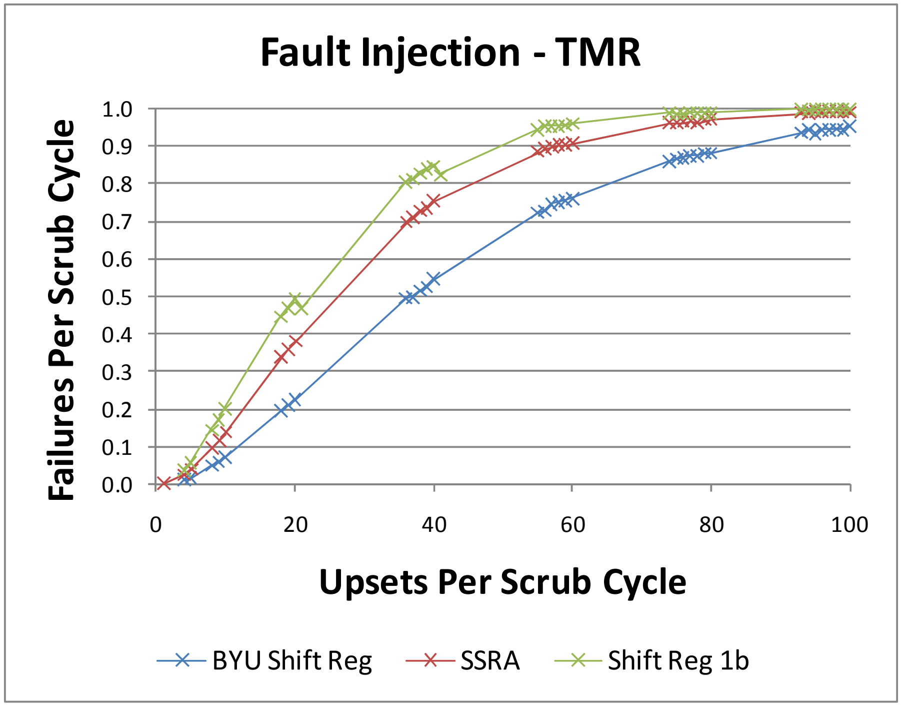
- BYU Shift Reg
  - 32-bit wide, 250 stage shift register with arbitrary combinational logic between each stage
- Shift Reg 1b
  - 1-bit wide, 16,200 stage shift register
- SSRA
  - Digital signal processing kernel

Design	Design Utilization - Slices	
	No TMR	TMR
BYU Shift Reg	4011 (16%)	12014 (48%)
Shift Reg 1b	8111 (33%)	24314 (98%)
SSRA	5381 (21%)	18591 (75%)



Results :: Fault Injection





Note: A minimum of 1000 events were observed for each data point.

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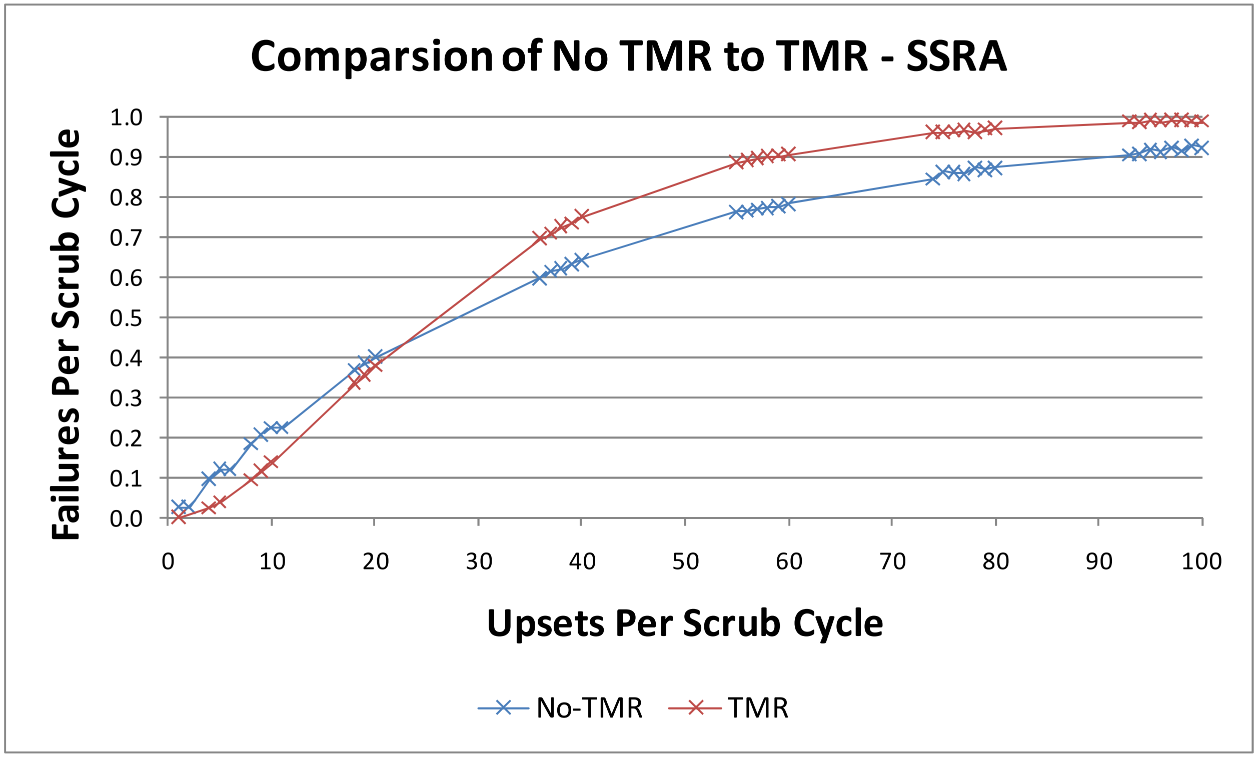
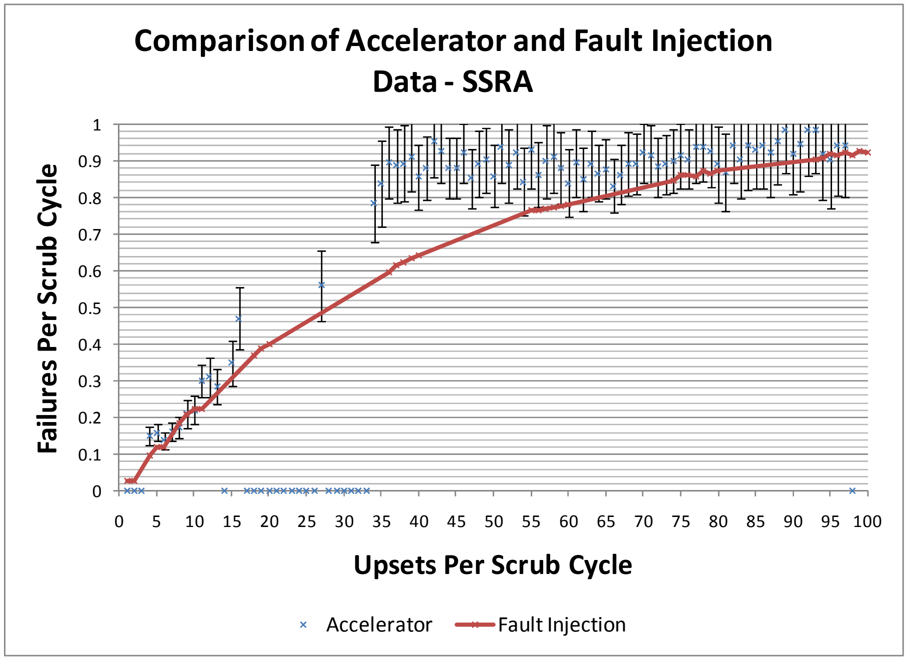
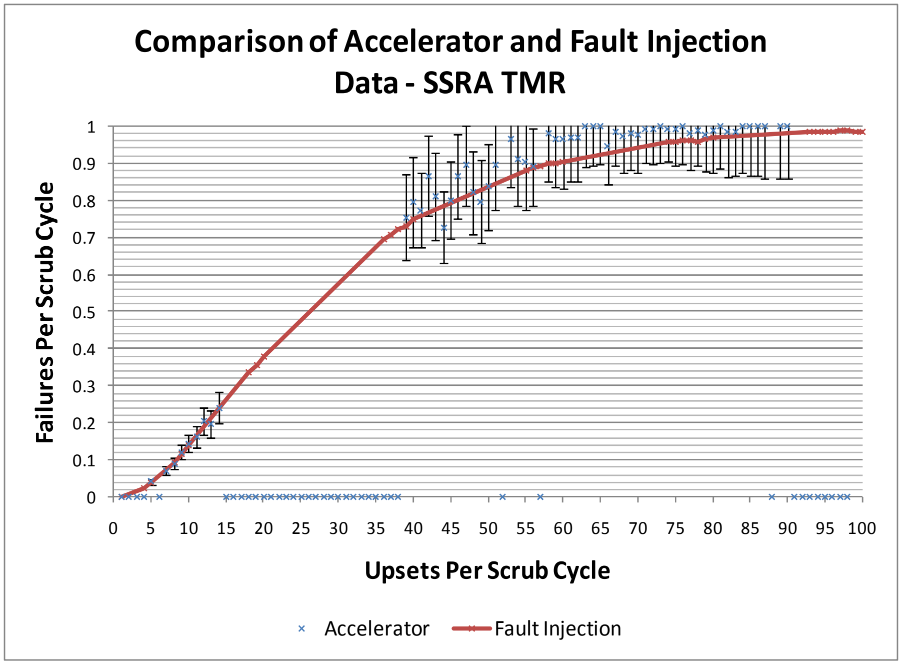
Results :: Fault Injection



Results :: Accelerator





Note: A minimum of 30 events were observed for each data point.

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SEU Rate Models

Orbit	Apogee (km)	Perigee (km)	Inclination (deg)	Peak 5-Minute SEU Rate (SEUs/Device/s)
GEO	35786	35786	0	3.29E-1
GPS	20200	20200	55	2.85E-1
Molniya	39305	1507	63.2	3.08E-1
Polar	833	833	98.7	7.84E-2

- SEU Rate Models
  - CREME96: Worst Week, Worst Day, Peak 5-minutes (see data above)
  - What actually happens during that peak 5-minutes?
    - Real Answer: Nobody Knows!!
    - But we can bound the problem…
      - Best Case: Fluence is perfectly averaged over 5 minutes
      - Worst Case: Fluence all comes during one scrub cycle

Estimating Probability of Failure

- Goal: Estimate probability of failure $P(F_{5\text{-min}})$ for the CREME96 peak 5 minutes
  - Requires probability of i upsets per scrub cycle $P(A_i)$
  - Requires conditional probability of failure for a particular scrub cycle given i upsets occurred during that particular scrub cycle $P(F_{1\text{-cycle}} | A_i)$
  - Requires probability of failure $P(F_{1\text{-cycle}})$ for one trial (i.e. one scrub cycle)
- We measured $P(F_{1\text{-cycle}} | A_i)$ using fault injection and the accelerator
- We assume that $P(A_i)$ has a Poisson probability density function (pdf) since $n >> 1$ and $t_a << T$; with parameter $\lambda = (t_a * n)/T$, i.e. λ = the SEU rate
  - T = interval, e.g. 5 minutes
  - n = number of upsets, e.g. 100 upsets in peak 5 minutes
  - t_a = length of sub-interval, e.g. 15 millisecond scrub cycle
- We calculate $P(F_{1\text{-cycle}})$ for one scrub cycle using the following equation

$$P(F_{1-\text{cycle}}) = \sum_{i=0}^{\infty} P(F_{1-cycle} | A_i) P(A_i)$$

Estimating Probability of Failure

- If we assume that each scrub cycle is an independent trial (valid if scrubbing works correctly), then we can use the following fundamental theorem from Bernoulli to compute $P(F_{5\text{-min}})$ over the entire 5 minute interval

$$P(F_{5-\min}) = \sum_{i=1}^{m} \binom{m}{i} P(F_{1-cycle})^{i} (1 - P(F_{1-cycle}))^{m-i}$$

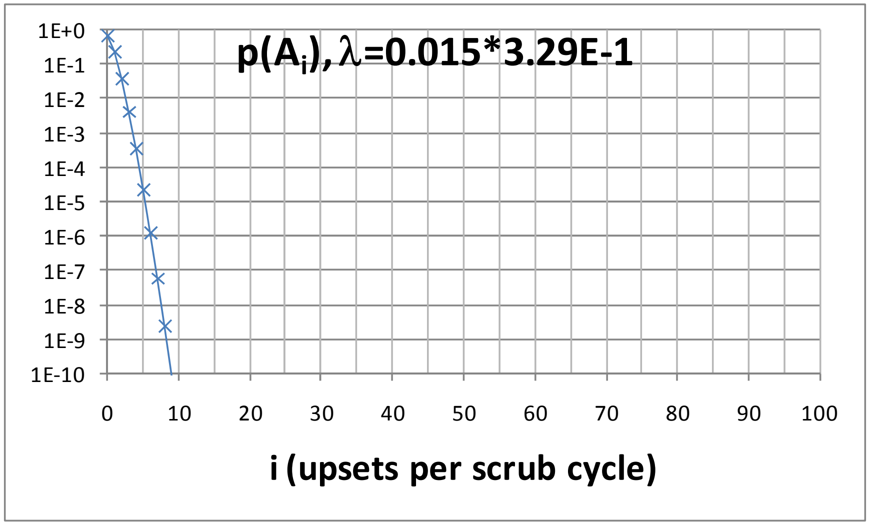
$$or$$

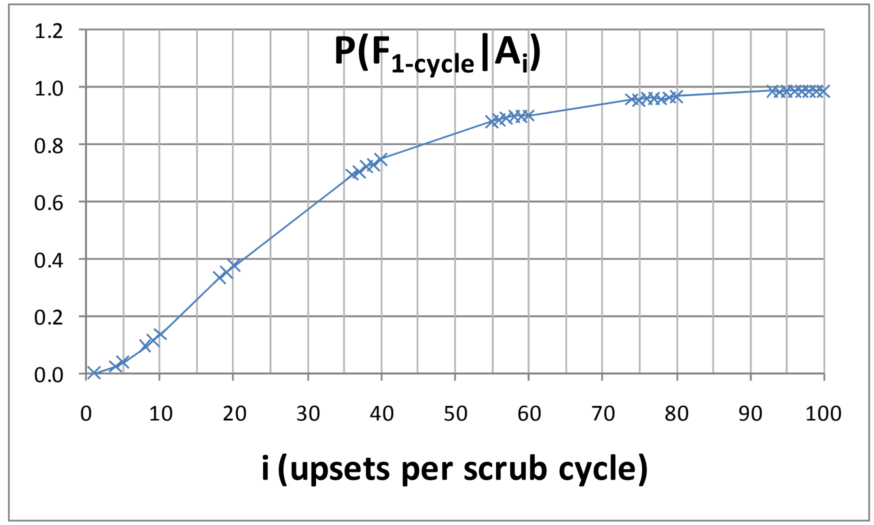
$$P(F_{5-\min}) = 1 - \sum_{i=0}^{0} \binom{m}{i} P(F_{1-cycle})^{0} (1 - P(F_{1-cycle}))^{m-0}$$

$$= 1 - (1 - P(F_{1-cycle}))^{m}$$

  - m = number of trials (assuming 15 millisecond scrub cycle, m=20,000 in five minutes)

Estimating Probability of Failure :: Example (SSRA TMR design, GEO orbit, CREME96 “Best Case” model)





$$P(F_{1-cycle}) = \sum_{i=0}^{\infty} P(F_{1-cycle} \mid A_i) P(A_i)$$

$$= 9.7x10^{-8}$$

$$P(F_{5-\min}) = 1-(1-P(F_{1-cycle}))^m$$

$$= 1-(1-9.7x10^{-8})^{20000}$$

$$= 1.9x10^{-3}$$

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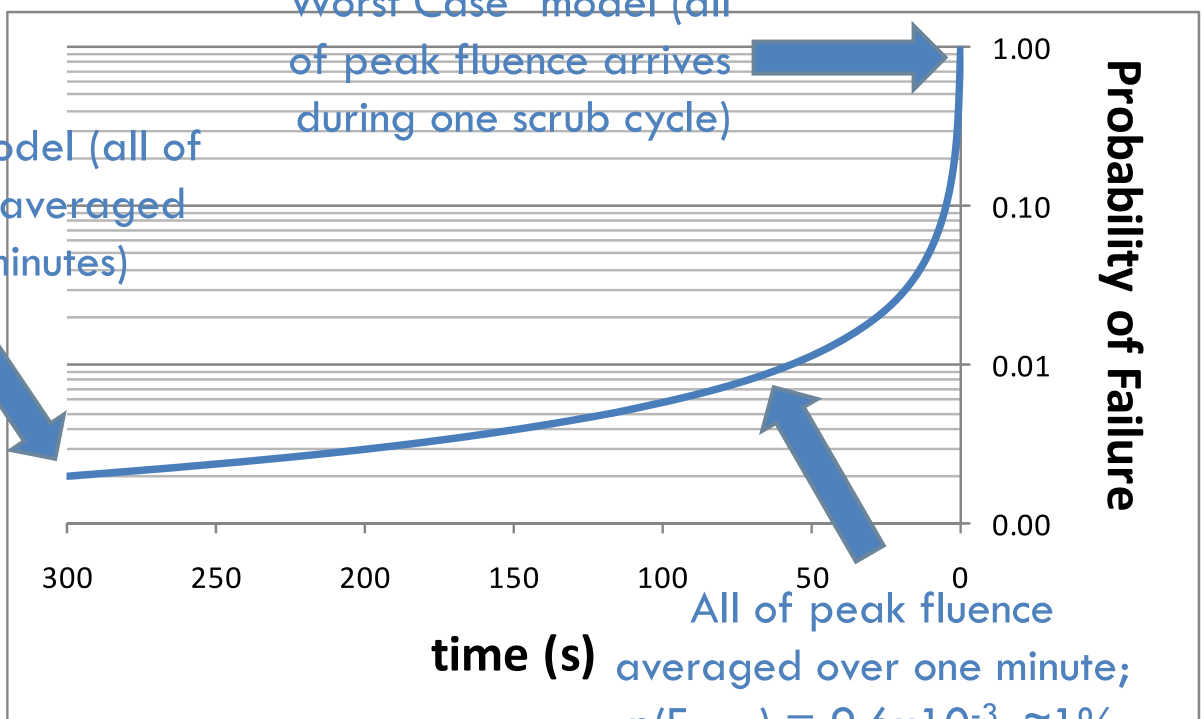
Estimating Probability of Failure :: P(F) Estimates

Design	Orbit	$P(F_{5\text{-min}})$		$P(F_{worst\text{-}day})$	$P(F_{worst\text{-}week})$
		Best Case	Worst Case		
SSRA	GEO	1.99×10^{-3}	.987	3.3×10^{-2}	1.8×10^{-2}



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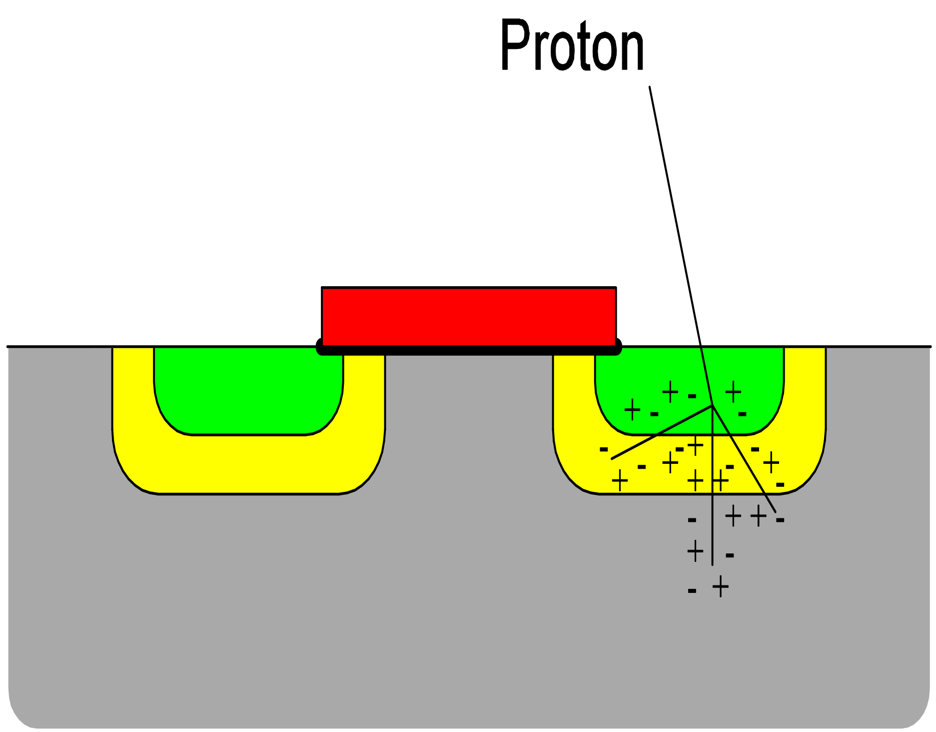
Conclusion

- Multiple independent upsets (MIUs) can defeat TMR and scrubbing
- SEP events can cause MIUs, particularly in strategic orbits with little or no protection provided by the Earth's magnetic field
- An example circuit's response to various sizes of MIUs was measured using fault injection and verified at a proton accelerator
- Probability of failure can be estimated using CREME96 SEU rates and MIU response data (fault injection or accelerator), however CREME96 SEU rate data are insufficient to make high fidelity estimates
  - We tried creating a model based on an extrapolation from the CREME96 worst week, worst day and peak 5 minutes, but $p(F_{5\text{-min}})$ was approximately the same as the "best case" model
  - Better models are needed
- Probability of failure estimates for an example circuit were presented
  - P(F) = 1.99E-3 in the best case
  - P(F) = .987 in the worst case

BACKUP SLIDES

Background :: Single Event Effects

- Single Event Upsets (SEU)
  - Change of state in memory structure



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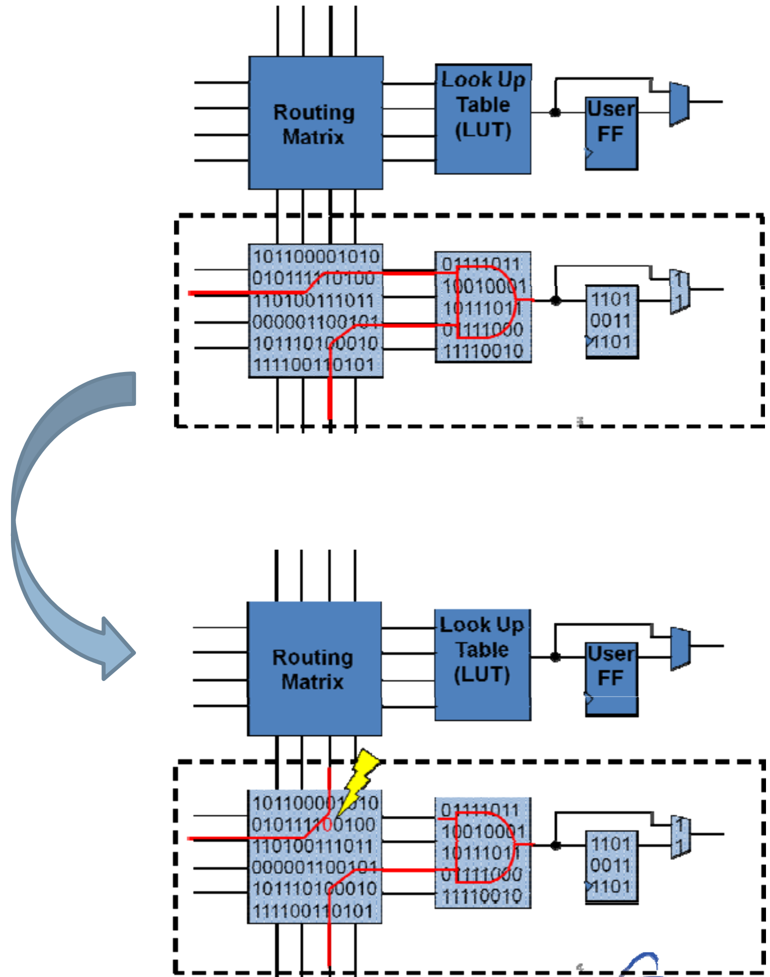
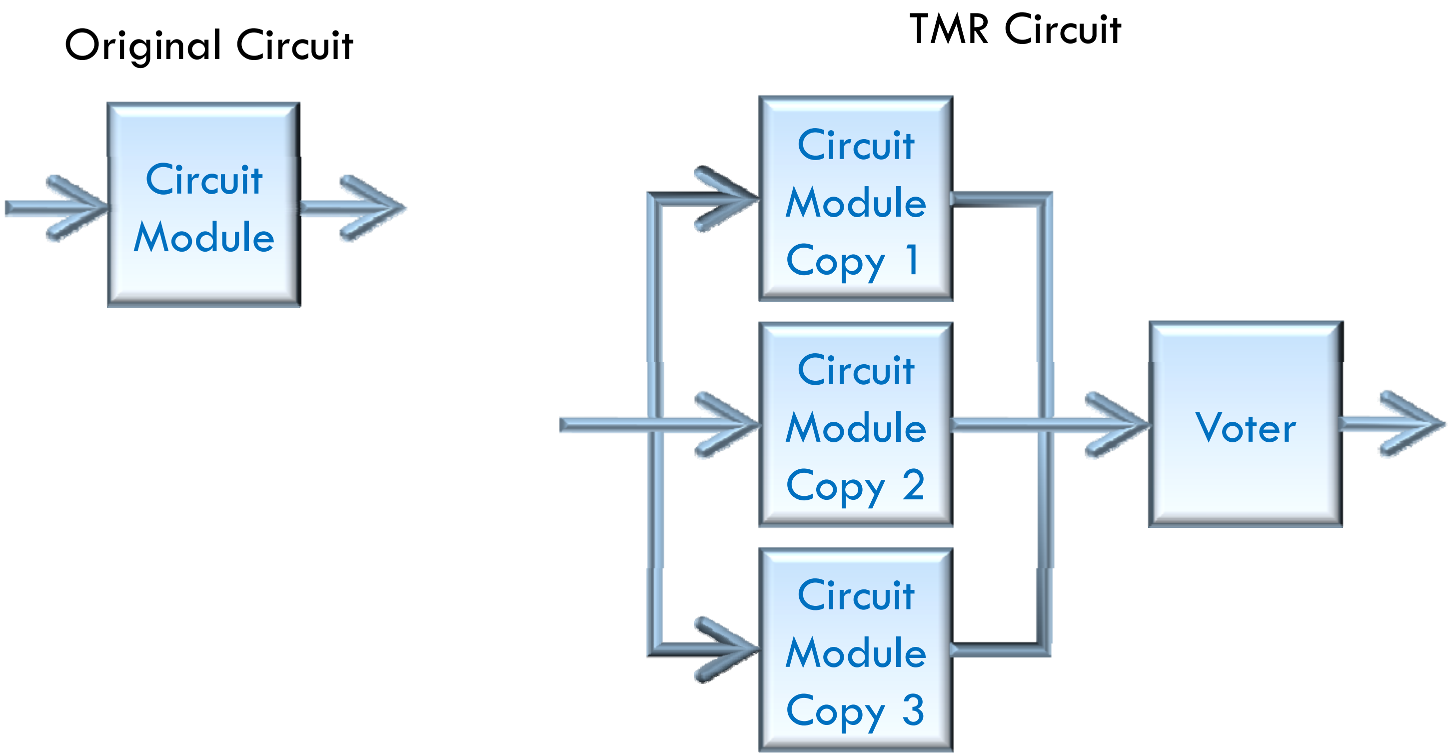


Background :: Mitigating FPGA Radiation Effects

- Triple Modular Redundancy



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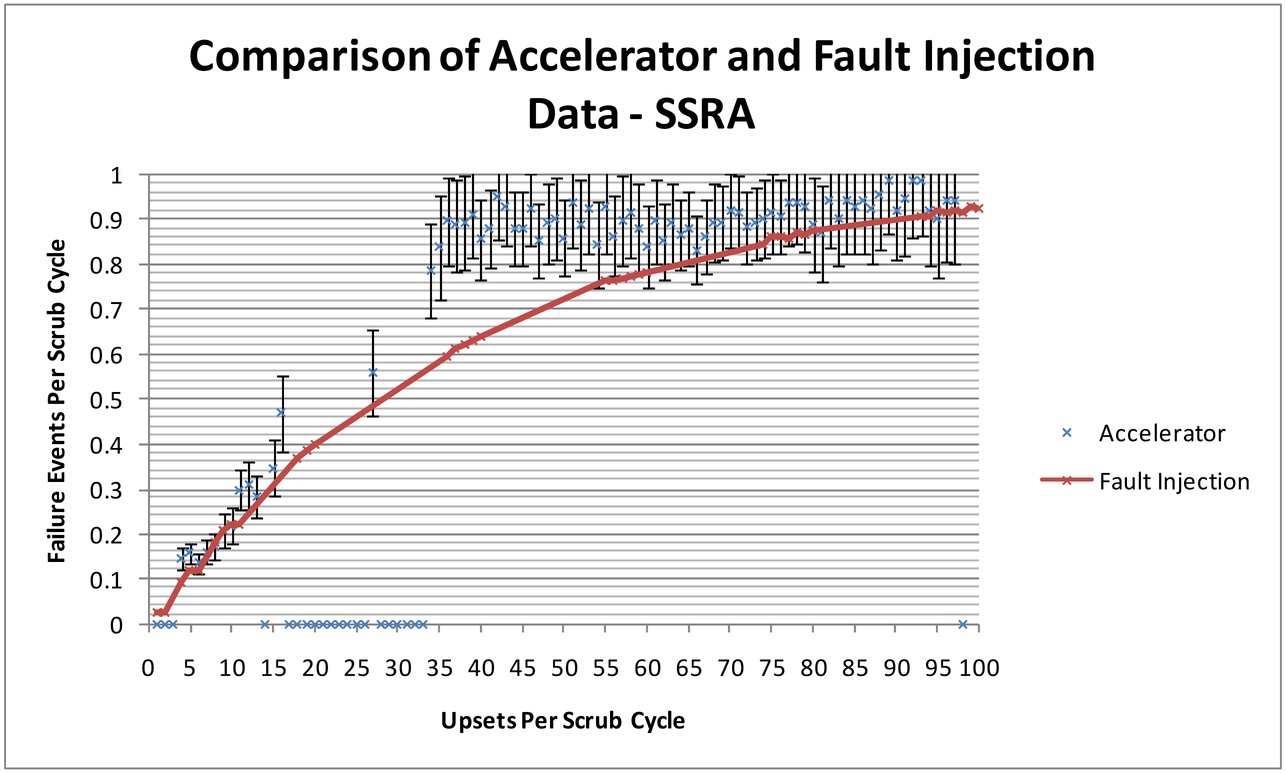

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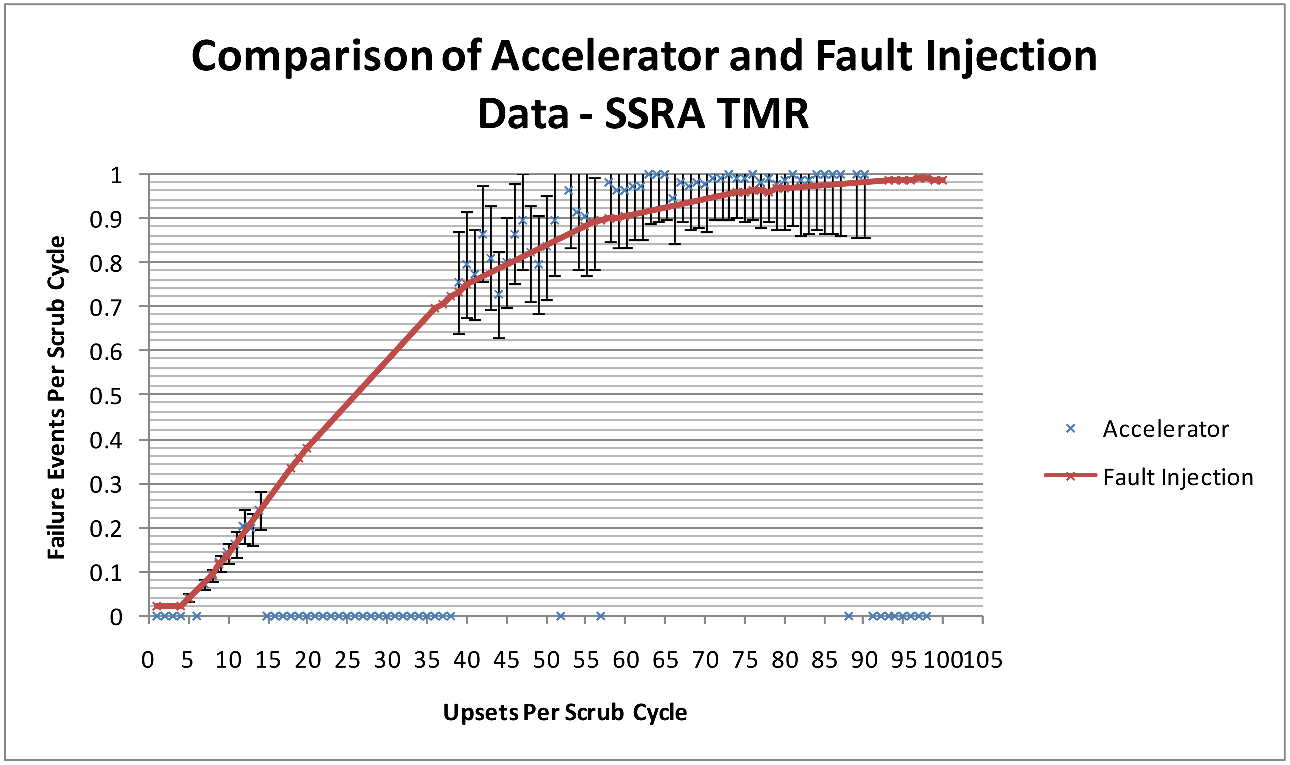

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SEU Rate Models :: Logarithmic Fit SEU Rate Model