International Planetary Probes Workshop – 6
Atlanta, GA, USA

Exploration Technology Development Program's

Radiation Hardened Electronics for Space Environments (RHESE) Project Overview

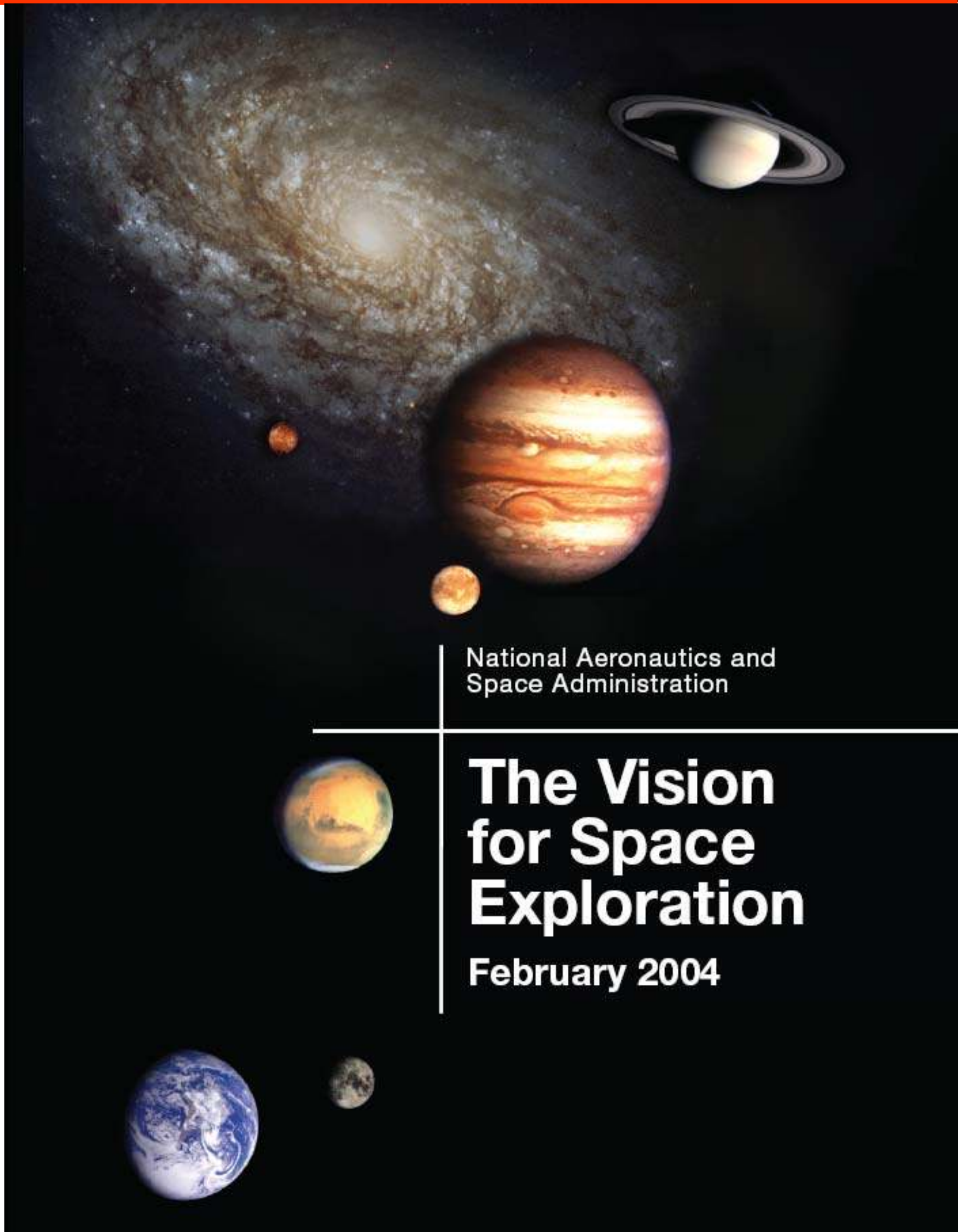
Andrew S. Keys, James H. Adams, Ronald C. Darty, and Marshall C. Patrick
NASA Marshall Space Flight Center, Huntsville, AL 35812
Michael A. Johnson
NASA Goddard Space Flight Center, Greenbelt, MD 20771
John D. Cressler
Georgia Institute of Technology, Atlanta, GA 30332-0250

IPPW-6, 23-27 June 2008

U.S. Space Exploration Policy (a.k.a. VSE)

- **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.
  - Develop a Crew Exploration Vehicle by 2008, first manned mission no later than 2014.
  - 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.



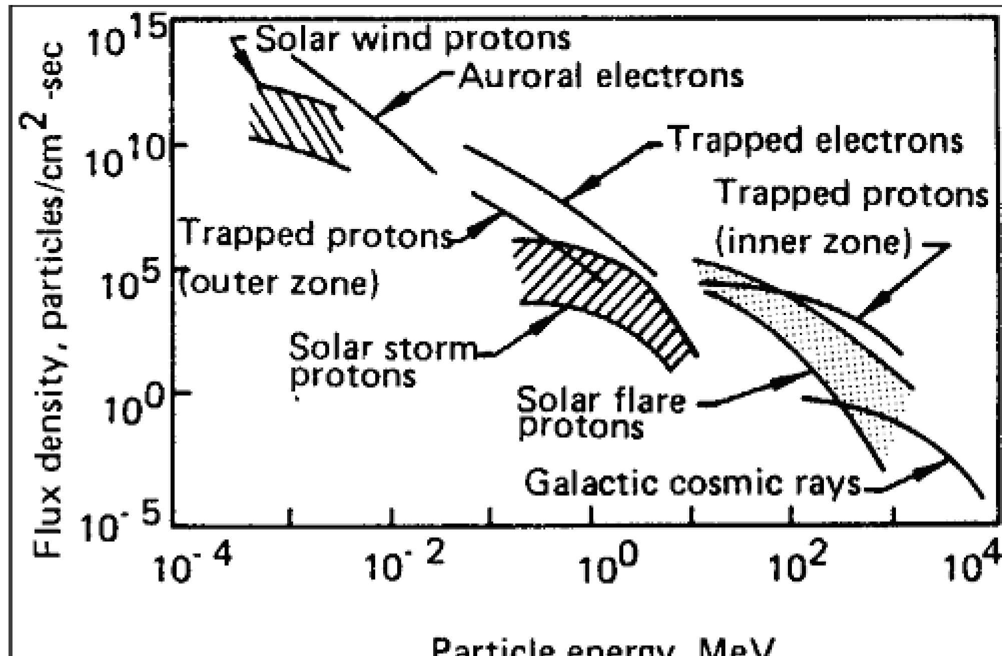
ETDP Organizational Chart

Exploration Technology Development Program
Frank Peri, Director

- **Diane Hope - Program Element Manager**
  - LaRC — **Structures, Materials & Mechanisms (SMM)** — Judith Watson
  - GRC — **Propulsion and Cryogenic Advanced Development (PCAD)** — Mark Klem
  - GRC — **Cryogenic Fluid Management System (CFM)** — Sue Motil
  - GRC — **Energy Storage and Power Systems** — Carolyn Mercer
  - MSFC — **High Performance and Radiation Hardened Electronics (RHESE)** — Andrew Keys
  - GRC — **Fission Surface Power Systems (FSPS)** — Don Palac
  - JSC — **In-Situ Resource Utilization (ISRU)** — Jerry Sanders
  - LaRC — **Supportability** — Barmac Taleghani
  - JSC — **Human Robotic Systems (HRS)** — Rob Ambrose
  - ARC — **Thermal Protection System (TPS)** — James Reuther
  - LaRC — **Advanced Composites Technologies (ACT)** — Mark Shuart
- **Dana Gould - Program Element Manager**
  - GRC — **Dust Mitigation** — Mark Hyatt
  - JSC — **Thermal Control for Surface Systems** — Ryan Stephan
  - ARC — **Integrated System Health Management (ISHM)** — Dave Korsmeyer
  - ARC — **Autonomy for Operations (A4O)** — David Alfano
  - ARC — **Intelligent Software Design (ISD)** — Joe Coughlin
  - JSC — **Autonomous Landing & Hazard Avoidance Technology (ALHAT)** — Chirold Epp
  - JSC — **Automated Rendezvous & Docking (AR&D) Sensors** — Jennifer Mitchell
  - JSC — **Exploration Life Support (ELS)** — Dan Barta
  - JPL — **Advanced Environmental Monitoring & Control (AEMC)** — Darrell Jan
  - GRC — **Fire Prevention, Detection, & Suppression (FPDS)** — Gary A. Ruff
  - JSC — **Extra Vehicular Activity (EVA) Technology** — David Westheimer
  - GRC — **ISS Research** — Fred Kohl

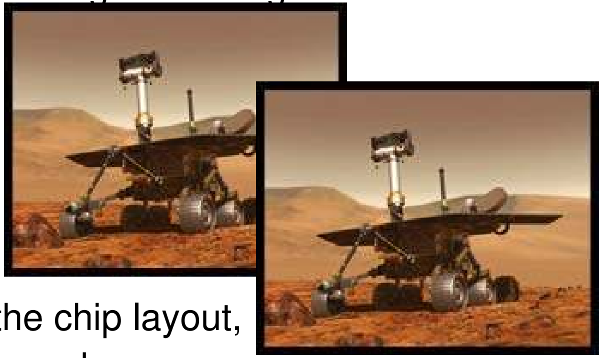
Surviving the Radiation Environment

- **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.



The Radiation 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.

RHESE Overview and Objectives

The **Radiation Hardened Electronics for Space Environments (RHESE)** project expands the current state-of-the-art in radiation-hardened electronics to develop high performance devices robust enough to withstand the demanding radiation and thermal conditions encountered within the space and lunar environments.

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.

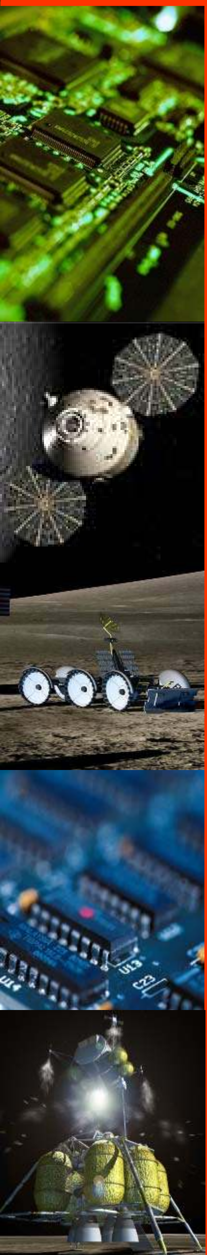
Customer Requirements and Needs

- 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.

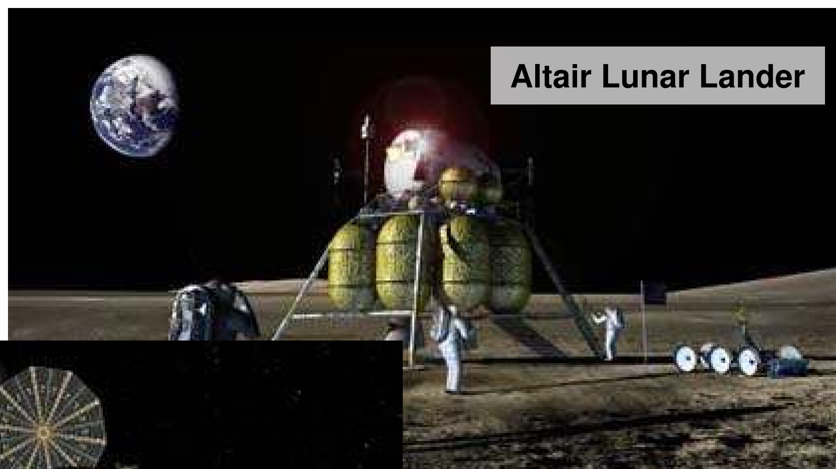
    …should include RHESE in its *implementation trade space*.
- Constellation Program requirements for avionics and electronics continue to evolve and become more defined.
- RHESE develops products per derived requirements based on the Constellation Architecture’s Level I and Level II requirements defined 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



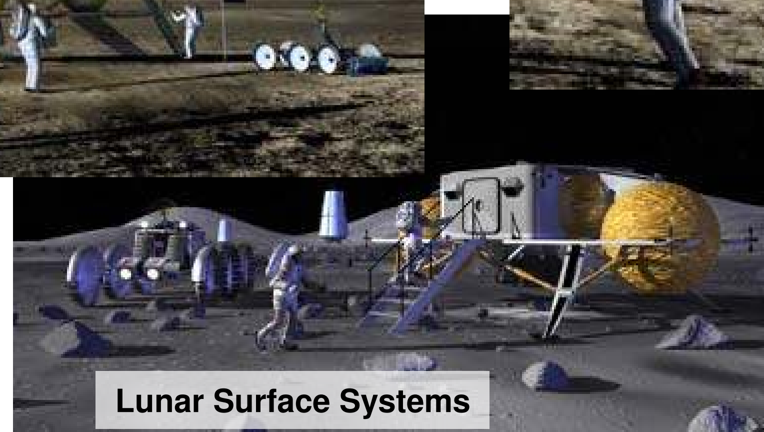
- **RHESE's products are developed in response to the needs and requirements of multiple Constellation program elements, including:**
  - Ares V Crew Launch Vehicle (Earth Departure Stage),
  - Orion Crew Exploration Vehicle (Lunar Capability),
  - Altair Lunar Lander,
  - Lunar Surface Systems,
  -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



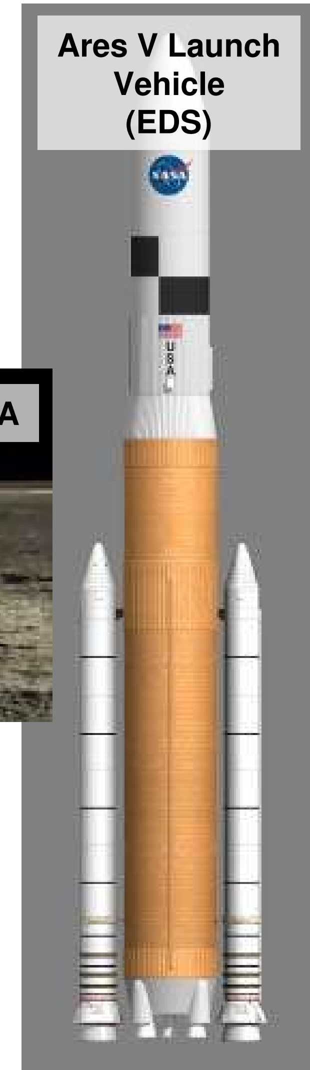
Altair Lunar Lander

EVA

Orion Crew Exploration Vehicle

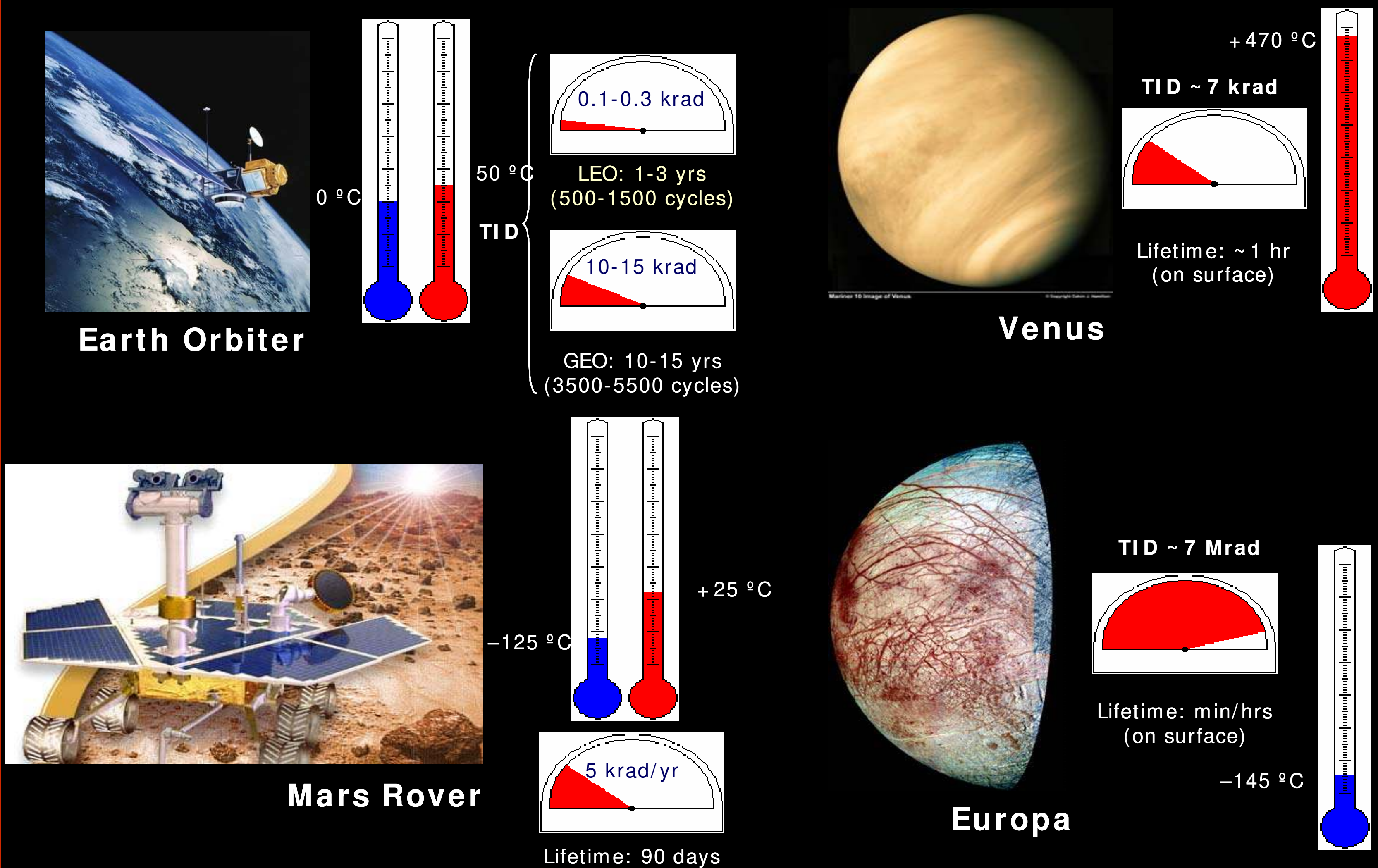


Lunar Surface Systems



Ares V Launch Vehicle (EDS)

Potential RHESE Support to Science Missions



RHESE Work Breakdown Structure

1.0 - RHESE Project

1.1 - RHESE Project Management
MSFC - Andrew Keys
MSFC - Kathryn Vernor/Jacobs

1.2 - Radiation Hardened Electronics

1.2.1 - Radiation Hardened Materials
- 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

1.3.1 – SiGe Electronics for Extreme Environments
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

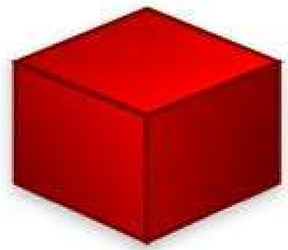
- **Primary Objective**
  - A computational tool to accurately predict electronics performance in the presence of space radiation in support of spacecraft design
    - Total dose
    - Single Event Effects
    - Mean Time Between Failure

  (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

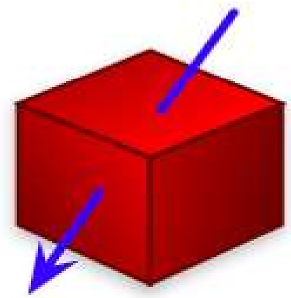
Update the Method for SEE Calculation

CREME96

Device/Circuit/System Virtualization



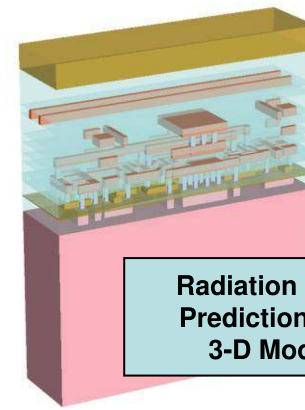
Radiation Event Generation



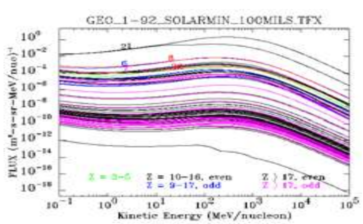
Response Prediction

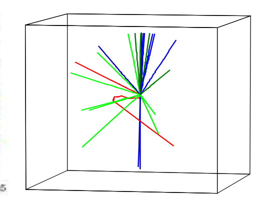
Integral over path length Distribution + critical charge

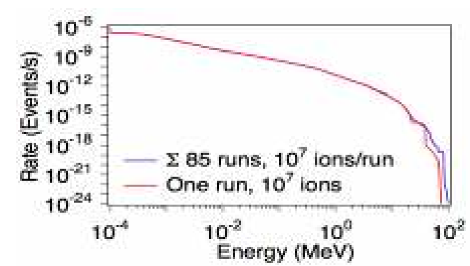
MREE



Radiation Damage Predictions Using 3-D Modeling







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

SIRF
(Single-Event Immune Reconfigurable FPGA)

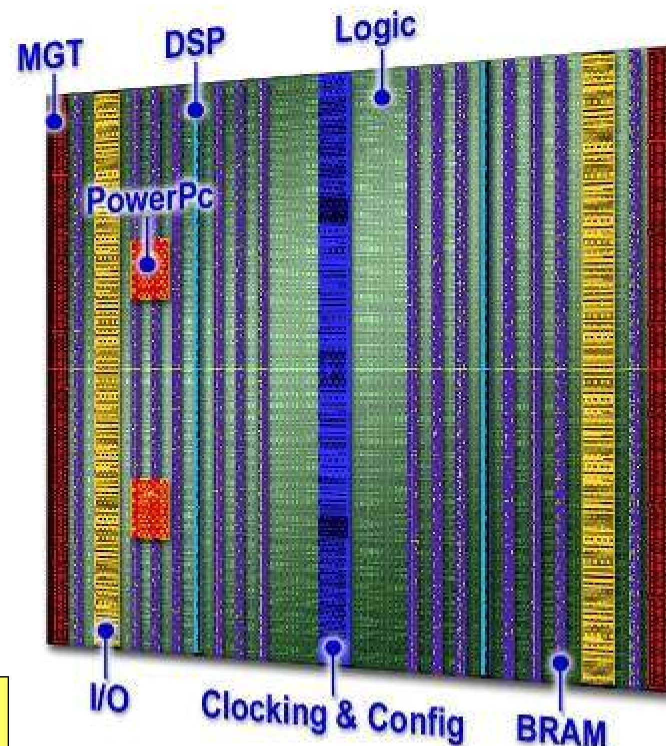
- **Key Development Objectives**

- **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 SEFIs
    - 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

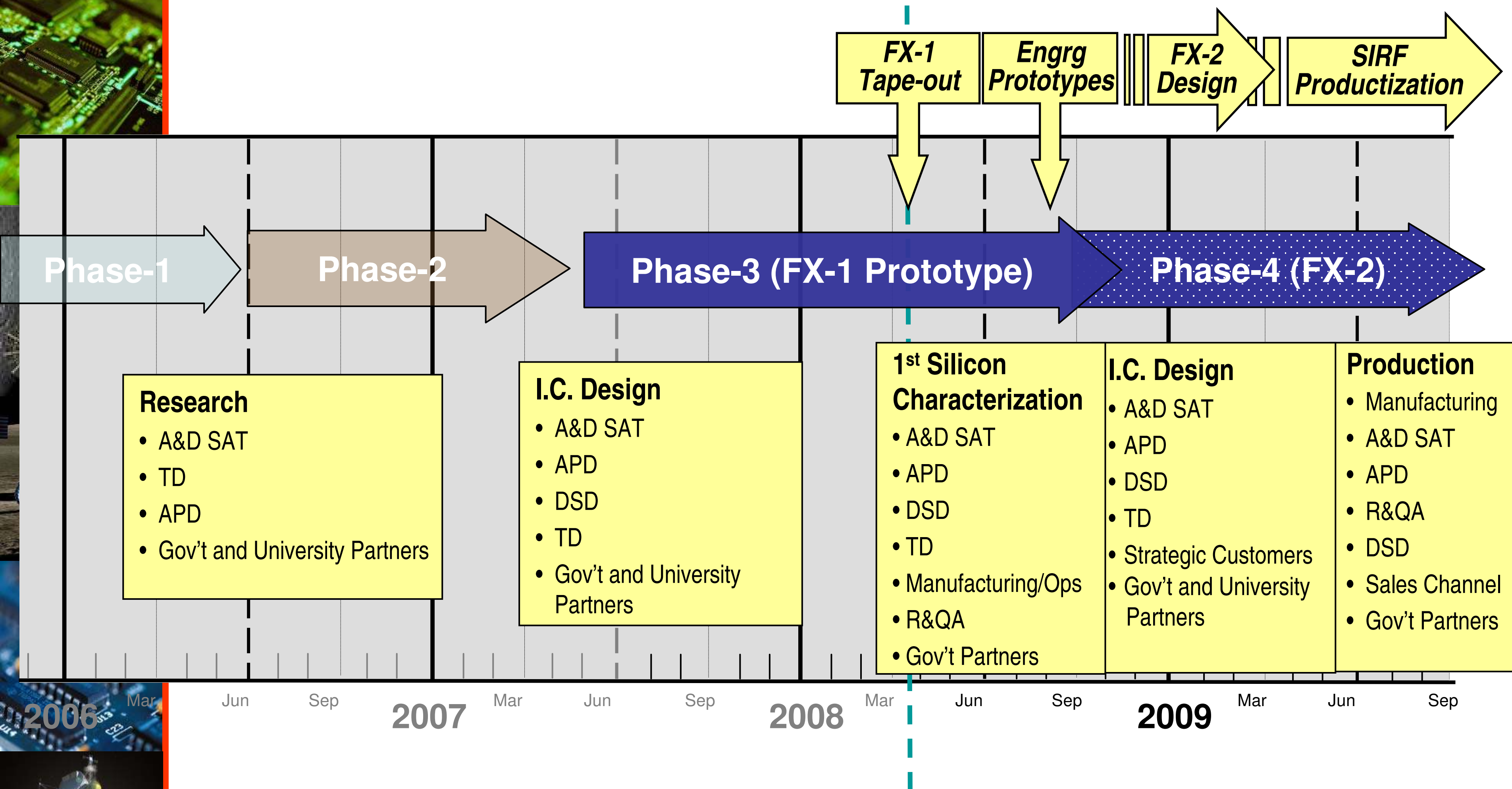
- **Columnar Architecture enables resource "dial-in" of**
  - Logic
  - Block RAM
  - I/O
  - DSP Slices
  - PowerPC Cores



Fabrication process and device architecture yield a high speed, flexible component

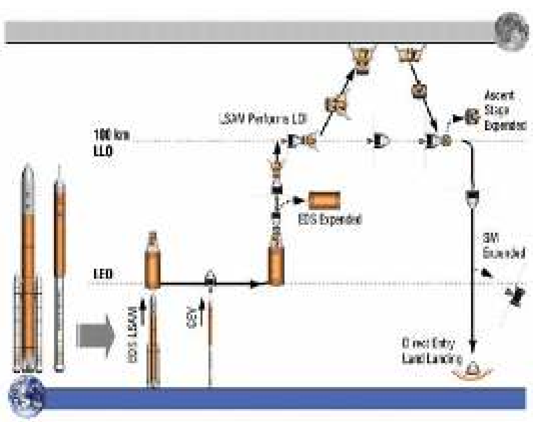
SIRF Program

Functional Phases



HPP Drivers

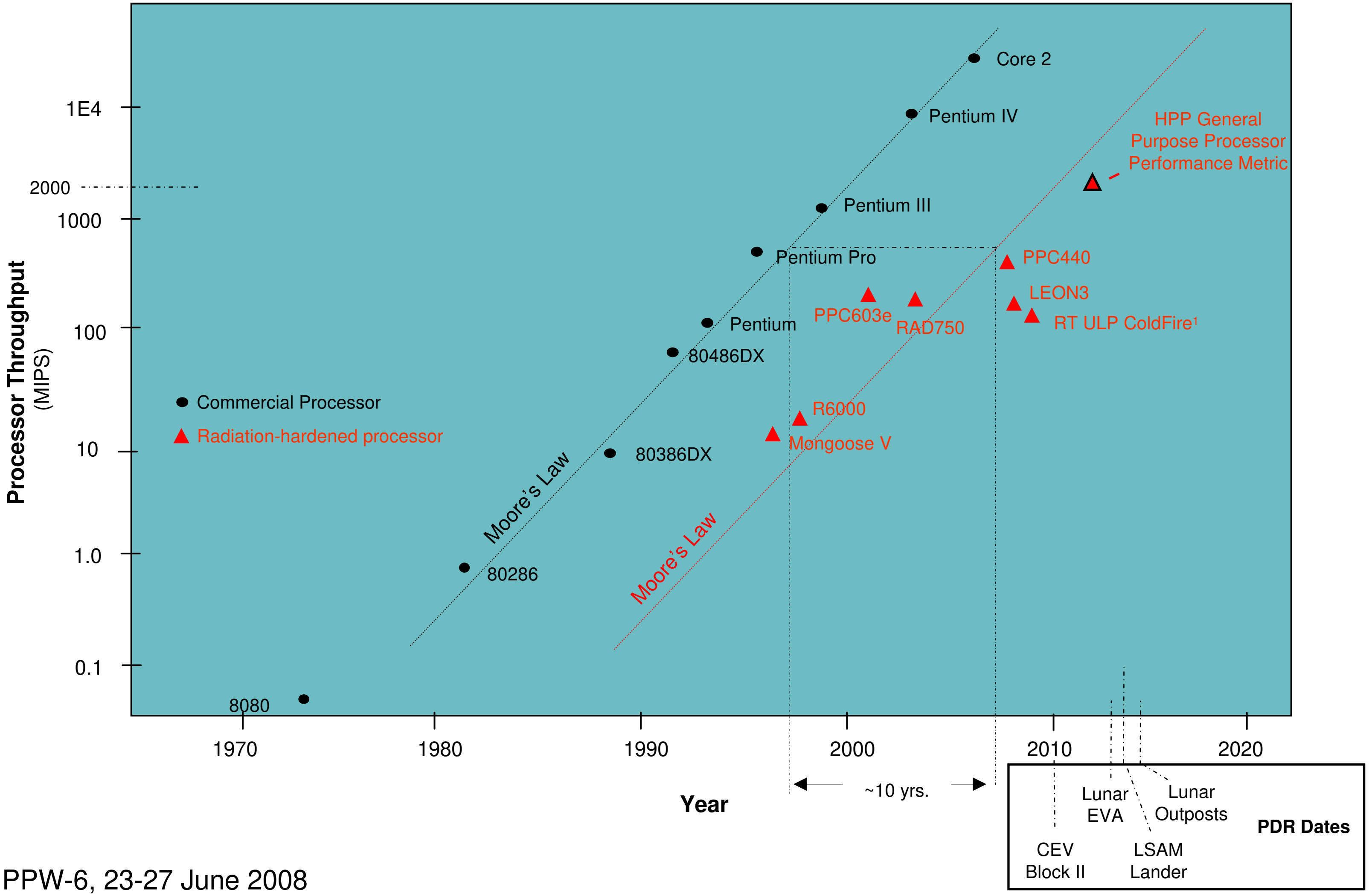
- **Problem:** Exploration Systems Missions Directorate objectives and strategies can be constrained by computing capabilities and power efficiencies
  - Autonomous landing and hazard avoidance systems
  - Autonomous vehicle operations
  - Autonomous rendezvous and docking
  - Vision systems



HPP Technical Approach

Multi-generation Performance Lag

- 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)



Reconfigurable Computing Subproject

- **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

RC Technical Justification

Reconfigurable Computing Subproject

- **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:

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

Radiation:

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

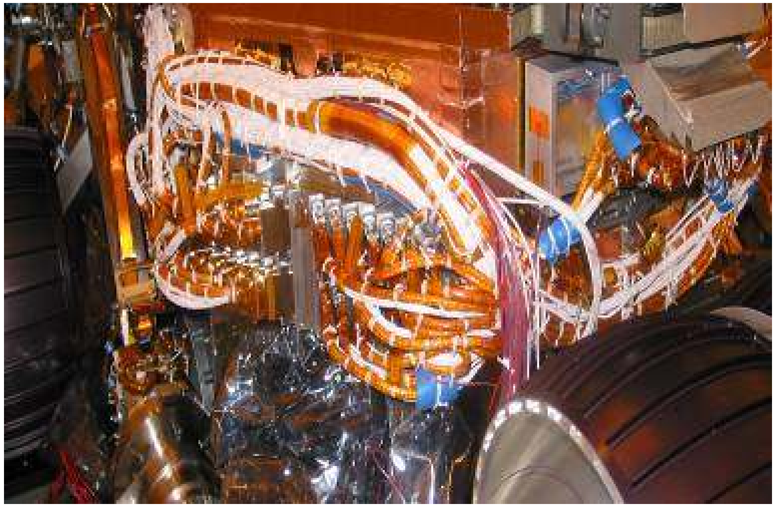
Many Different Circuit Needs:

- digital building blocks
- analog building blocks
- data conversion (ADC/DAC)
- RF communications
- actuation and control
- sensors / sensor interfaces

→ **Highly Mixed-Signal Flavor**

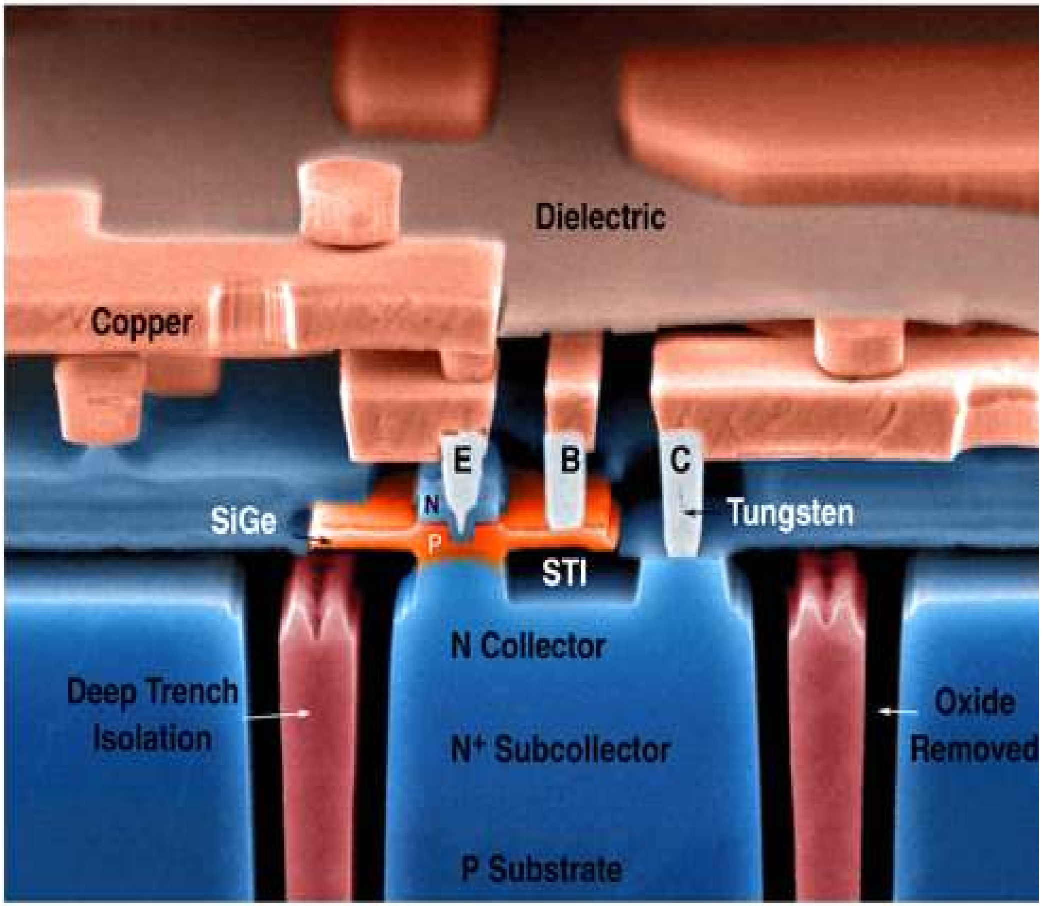
Current Rovers / Robotics

Requires "Warm Box"

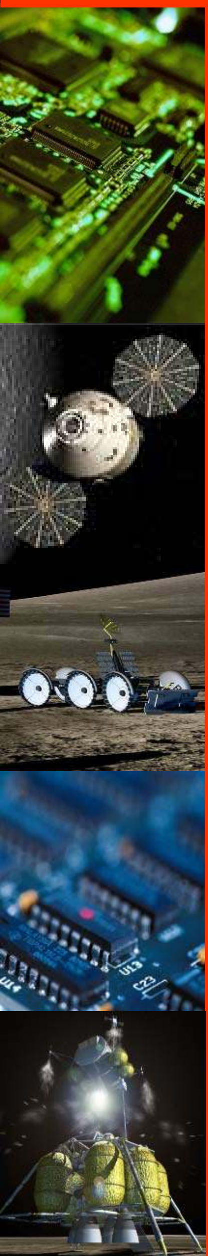


SiGe Technology

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

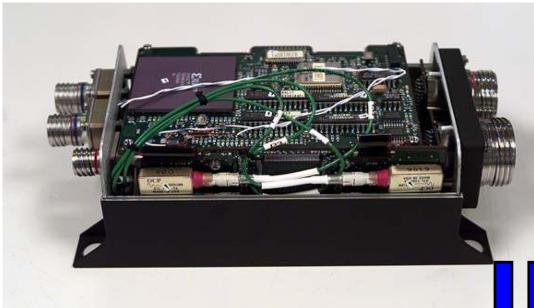


SiGe Electronics Development Team



- **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)
- **Lynguent / 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)

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

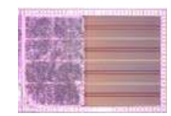
Our Project End Game:

The SiGe ETDP Remote Electronics Unit, circa 2009

REU in connector housing!

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:

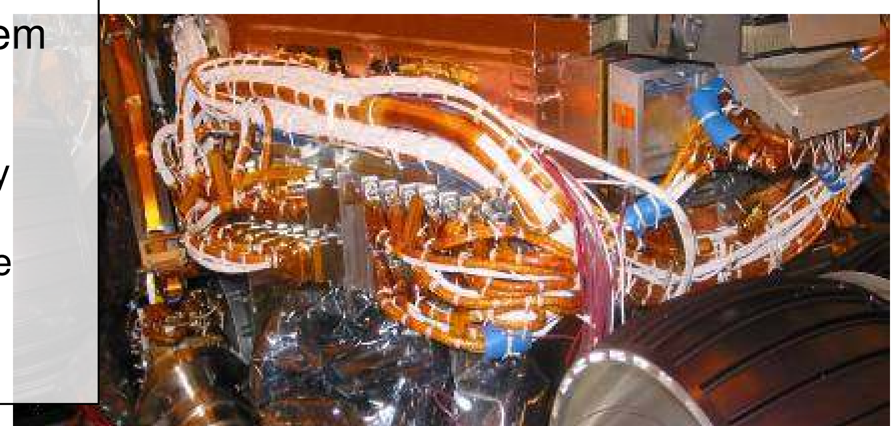
Temperature, Strain, Pressure, Acceleration, Vibration, Heat Flux, Position, etc.

Use This REU as a Remote Vehicle Health Monitoring Node

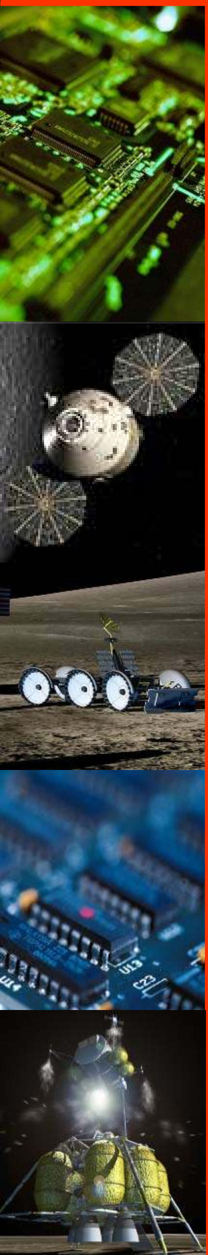
RHESE Summary

- 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.