Exploration Technology Development Program’s

Radiation Hardened Electronics for Space Environments (RHESE)

Project Overview

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The U.S. Space Exploration Policy directs NASA to pursue a long-term human and robotic program to explore the solar system.

The policy is based on the following goals:

- Return the shuttle to flight (following the Columbia accident) and complete the International Space Station by 2010.
- Return to the Moon as early as 2015 and no later than 2020.
  - Gain experience and knowledge for human missions to Mars.
- Explore Mars and other destinations with robotic and crewed missions
  - Increase the use of robotic exploration to maximize our understanding of the solar system.
- Gain experience and knowledge for human missions to Mars.
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Surviving the Radiation Environment

- **Space Radiation affects all spacecraft.**
  - Spacecraft electronics have a long history of power resets, safing, and system failures due to:
    - Long duration exposures,
    - Unpredictable solar proton activity,
    - Ambient galactic cosmic ray environment.
• **Multiple approaches may be employed (independently or in combination) to protect electronic systems in the radiation environment:**
  
  – Shielding,
  
  – Mission Design (radiation avoidance),
  
  – Radiation Hardening by Architecture,
    
    • Commercial parts in redundant and duplicative configurations (Triple Module Redundancy)
      
      – Determine faults by voting schemes
      
      – Increases overhead in voting logic, power consumption, flight mass
    
    • Multiple levels of redundancy implemented for rad-damage risk mitigation:
      
      – Component level
      
      – Board level
      
      – Subsystem level
      
      – Spacecraft level
  
  – Radiation Hardening by Design,
    
    • TMR strategies within the chip layout,
    
    • designing dopant wells and isolation trenches into the chip layout,
    
    • implementing error detecting and correction circuits, and
    
    • device spacing and decoupling.
  
  – Radiation Hardening by Process,
    
    • Employ specific materials and non-conventional processing techniques
    
    • Usually performed on dedicated rad-hard foundry fabrication lines.
The specific goals of the RHESE project are to foster technology development efforts in radiation-hardened electronics possessing these associated capabilities:

- improved total ionization dose (TID) tolerance,
- reduced single event upset rates,
- increased threshold for single event latch-up,
- increased sustained processor performance,
- increased processor efficiency,
- increased speed of dynamic reconfigurability,
- reduced operating temperature range’s lower bound,
- increased the available levels of redundancy and reconfigurability, and
- increased the reliability and accuracy of radiation effects modeling.
Customer Requirements and Needs

- RHESE is a “requirements-pull” technology development effort.
- RHESE is a “cross-cutting” technology, serving a broad base of multiple project customers within Constellation.
  - Every project requiring…
    - operation in an extreme space environment,
    - avionics, processors, automation, communications, etc.
  …should include RHESE in its implementation trade space.
- Constellation Program requirements for avionics and electronics continue to evolve and become more defined.
- RHESE develops products per derived requirements based on the Constellation Architecture’s Level I and Level II requirements defined to date.
- RHESE is actively working CSAs with all Constellation customers.

Today, RHESE’s only customer is the Constellation program, but Science could greatly benefit from leveraged products.
RHESE Supports Multiple Constellation Projects

- RHESE’s products are developed in response to the needs and requirements of multiple Constellation program elements, including:
  - Ares V Crew Launch Vehicle (Earth Departure Stage),
  - Orion Crew Exploration Vehicle (Lunar Capability),
  - Altair Lunar Lander,
  - Lunar Surface Systems,
  - Extra Vehicular Activity (EVA) elements,
  - Future applications to Mars exploration architecture elements.
Potential RHESE Support to Science Missions

**Earth Orbiter**
- TID ~7 Mrad
- LEO: 1-3 yrs (500-1500 cycles)
- GEO: 10-15 yrs (3500-5500 cycles)
- Life expectancy: min/hrs

**Venus**
- TID ~7 krad
- Lifetime: ~1 hr (on surface)

**Mars Rover**
- TID 0.1-0.3 krad
- LEO: 1-3 yrs (500-1500 cycles)
- GEO: 10-15 yrs (3500-5500 cycles)
- Life expectancy: min/hrs

**Europa**
- TID ~7 Mrad
- Lifetime: min/hrs (on surface)
- Life expectancy: 90 days

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### RHESE Work Breakdown Structure

#### 1.0 - RHESE Project

<table>
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| 1.1 - RHESE Project Management | MSFC - Andrew Keys  
MSFC - Kathryn Vernor/Jacobs |

#### 1.2 - Radiation Hardened Electronics

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1.2.1.2 – Modeling of Radiation Effects on Electronics  
MSFC – James Adams |
| 1.2.2 - Radiation Hardened By Design |  
1.2.2.1 – SEE-Immune Reconfigurable FPGA  
GSFC – Michael Johnson |
| 1.2.4 – High Performance Processor |  
GSFC – Michael Johnson  
JPL – Elizabeth Kolawa |
| 1.2.5 – Reconfigurable Computing |  
MSFC – Clint Patrick  
MSFC – Anne Atkinson/Jacobs  
LaRC – Tak Ng |

#### 1.3 - Low Temperature Electronics

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<td>1.3.1 – SiGe Electronics for Extreme Environments</td>
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LaRC – Marvin Beaty  
LaRC – Arthur Bradley  
LaRC – Denise Scearce  
Ga.Tech - John Cressler |
RHESE Tasks

- **Specifically, the RHESE tasks for FY08 are:**
  - Model of Radiation Effects on Electronics (MREE),
    - Lead Center: MSFC
    - Participants: Vanderbilt University
  - Single Event Effects (SEE) Immune Reconfigurable Field Programmable Gate Array (FPGA) (SIRF),
    - Lead Center: GSFC
    - Participants: AFRL, Xilinx
  - Radiation Hardened High Performance Processors (HPP),
    - Lead Center: GSFC
    - Participants: LaRC, JPL, Multiple US Government Agencies
  - Reconfigurable Computing (RC),
    - Lead Center: MSFC
  - Silicon-Germanium (SiGe) Integrated Electronics for Extreme Environments.
    - Lead Center: LaRC
    - Participants: Georgia Tech. leads multiple commercial and academic participants.

…and **(re)starting in FY09…**
- Radiation-Hardened Volatile and Non-Volatile Memory
  - Lead Center: MSFC
  - Participants: LaRC, Multiple Vendors
MREE Technology Objectives

• Primary Objective
  – A computational tool to accurately predict electronics performance in the presence of space radiation in support of spacecraft design
    • Total dose
    • Single Event Effects
    • Mean Time Between Failure

(Developed as successor to CRÈME96.)

• Secondary Objectives
  – To provide a detailed description of the natural radiation environment in support of radiation health and instrument design
    • In deep space
    • Inside the magnetosphere
    • Behind shielding
Update the Method for SEE Calculation

CREME96

Device/Circuit/System Virtualization

Radiation Event Generation

Response Prediction

Integral over path length Distribution + critical charge

MREE

Multi-volume Calorimetry + Charge-collection models + Critical charge

Radiation Damage Predictions Using 3-D Modeling
**SIRF**
*(Single-Event Immune Reconfigurable FPGA)*

- **Key Development Objectives**
  
- **Deliver Radiation Hardened by Design, Space qualified Virtex-5 FPGA**
  
- **Minimize design complexities and overhead required Space applications of FPGAs**
  - Eliminate additional design effort and chips for configuration management, scrubbing, TMR and state recovery

- **Maintain compatibility with commercial V-5 product for rapid development**
  - Feature set, floor plan and footprint compatible with commercial product
    - Address critical SEE sensitive circuits and eliminate all SEFIIs
    - Transparent to S/W Development Tools
SIRF Architecture
Based on Commercial Devices

- **5th generation Virtex™ device**
  - 90 nm process
  - 11 metal layers
  - Up to 8M gates

- **Columnar Architecture enables resource “dial-in” of**
  - Logic
  - Block RAM
  - I/O
  - DSP Slices
  - PowerPC Cores

Fabrication process and device architecture yield a high speed, flexible component
**Problem:** Exploration Systems Missions Directorate objectives and strategies can be constrained by computing capabilities and power efficiencies

- Autonomous landing and hazard avoidance systems
- Autonomous vehicle operations
- Autonomous rendezvous and docking
- Vision systems
Radiation-hardened processors lag commercial devices by several technology generations (approx. 10 years)

- RHESE High performance Processor project full-success metric for general purpose processors conservatively keeps pace with historical trend (~Moore’s Law)

![Diagram showing the comparison between radiation-hardened and commercial processors over time.](image-url)
• **Develop reconfigurable computing capabilities for spaceflight vehicles:**
  – Allow the ability to change function and performance of a particular computing resource in part or entirely, manually or autonomously.

• **Objectives of RC include:**
  – **Interface (Spares) Modularity**
    • Ability for a single board to reconfigure to multiple dedicated external data and communication systems as needed, both in physical interconnection and protocol.
  – **Functional Modularity**
    • Ability for a single board to reconfigure to multiple functions within a single multi-use data and communication system, both in physical interconnection and protocol.
  – **Processor (Internal) Modularity**
    • Ability for a single board to reconfigure in response to internal errors or faults while continuing to perform a (potentially critical) function. Includes:
      – Fault Tolerance
      – Fault Detection, Isolation, and Mitigation, Notification
• Flight-Qualified, Multi-String Redundant Hardware is Expensive
  – Development, Integration, IV&V, and Flight Qualification
  – Space and Weight
  – Power Consumption and Cooling
• Custom Design of Computing Resources for Every New Flight System or Subsystem is Unnecessary and Wasteful
• Requirements for Flexibility are Increasing and Make Sense
  – Reconfigurable (Flexible) and Modular Capabilities
  – For Dissimilar Spares, and Incremental Changeover to New Technology: Capacity to use one system to back up any number of others
  – General Reusability
• Current Options for Harsh/Flight Environment Systems are Limited
  – Custom Hardware, Firmware, and Software
  – Dedicated and Inflexible
  – Often Proprietary: Collaboration Inhibited
• Modular Spares == Fewer Flight Spares
The Moon: **A Classic Extreme Environment!**

**Extreme Temperature Ranges:**
- +120°C to -180°C (**300°C T swings**)!
- 28 day cycles
- -230°C in shadowed polar craters

**Radiation:**
- 100 krad over 10 years
- single event effects (SEE)
- solar events

**Many Different Circuit Needs:**
- digital building blocks
- analog building blocks
- data conversion (ADC/DAC)
- RF communications
- actuation and control
- sensors / sensor interfaces

**Highly Mixed-Signal Flavor**

Current Rovers / Robotics

Requires “Warm Box”
SiGe Technology

- SiGe HBT + CMOS + full suite of passives (Integration)
- 100% Si Manufacturing Compatibility (MOSIS Foundry)
- Wide-Temperature Capable + Radiation Tolerant
SiGe Electronics Development Team

- **Georgia Tech** *(Device Technology IPT lead)*
  - John Cressler *et al.* (PI, devices, reliability, circuits)
  - Cliff Eckert (program management, reporting)
- **Auburn University** *(Packaging IPT lead)*
  - Wayne Johnson *et al.* (packaging); Foster Dai *et al.* (circuits); Guofu Niu *et al.* (devices)
- **University of Tennessee** *(Circuits IPT lead)*
  - Ben Blalock *et al.* (circuits)
- **University of Maryland** *(Reliability IPT lead)*
  - Patrick McCluskey *et al.* (reliability, package physics-of-failure modeling)
- **Vanderbilt University**
  - Mike Alles, Robert Reed *et al.* (radiation effects, TCAD modeling)
- **JPL** *(Applications IPT lead)*
  - Mohammad Mojarradi *et al.* (applications, reliability testing, circuits)
- **Boeing**
  - Leora Peltz *et al.* (applications, circuits)
- **Lynguient / University of Arkansas** *(Modeling IPT lead)*
  - Alan Mantooth / Jim Holmes *et al.* (modeling, circuits)
- **BAE Systems**
  - Richard Berger, Ray Garbos *et al.* (REU architecture, maturation, applications)
- **IBM**
  - Alvin Joseph *et al.* (SiGe technology, fabrication)
SiGe-Based Remote Electronics Unit (REU)

The X-33 Remote Health Monitoring Node, circa 1998 (BAE)

Our Project End Game: The SiGe ETDP Remote Electronics Unit, circa 2009

Specifications
- 5” wide by 3” high by 6.75” long = 101 cubic inches
- 11 kg weight
- 17.2 Watts power dissipation
- -55°C to +125°C

Analog front end die
Digital control die
Conceptual integrated REU system-on-chip SiGe BiCMOS die

Our Goals
- 1.5” high by 1.5” wide by 0.5” long = 1.1 cubic inches
- < 1 kg
- < 1-2 Watts
- -180°C to +125°C, rad tolerant!

Supports MANY Sensor Types:
- Temperature
- Strain
- Pressure
- Acceleration
- Vibration
- Heat Flux
- Position
- etc.

Use This REU as a Remote Vehicle Health Monitoring Node

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REU in connector housing!

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RHESE Summary

- RHESE’s products are developed in response to the needs of multiple Constellation program elements.
- RHESE enables an avionics application-dependent trade space defined by:
  - Radiation Hardening by Architecture using COTS electronics in redundancy,
  - Radiation Hardening By Design using Si-based processes and techniques.
  - Radiation Hardening by Process using proprietary foundries.
Considerations include performance requirements, power efficiency, design complexity, radiation, etc.
- Radiation and low temperature environments drive spacecraft system architectures.
  - Centralized systems to keep electronics warm are costly, weighty and use excessive cable lengths.
  - Mitigation can be achieved by active SiGe electronics.
RHESE Summary

- **Radiation Environmental Modeling** is crucial to proper predictive modeling and electronic response to the radiation environment.
  - When compared to on-orbit data, **CREME96** has been shown to be inaccurate in predicting the radiation environment.

- Close coordination and partnership with **DoD radiation-hardened efforts** will result in leveraged - not duplicated or independently developed - technology capabilities of:
  - Radiation-hardened, reconfigurable FPGA-based electronics,
  - High Performance Processors (NOT duplication or independent development).

- **Constellation is the RHESE customer**, but Science is invited to leverage and mature products as well.