RadSat
Radiation Tolerant SmallSat Computer System
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Objective of the RadSat Mission

Demonstrate a Novel Computer Technology in a Space Environment

- The computer is implemented on a commercial off-the-shelf (COTS) FPGA.
- The computer delivers radiation tolerance through a reconfigurable/redundant architecture.
- The computer delivers low cost using COTS parts.
- The computer delivers higher performance (computation & power efficiency) by exploiting modern process nodes (28nm).
**Computation**

- SmallSats are doing more and more on-board data processing (e.g., images, sensor data, communications).

**Radiation Tolerance**

- Cutting edge process nodes (28nm) provide increased computation but are becoming more susceptible to radiation induced faults (SEEs).
- As SmallSat missions achieve longer duration and move into deep space, radiation becomes more and more of a concern (both TID & SEE).

**Cost**

- Any SmallSat computing solution must be cost effective to align with SmallSat theme.

  (i.e., “launch more, inexpensive, satellites”)
What are the Radiation Effects?

1. Total Ionizing Dose (TID)
   - Cumulative long term damage due to ionization.
   - Primarily due to low energy protons and electrons due to higher, more constant flux, particularly when trapped.
   - Oxide Breakdown cases
     - Threshold Shifts
     - Leakage Current
     - Timing Changes
What are the Radiation Effects?

2. Single Event Effects (SEE)

- Electron/hole pairs created by a single particle passing through semiconductor.
- Primarily due to heavy ions and high energy protons.
- Excess charge carriers cause current pulses.
- Creates a variety of destructive and non-destructive damage.

“Critical Charge” = the amount of charge deposited to change the state of a gate
What are the Radiation Effects?

2. Single Event Effects (SEE) Cont…

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.

All of these effects occur in FPGAs
Shielding?

- It helps, but not has much as you might think…

- For higher energy particles, the secondary effects can make the problem worse.
How We Currently Deal with Radiation

Dealing with Total Ionizing Dose

- Radiation Hardened by Design (RHBD)
- Radiation Hardened by Process (RHBP)
Dealing with Total Ionizing Dose

- Radiation Hardened by Design (RHBD)

- Radiation Hardened by Process (RHBP)

or

Nothing...

- If the mission is short enough, TID may not be a concern.
How We Currently Deal with Radiation

Total Ionizing Dose – The Issue with Existing Techniques

- The unique processing techniques lowers the volume, which increases cost.
- The unique processing techniques reduces the performance.

- Rad-Hardened Processors lag in performance to their commercial counterparts by ~10 years.
Dealing with Single Event Effects

- **Architecture: Triple Module Redundancy**
  - Triplicate each circuit
  - Use a majority voter to produce output

- **Background Memory 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
Dealing with Single Event Effects

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The issue? It takes resources and care must be taken to get the intended results.
The Current State of Radiation

Radiation vs. Process Node

• Larger Transistors
  o TID is primary concern
  o SEE isn’t as bad
  o Slow & Power Hungry

Xilinx FPGA
Virtex-4
Virtex-5
Virtex-7

• Small Transistors
  o SEE is primary concern
  o TID isn’t as bad
  o Fast & Power Efficient

TID
~300 krad
~500 krad
>500 krad_{est}

(Allen, 2014)
The Current State of Radiation

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<td>~300 krad</td>
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<tr>
<td>Virtex-5</td>
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<tr>
<td>Virtex-7</td>
<td>&gt;500 krad&lt;sub&gt;est&lt;/sub&gt;</td>
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</tbody>
</table>

- What does this mean?
  - If we use the most recent process node, we get TID tolerance inherently PLUS low cost, high performance, & power efficiency.
  - Except we need to do something about SEE…

(Allen, 2014)
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 **partial reconfiguration (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

Precedent: Shuttle Flight Computer (TMR + Spare)

16 MicroBlaze Processors on Virtex-6
Why do it this way?

With **Spares**, it basically becomes a flow-problem:
- Partial Reconfiguration is faster than Full Reconfiguration.
- Brining on a spare is faster than Partial Reconfiguration.
- 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)
Our Approach

Modeling: Is this an improvement to TMR+Scrubbing?

- We use a Markov Model to predict Mean-Time-Before-Failure.
- We want to see if it improves MTBF over non-redundant & TMR+scrubbing.
- The fault rate was extracted from CREME96 for 4 different orbits for Virtex-6 FPGA.
- The repair rate was found empirically.

Ok, it looks promising…
Ok, Let’s build it and test it…

Technology Readiness Level (TRL)

- TRL 1 – an idea
- TRL 9 – mission proven
Technical Readiness Level (TRL-1)

Step 1 – Build a Prototype to See if it is Possible

- The Montana Space Grant Consortium funds an investigation into conducting radiation tolerant computing research at MSU. The goal is to understand the problem, propose a solution, and build relationships with scientists at NASA.

Timeline of Activity at MSU

Clint Gauer (MSEE from MSU 2009) demo's computer to MSFC Chief of Technology Andrew Keys

Proof of Concept

(2008-2010)
Technical Readiness Level (TRL-3)

Step 2 – Test in a Cyclotron

- NASA EPSCoR funds the development of a more functional prototype and testing under bombardment by radiation at the Texas A&M Radiation Effects Facility.

Timeline of Activity at MSU

- **Proof of Concept**
  - (2008-2010)

- **Prototype Development & Cyclotron Testing**
  - (2010-2012)

Ray Weber (Ph.D., EE from MSU, 2014) prepares experiment.
Step 3 – Demonstrate as Flight Hardware on High Altitude Balloons

- **NASA Education Office** funds the development of the computer into flight hardware for demonstration on high altitude balloon systems, both in Montana and at NASA.

**MSU students get NASA experience sending experiments to the edge of space**

July 21, 2011 -- Melynda Harrison, MSU News Service

Two groups of students, staff and faculty from Montana State University and the Montana Space Grant Consortium gathered on a plateau overlooking the Yellowstone River east of Livingston on Thursday morning. Some checked the rigging on what looked to be cardboard and styrofoam boxes—their modest exteriors belying the high tech equipment inside. Other team members filled a giant latex balloon with helium.

The two groups were working on launching their experiments into near space, 100,000 feet above the Livingston airport runway where the groups met. The hands-on summer projects are giving Montana students an opportunity to engage in real world science and build their resumes.

Members of the Balloon Outreach, Research, Exploration and Observation (BOREALIS) Project, part of the MSU, sent temperature and pressure sensors, still and video cameras, and a “command center” used to control the release of a parachute and send GPS coordinates, into the sky. Under the direction of Berk Knighton, BOREALIS flight director, the nine undergraduate interns, three from Tribal Colleges, and one high school student from across Montana, spent 10 weeks designing and building experiments for several balloon flights.

**Timeline of Activity at MSU**

- **Proving of Concept**
  - (2008-2010)

- **Prototype Development & Cyclotron Testing**
  - (2010-2012)

- **High Altitude Balloon Demos**
  - (2011-2013)

Justin Hogan (Ph.D., EE from MSU, 2014) prepares payload.
Technical Readiness Level (TRL-6)

Step 4 – Demonstrate as Flight Hardware on a Sounding Rocket

- **NASA OCT & FOP** fund the demonstration of the computer system on sounding rocket.

**Timeline of Activity at MSU**

- **Proof of Concept** (2008-2010)
- **Prototype Development & Cyclotron Testing** (2010-2012)
- **High Altitude Balloon Demos** (2011-2013)
- **Sounding Rocket Demo** (2012-2016)
Technical Readiness Level (TRL-7)

Step 5 – Demonstrate on the International Space Station

- NASA EPSCoR funds the demonstration of computer system on ISS

Timeline of Activity at MSU

<table>
<thead>
<tr>
<th>Year</th>
<th>Activity</th>
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<tbody>
<tr>
<td>2008</td>
<td>Proof of Concept</td>
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<td>2009</td>
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<td>2013</td>
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<tr>
<td>2014-15</td>
<td>ISS Demo</td>
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Besides being tested on the International Space Station, MSU's radiation-tolerant computer may eventually orbit the Earth as a stand-alone satellite.
Step 6 – Demonstrate as a Stand-Alone Satellite

- **NASA SmallSat Technology Partnership Program (SSTP)** funds the development of a stand-alone satellite for LEO mission.
- This work is being conducted through a partnership between MSU & GSFC.
Where We Are Today

1. Engineering Unit Will be Complete by September-15

2. Selected #2 by 2015 CubeSat Launch Initiative

Remaining Work

- Build & Qualify Flight Units
- Deliver to Pad