MSU Project Update: 4/26/13

"Radiation Tolerant Computing"

NASA Marshall Space Flight Center
Huntsville, AL

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Associate Professor

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(Ph.D., exp May 2014)

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(Ph.D., exp May 2014)
Currently at Cyclotron…

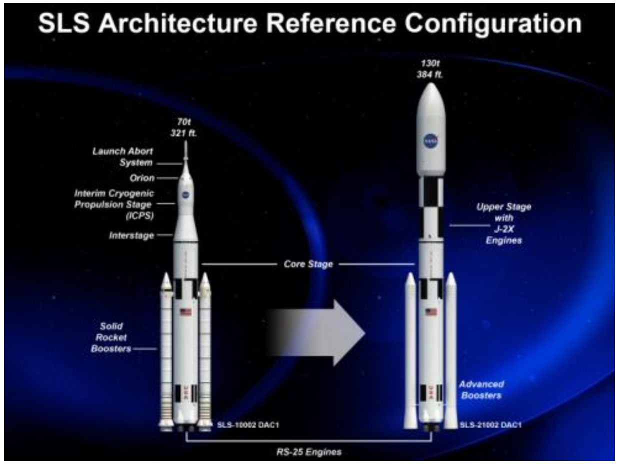
Electrical & Computer Engineering
Montana State University

Research Statement

Support the Computing Needs of Space Exploration & Science

- Computation (2,000 MIPs)
- Power Efficiency (200 MIPs/Watt)
- Mass ($100/lb by 2025)
- Reliability (99.99999% availability, instant recovery during critical operation)

Space Launch System (SLS)

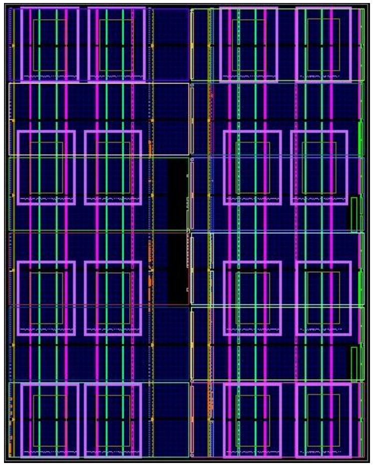


MSU's Approach

Use COTS FPGAs as the Computing Fabric

- Take advantage of process trends for computation and power efficiency

Support Reconfigurable Computing



- RC can increase computation through hardware optimization
- RC can decrease power through hardware efficiency
- RC can reduce mass through hardware reuse
- RC enables novel fault mitigation architectures

Radiation Tolerance Through Underlying Architecture

- Extend Triple Modular Redundancy (TMR) to include ***spares***
- Spatial Avoidance of faults to increase foreground availability
- Continually *scrub* configuration memory in background

Radiation "Awareness" through an External Sensor

- Provides potential fault awareness in unused regions (e.g., no TMR)
- Direct scrubber location to decrease correction latency

On Earth Our Computers are Protected

- Our magnetic field deflects the majority of the radiation
- Our atmosphere attenuates the radiation that gets through our magnetic field

Our Satellites Operate In Trapped Radiation in the Van Allen Belts

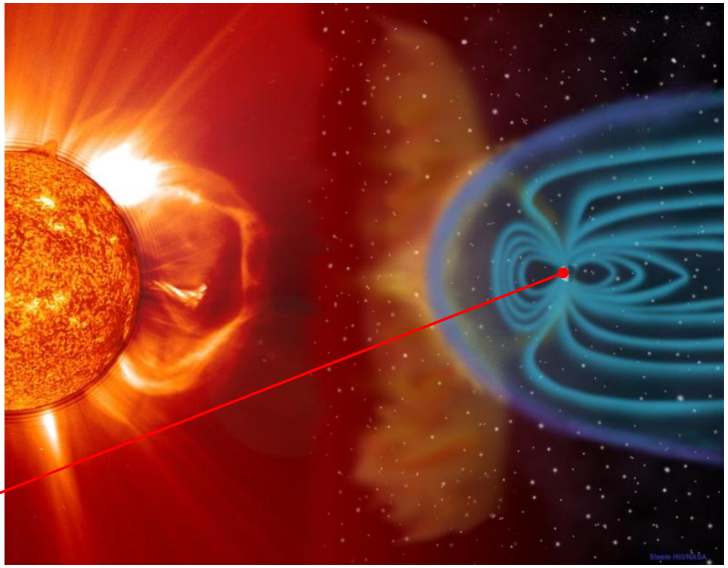
- High flux of trapped electrons and protons

In Deep Space, Nothing is Protected

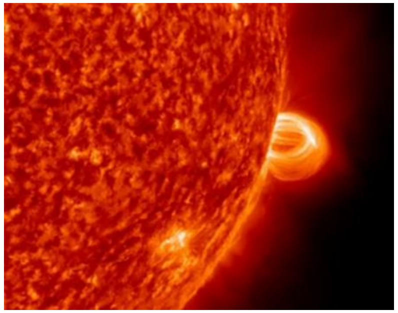
- Radiation from our sun
- Radiation from other stars
- Particles & electromagnetic

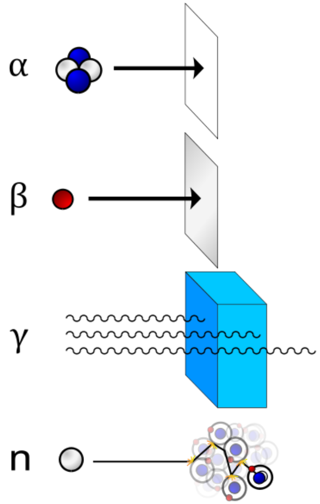
We Care About Ionizing Radiation

- Unwanted charge injection effects semiconductors
- High energy protons, Heavy Ions

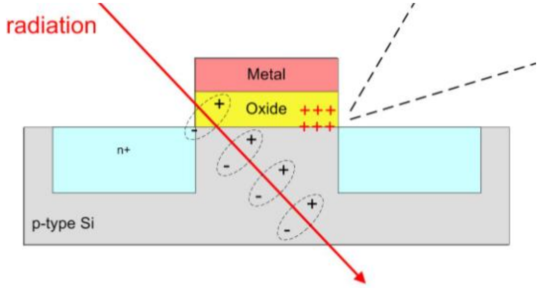


There are two broad categories of radiation effects:



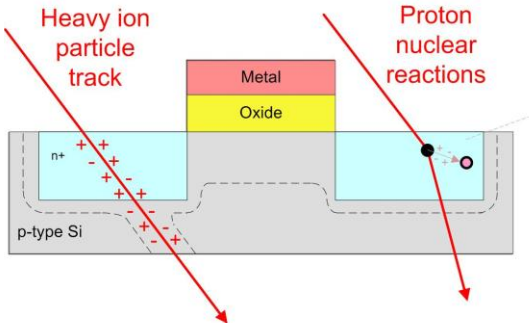


1) Total Ionizing Dose (TID)



- Long term, cumulative damage due to lower energy proton and electrons
- Charge trapping results in permanent damage to devices.

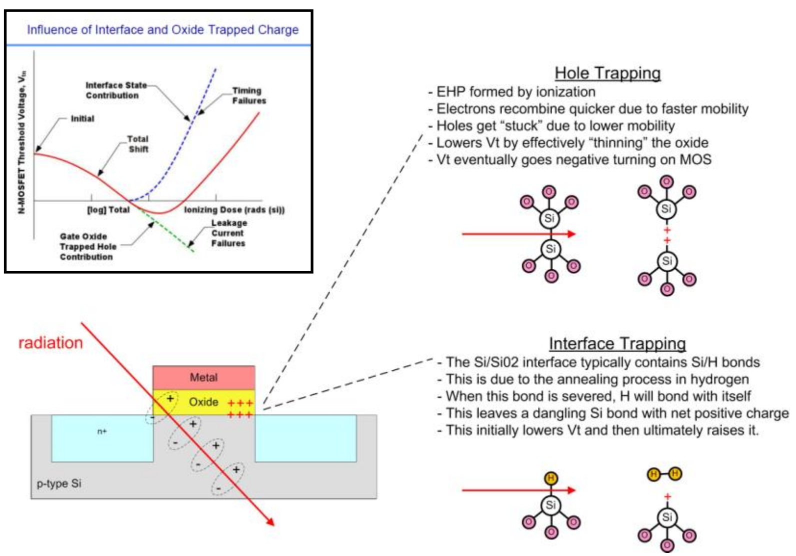
2) Single Event Effects (SEE)



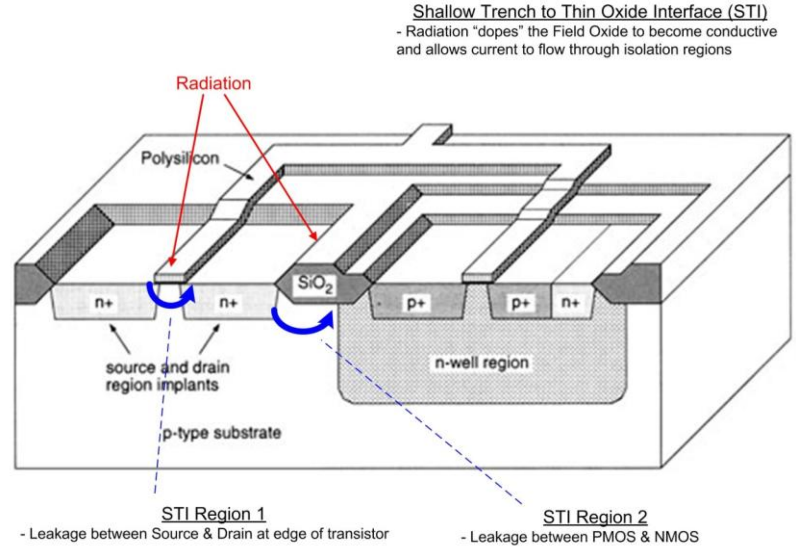
- By itself, does not cause permanent damage.
- Electron/hole pair creation leads to current transients that can change the state of a logic circuit.
- Permanent damage can result from secondary interactions (e.g., latch-up)

TID Failure Mechanisms

1. Oxide Breakdown
   - Threshold shifts,
   - Gate leakage,
   - Timing changes
   - Actually gets better in modern processes



2. Leakage Currents
   - Hole trapping slowly "dopes" field oxides to become conductive
   - Dominant failure mechanism for commercial processes

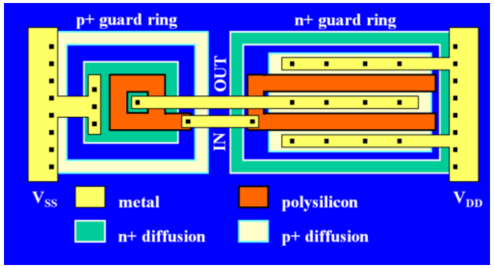


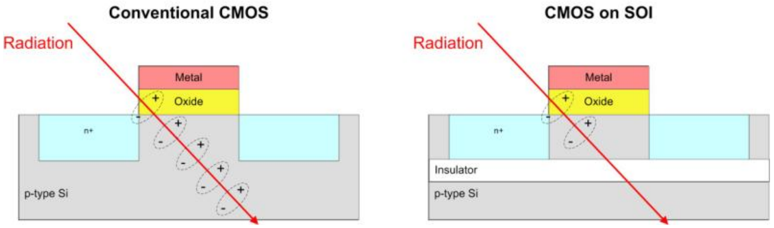
TID Mitigation Techniques

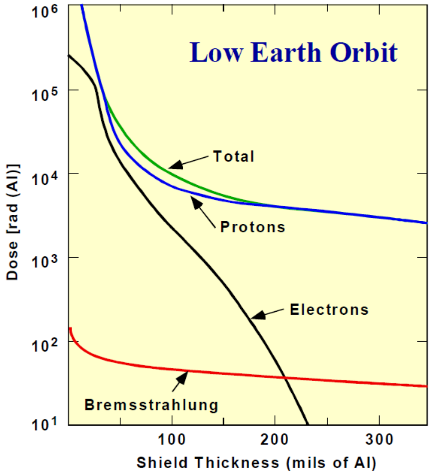
1. Radiation Hardened by Design (RHBD)
   - Special layout techniques in commercial process
   - Enclosed Transistors
   - Guard Rings

2. Radiation Hardened by Process (RHBP)
   - Special materials used (e.g., SOI)

3. Shielding
   - Effective for lower energy particles
   - Diminishing returns above 0.25” (Al)







Shield Thickness vs. Dose Rate (LEO)

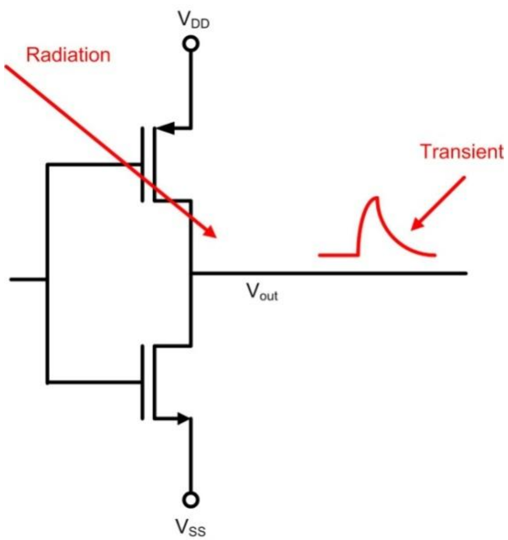
MSU Approach Does Not Target TID

- Although modern COTS parts are less susceptible to TID than older parts.
- Spatial avoidance technique “could” avoid permanently damaged regions of IC

SEE Fault Mechanisms

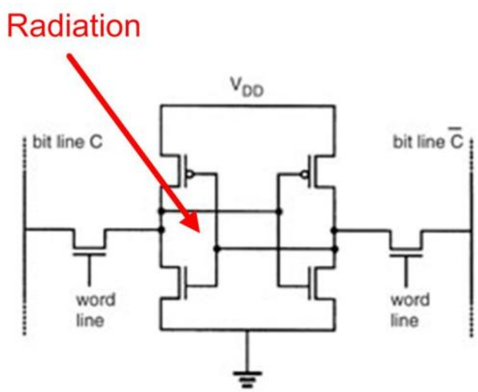
1. Single Event Transients (SET)

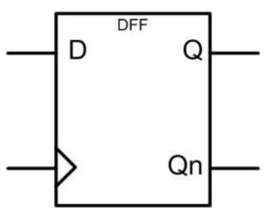
- A pulse that can flip a gate
- Glitches in combinational logic



2. Single Event Upset (SEU)

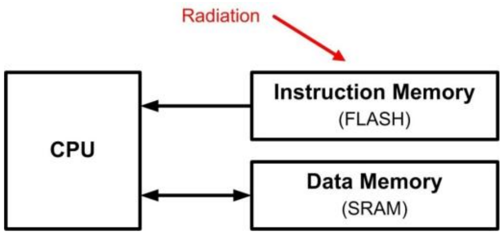
- The glitch is captured by a storage device resulting in a state change

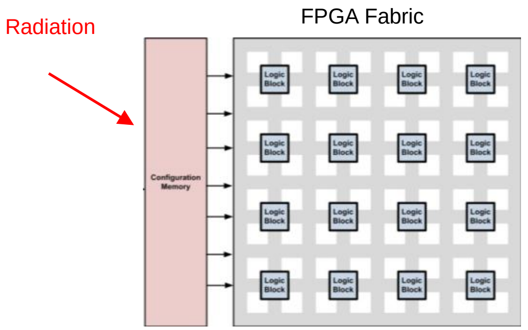




3. Single Event Functional IRQ (SEFI)

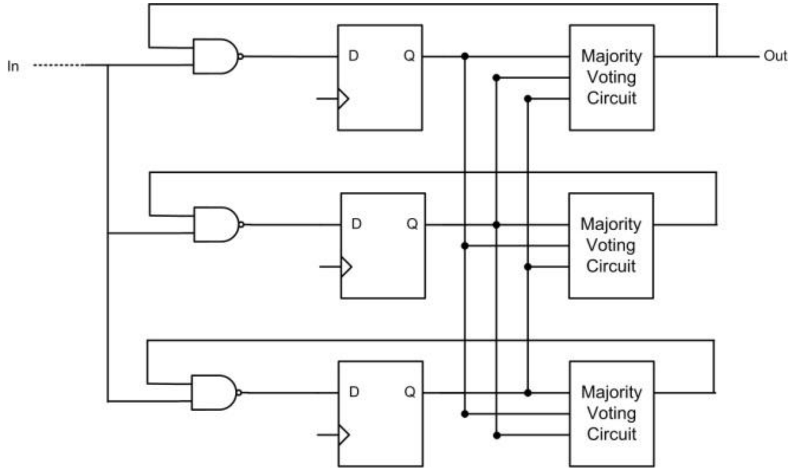
- The system is put into a state that causes function failure that cannot be resolved through normal operation.
- Requires reset, power cycling or reprogramming.



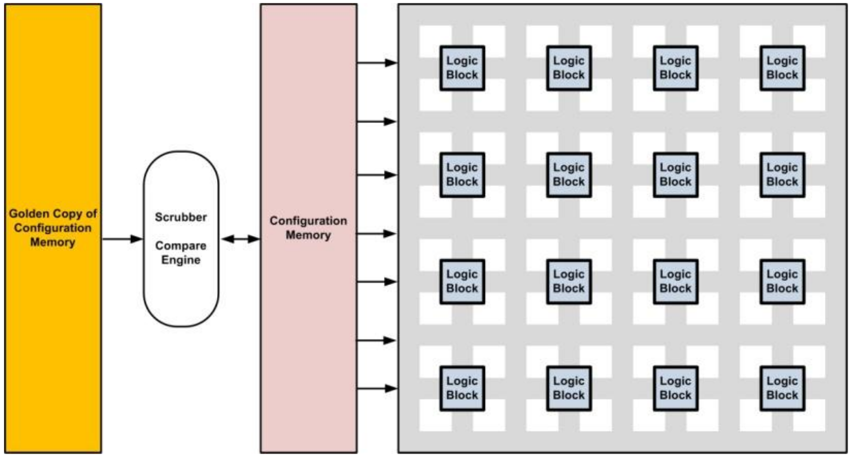


SEE Mitigation Techniques

1. Architecture: Triple Module Redundancy
   - Triplicate each circuit
   - Use a majority voter to produces output



2. Background Checking: Scrubbing
   - Compare contents of a memory device to a "Golden Copy"
   - Golden Copy is contained in a radiation immune technology
     (fuse-based memory, MROM, etc…)



Note: TMR+Scrubbing is the recommended mitigation approach for FPGA-based aerospace computers

MSU Approach

Our Approach

Use COTS FPGAs

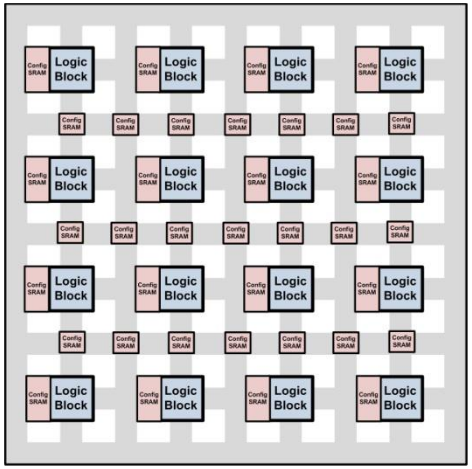
1. Increased Computation by Tracking Commercial Processes
2. Increased Power Efficiency by Tracking Commercial Processes
3. SRAM-based FPGAs support Reconfigurable Computing

However, FPGA's are Uniquely Susceptible

1. Single Event Effects
   - SETs/SEUs in the logic blocks
   - SETs in the routing
   - SEUs in the configuration memory for the logic blocks (SEFI)
   - SEUs in the configuration memory for the routing (SEFI)

A Comprehensive, Radiation Tolerant Architecture Is Needed…

Radiation Strikes
in the
Circuit Fabric
(Logic + Routing)



Radiation Strikes
in the
Configuration Memory
(Logic + Routing)

Our Approach

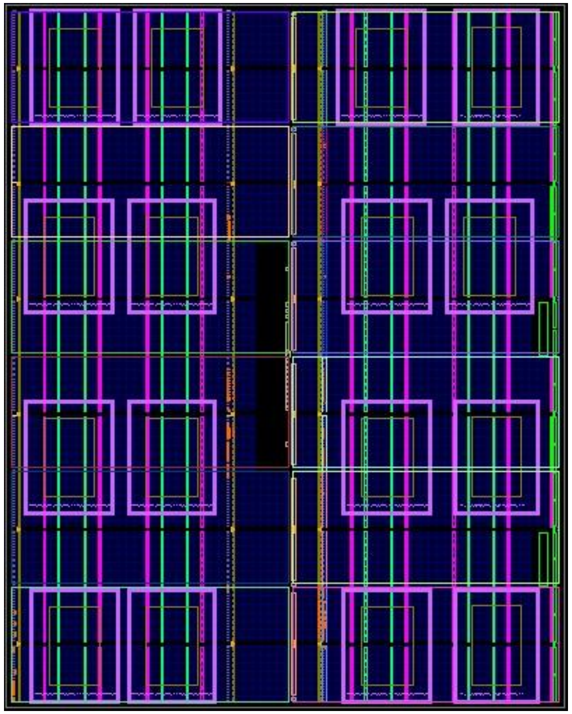
Fault Tolerance Through Abundant Spares

1. TMR + Spares
   - 3 Tiles run in TMR with the rest reserved as spares

2. Spatial Avoidance and Background Repair
   - If TMR detects a fault, the damaged tile is replaced with a spare and foreground operation continues
   - The tile is “repaired” in the background via PR

3. Scrubbing
   - Blind scrubbing continually runs through tiles (fast)
   - Readback scrubbing periodically runs through rest of fabric (slower)

4. External Radiation Sensor
   - An external spatial radiation sensor provides awareness of potential strike



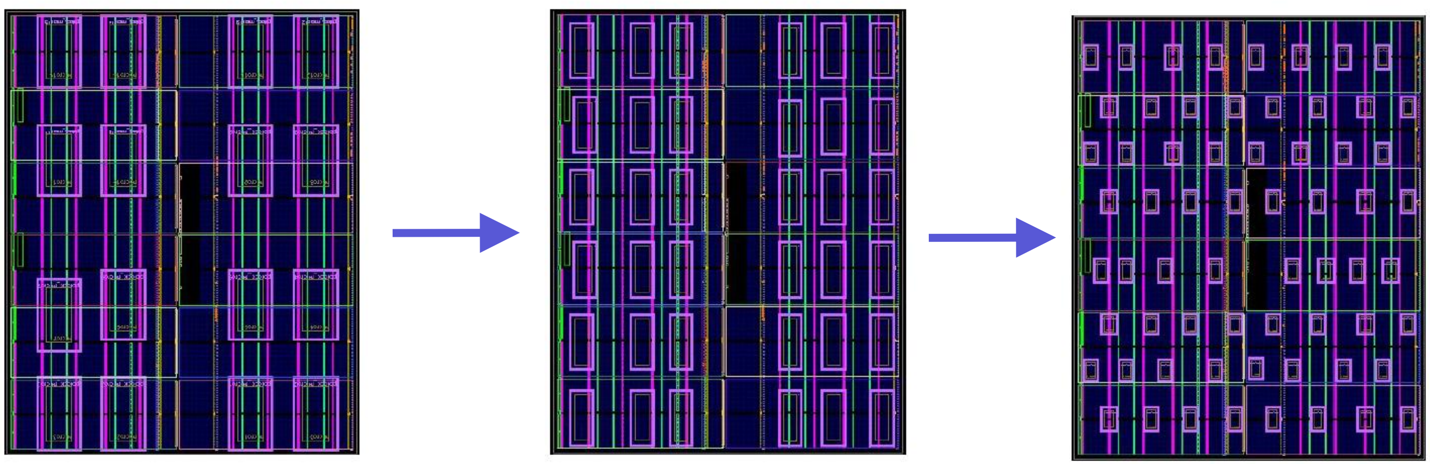
16 MicroBlaze Processors on Virtex-6

Precedent: Shuttle Flight Computer (TMR + Spare)

Why do it this way?

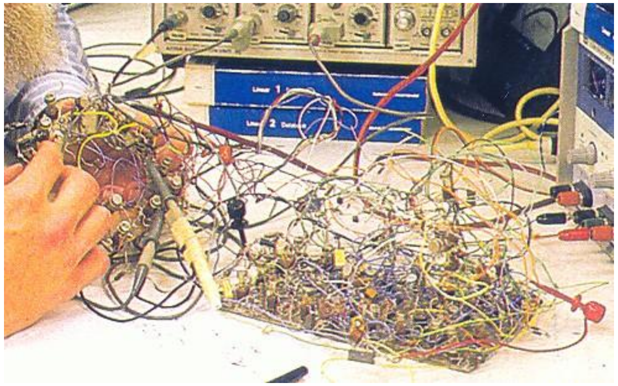
With Spares, it basically becomes a flow-problem:

- If the repair rate is faster than the incoming fault rate, you're safe.
- If the repair rate is slightly slower than the incoming fault rate, spares give you additional time.
- The additional time can accommodate varying flux rates.
- Abundant resources on an FPGA enable dynamic scaling of the number of spares. (e.g., build a bigger tub in real time)



Practical Reason’s for Doing It this Way

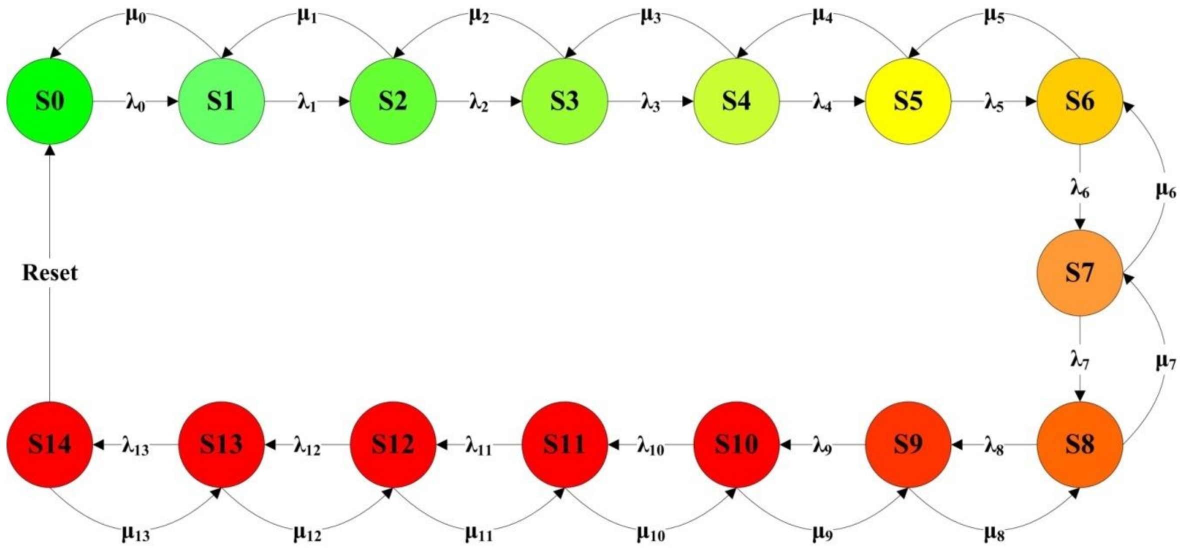
- Bringing up a spare tile is faster than PR (us vs. ms). This means foreground availability can be increased if repair (e.g., PR of damaged tile) is conducted in the background..
- Performing PR of the entire tile is much simpler than trying to track at a finer granularity (e.g., a specific CLB). Partial bit streams generated by the tool contain all the necessary information about a tile configuration.
- PR of a tile also takes care of both SEUs in the circuit fabric & configuration SRAM so the system doesn’t care which one occurred.
- The “spares” are held in reset to reduce power. This is as opposed to running in N-MR with every tile voting.
- The sensor is faster at detecting faults that aren’t detected by active circuitry (e.g., a spare not in TMR) and the scrubber can be intelligently directed.



Our Approach

Modeling: Is this an improvement to TMR+Srubbing?

- We use a Markov Model to predict *Mean-Time-Before-Failure*
  - *16 tile MicroBlaze system on Virtex-6 (3+13)*
  - λ is fault rate
  - *μ* is repair rate



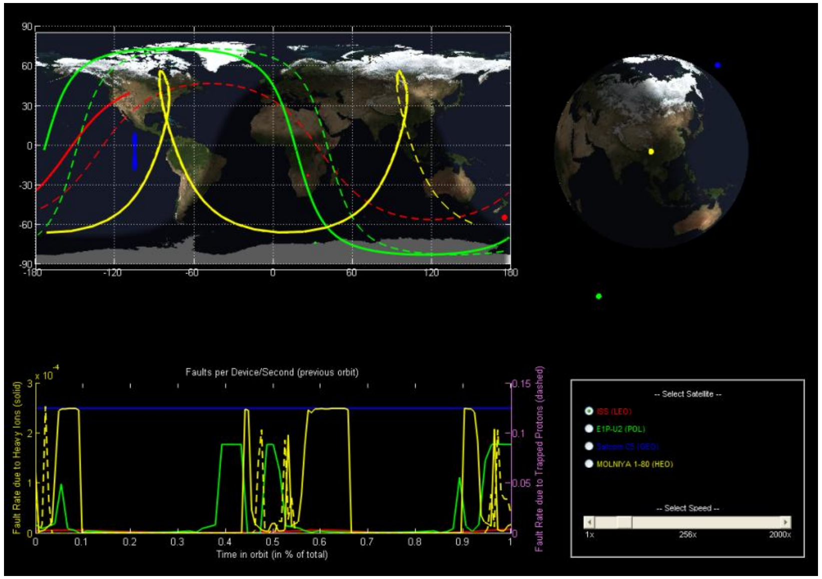
Modeling: Fault & Repair Rates

Fault Rate (λ)

- Derived from CREME96 tool for 4 different orbits
- Used LET fault data from V4

ORBITAL FAULT RATES FROM CREME96, IN FAULTS/DEVICE/SECOND

	Average	Worst Week	Peak 5 Minutes
ISS	0.0003479	3.544	72.96
HEO	0.08788	120.2	2398
E1P	0.003464	29.93	612.3
GEO	.0002494	149.8	3059



Repair Rate (μ)

- Measured empirically in lab on V6 system

MEASURED SCRUBBING RATES, IN SECONDS

Clock Rate	Blind	Readback, undamaged	Readback, damaged
25 MHz	2.97	5.31	6.35

Modeling Our Approach: Results

Baseline System (TMR+scrubbing)

MTBF FOR BASELINE TMR+SCRUBBING SYSTEM (IN SECONDS)

		Average	Worst Week	Peak 5 Min.
Blind	ISS	1.08E+08	3.19E+00	1.07E-01
	HEO	1.77E+03	6.43E-02	3.20E-03
	E1P	1.09E+06	2.69E-01	1.25E-02
	GEO	2.09E+08	5.14E-02	2.50E-03
RB	ISS	6.00E+07	2.73E+00	1.06E-01
	HEO	1.03E+03	6.39E-02	3.20E-03
	E1P	6.07E+05	2.63E-01	1.25E-02
	GEO	1.17E+08	5.12E-02	2.50E-03

Our System (TMR+scrubbing+spares)

MTBF FOR TMR+SCRUBBING+SPARES SYSTEM (IN SECONDS)

		Average	Worst Week	Peak 5 Min.
Blind	ISS	3.57E+43	7.83E+01	1.25E+00
	HEO	3.75E+11	7.41E-01	3.59E-02
	E1P	4.46E+29	3.30E+00	1.41E-01
	GEO	3.74E+45	5.90E-01	2.81E-02
RB	ISS	8.26E+41	5.49E+01	1.23E+00
	HEO	2.10E+10	7.33E-01	3.59E-02
	E1P	1.08E+28	3.16E+00	1.41E-01
	GEO	8.63E+43	5.85E-01	2.81E-02

Improvement

INCREASE IN MTBF AFTER ADDITION OF SPARES (%)

		Average	Worst Week	Peak 5 Min.
Blind	ISS	3.31E+35%	2356.07%	1067.45%
	HEO	2.12E+08%	1051.79%	1021.88%
	E1P	4.10E+23%	1127.98%	1031.20%
	GEO	1.78E+37%	1047.86%	1024.00%
RB	ISS	1.38E+34%	1912.98%	1058.51%
	HEO	2.05E+07%	1046.32%	1021.88%
	E1P	1.78E+22%	1103.77%	1028.80%
	GEO	7.40E+35%	1042.38%	1024.00%

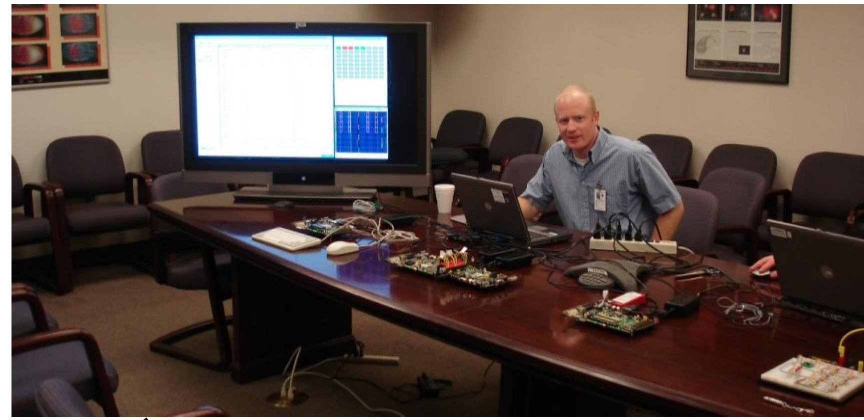
Ok, it looks promising…

Our Approach (2007-2010)

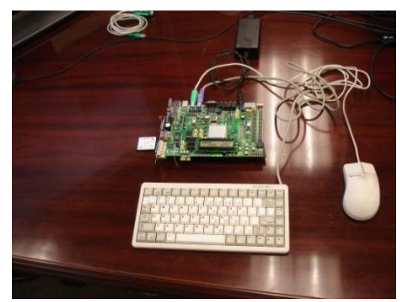
Let's Build and Test…

- Initial computer architecture tested on Xilinx Virtex-5 evaluation board (2007-2010).
- Initial sensor was fabricated as a 1-sided fabrication sequence, implemented on a breadboard.
- Funded through a variety of senior design projects from NASA and research start-up funds from Montana Space Grant.
- Bench top testing

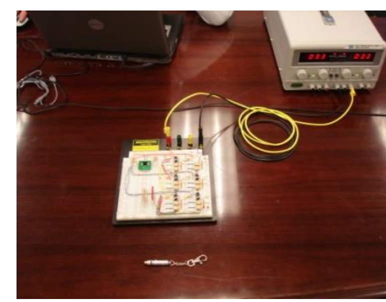
Clint Gauer (MSEE, 20010) giving demo at MSFC in 2010



"3+61 pBlaze Many Core"



"3+13 pBlaze Many Core w PR"



"Spatial Radiation Sensor"

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Let's Build and Test…

Clint Gauer (MSU) giving Andrew Keys (NASA) Dynamic Recovery IO System Demonstration

Brock LaMeres (MSU) giving Mike Watson (NASA) the Spatial Radiation Sensor Demo

Our Approach (2011)

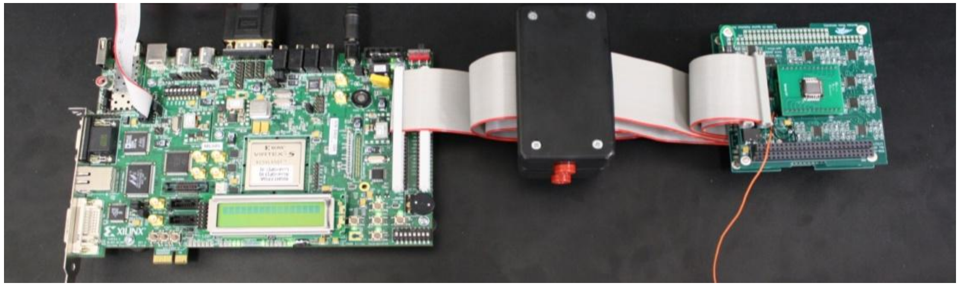
Build and Test Cont…

- Funding from NASA EPSCoR allows increasing TRL.

  EPSCoR Project Objectives
  - Increase many-tile system to TRL-5
  - Fabricate spatial radiation sensor
  - Integrated Sensor with many-tile system
  - Test full system in cyclotron

- Functional testing still on bench top.

Todd Buerkle (MSEE, 2011) and Jenny Hane (MSEE, 2011) giving demonstrations at MSFC (2011)



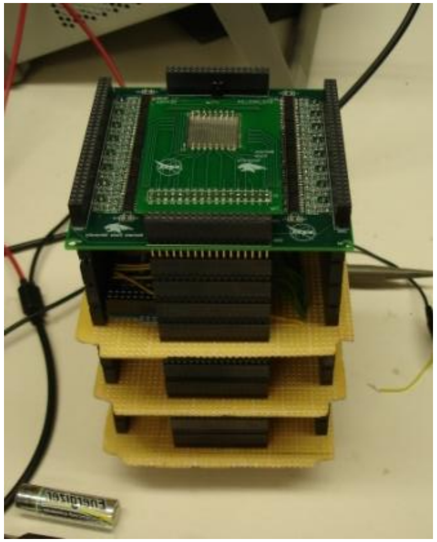
"Many-Tile Integrated with Custom Sensor"

Our Approach (2011)

Build and Test Cont…

- Funding from NASA Education Office allows local balloon flights of system.
- Tests allow more sophisticated payload form-factor to be pursued.

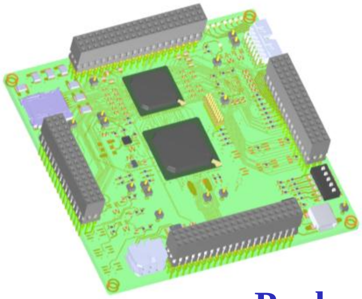
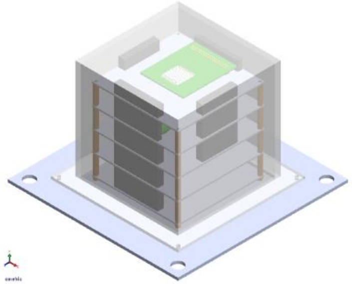
Balloon Flight in Montana, summer of 2011.



Our Approach (2012)

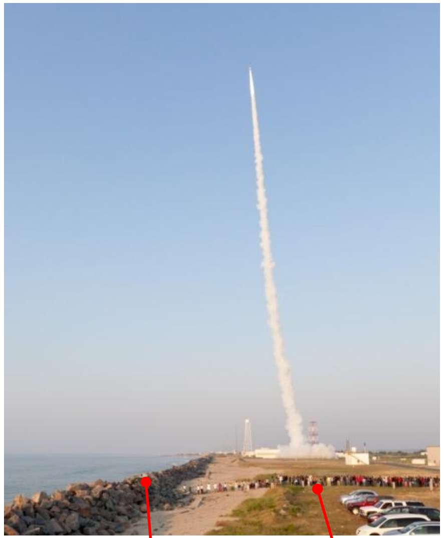
Build and Test Cont…

- Cyclotron testing of sensor commences.
- Accepted into & completed NASA/LSU HASP Balloon program (130,000 ft for 10 hours)
- Grad students sent to “Rock-On” program to learn how to develop sounding rocket payloads.
- Final Payload Form Factor Pursued (e.g., cube-sat.

Payload Form Factor

Rock-On Workshop, June 2012



HASP Flight, Sept 2012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Build and Test Cont…

- Funded by OCT-Game Changing Technology Program for sub-orbital flight demonstration (2013-2014…)

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WEDNESDAY, JULY 25, 2012

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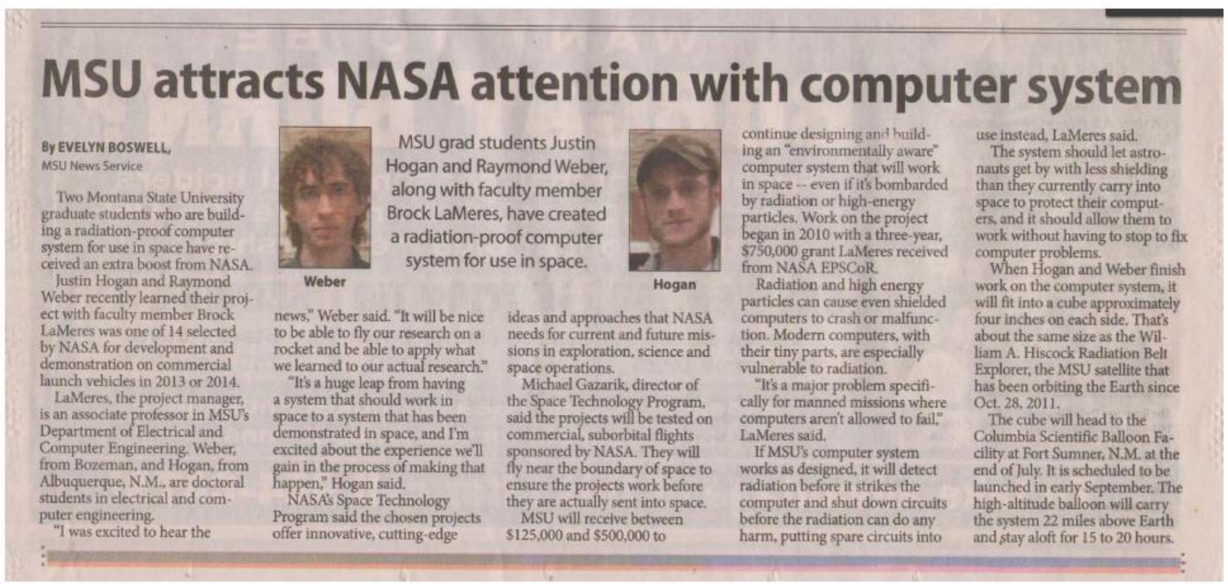
Police reports, obituaries PAGE A7



MSU attracts NASA attention with computer system

By EVELYN BOSWELL,
MSU News Service

MSU grad students Justin Hogan and Raymond Weber, along with faculty member Brock LaMeres, have created a radiation-proof computer system for use in space.

Weber

Hogan

Two Montana State University graduate students who are building a radiation-proof computer system for use in space have received an extra boost from NASA.

Justin Hogan and Raymond Weber recently learned their project with faculty member Brock LaMeres was one of 14 selected by NASA for development and demonstration on commercial launch vehicles in 2013 or 2014.

LaMeres, the project manager, is an associate professor in MSU's Department of Electrical and Computer Engineering. Weber, from Bozeman, and Hogan, from Albuquerque, N.M., are doctoral students in electrical and computer engineering.

"I was excited to hear the news," Weber said. "It will be nice to be able to fly our research on a rocket and be able to apply what we learned to our actual research."

"It's a huge leap from having a system that should work in space to a system that has been demonstrated in space, and I'm excited about the experience we'll gain in the process of making that happen," Hogan said.

NASA's Space Technology Program said the chosen projects offer innovative, cutting-edge ideas and approaches that NASA needs for current and future missions in exploration, science and space operations.

Michael Gazarik, director of the Space Technology Program, said the projects will be tested on commercial, suborbital flights sponsored by NASA. They will fly near the boundary of space to ensure the projects work before they are actually sent into space.

MSU will receive between $125,000 and $500,000 to continue designing and building an "environmentally aware" computer system that will work in space -- even if it's bombarded by radiation or high-energy particles. Work on the project began in 2010 with a three-year, $750,000 grant LaMeres received from NASA EPSCoR.

Radiation and high energy particles can cause even shielded computers to crash or malfunction. Modern computers, with their tiny parts, are especially vulnerable to radiation.

"It's a major problem specifically for manned missions where computers aren't allowed to fail," LaMeres said.

If MSU's computer system works as designed, it will detect radiation before it strikes the computer and shut down circuits before the radiation can do any harm, putting spare circuits into use instead, LaMeres said.

The system should let astronauts get by with less shielding than they currently carry into space to protect their computers, and it should allow them to work without having to stop to fix computer problems.

When Hogan and Weber finish work on the computer system, it will fit into a cube approximately four inches on each side. That's about the same size as the William A. Hiscock Radiation Belt Explorer, the MSU satellite that has been orbiting the Earth since Oct. 28, 2011.

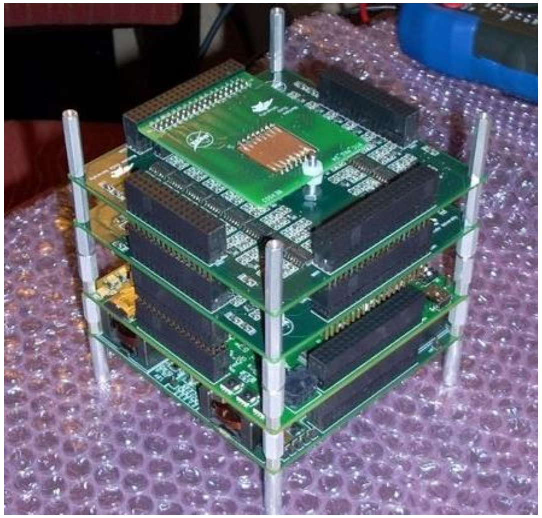
The cube will head to the Columbia Scientific Balloon Facility at Fort Sumner, N.M. at the end of July. It is scheduled to be launched in early September. The high-altitude balloon will carry the system 22 miles above Earth and stay aloft for 15 to 20 hours.

2012 News Article, Bozeman Chronicle

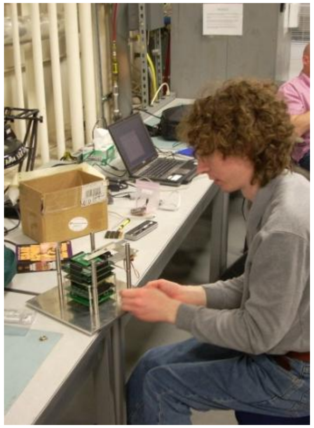
Build and Test Cont…

- Full Cube Fabrication Complete
  - Virtex-6, 9 processor many-tile system.
  - Relocation & Repair
  - Background scrubbing (blind & readback)
  - Support for 2 stacked sensors
  - Powered by single voltage (battery or provided) Many-Tile
- Full System Test at Cyclotron

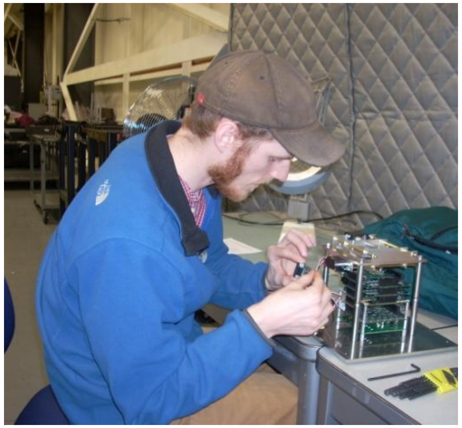
Full Custom Computer System Completed



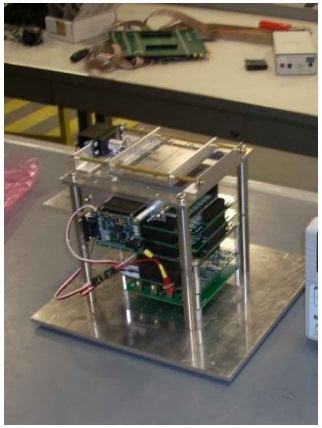
Texas A&M Cyclotron Testing



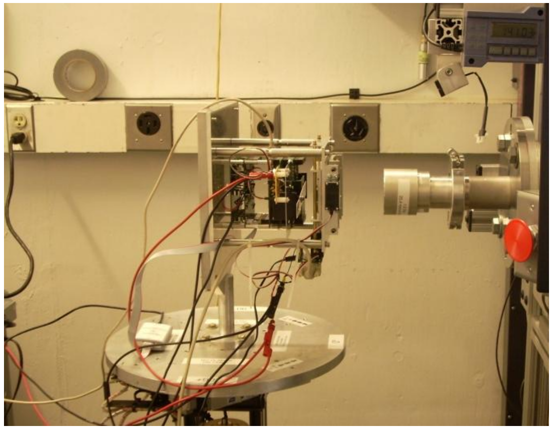
Ray Weber Assembling Stack



Justin Hogan Assembling Translation Stage



Stack Ready For Beam



MSU Stack in Beam

Upcoming Testing….

- Local Balloon Flights summer of 2013
- Will Fly on HASP again in September 2013
- Sounding Rocket Flight Late 2013 or early 2014

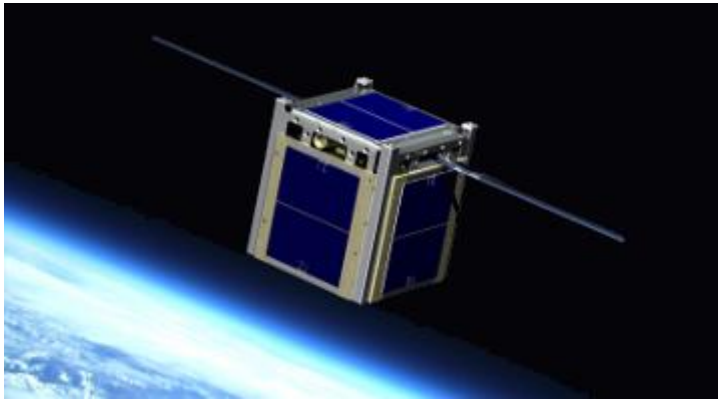
Our Approach (2014+)

What Research Has Been Uncovered?

- Faults in Routing – On-chip network could help
- Multiple Bit Upsets – Solutions for Single-Point of Failure
- New Applications of the Sensor
  - Thin, pixilated sensors to identify location AND species
  - Flexible sensing fabric for more accurate detection of ionizing radiation.
  - Dual sensor + solar cell technology

Where we want to go….

- More test data, more flights, cube-sat…



Demo