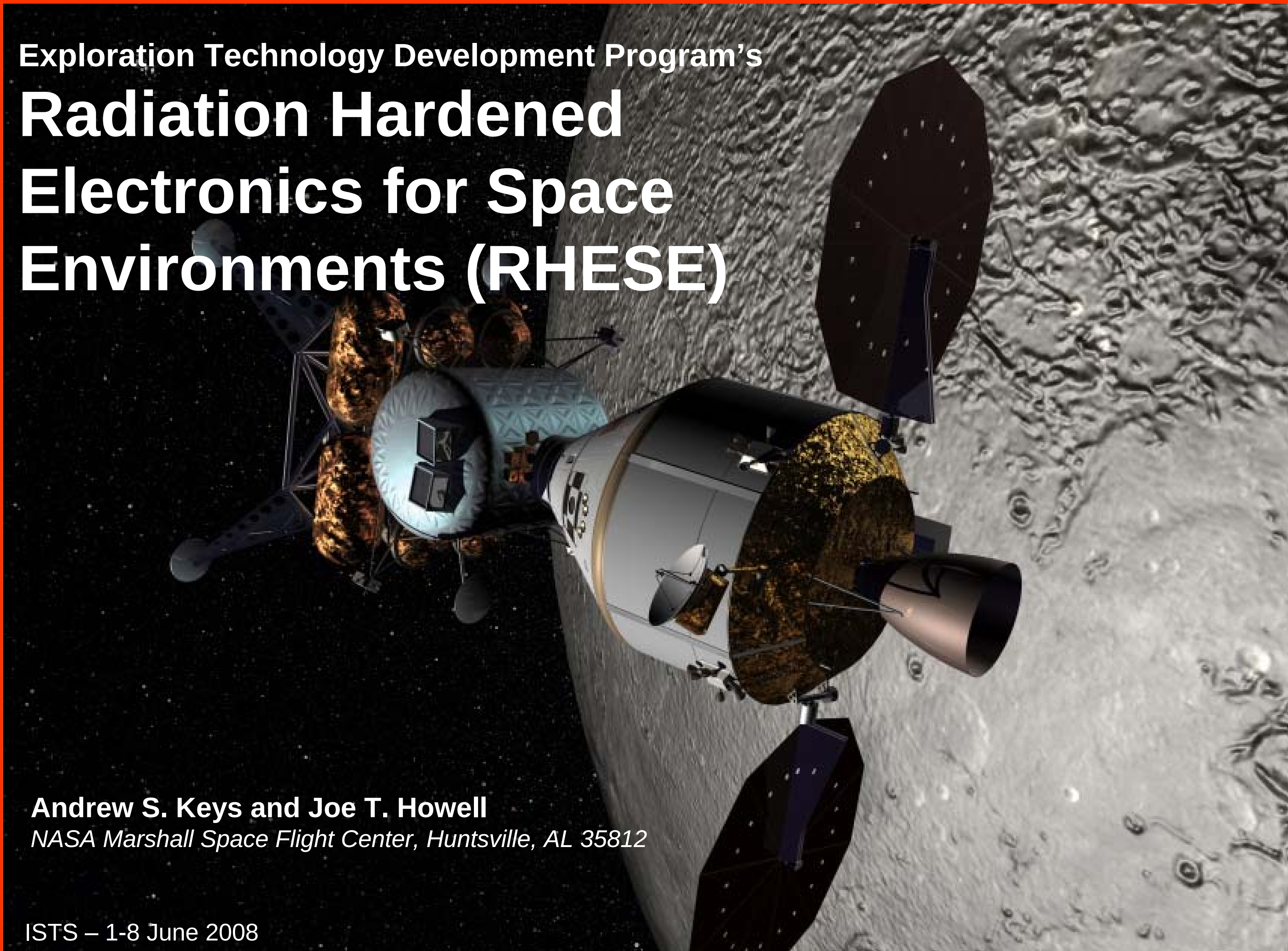
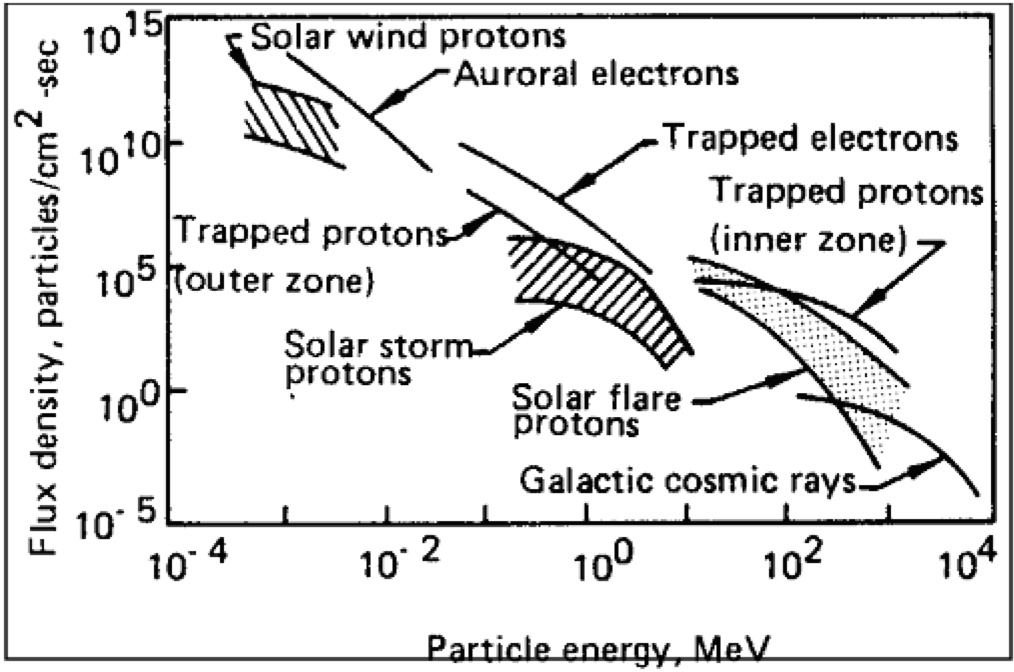


Exploration Technology Development Program's

Radiation Hardened Electronics for Space Environments (RHESE)

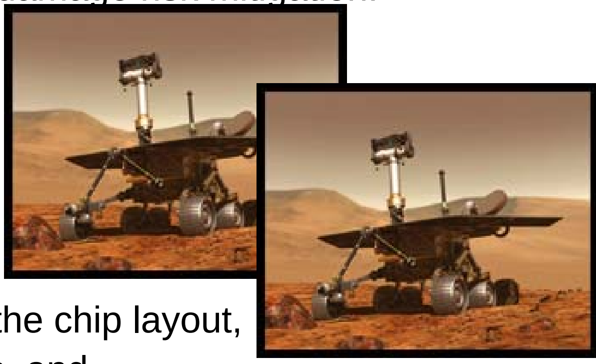
Andrew S. Keys and Joe T. Howell
NASA Marshall Space Flight Center, Huntsville, AL 35812

- **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.



Radiation Hardened Assurance

- **NASA spacecraft developers have defined a Radiation Hardness Assurance (RHA) methodology process*.**
- **In general, the process may be described by the following steps:**
  - 1) define the radiation hazard,
  - 2) evaluate the hazard,
  - 3) define the requirements to be met by the spacecraft's electronics,
  - 4) evaluate the electronics to be used,
  - 5) engineer processes to mitigate hazard damage, and
  - 6) iterate on the methodology, if and when necessary.
- **To promote the successful implementation of RHA for Constellation (and other NASA) missions, the RHESE project aims to deliver products that assist in *mitigating the hazard damage*.**

***LaBel, K. A., Johnson, A. H., Barth, J. L., Reed, R. A., and Barnes, C. E., "Emerging Radiation Hardness Assurance(RHA) Issues: A NASA Approach for Space Flight Programs," *IEEE Transactions on Nuclear Science*, Vol. 45, No. 6, Dec. 1998, pp. 2727-2736.**

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.

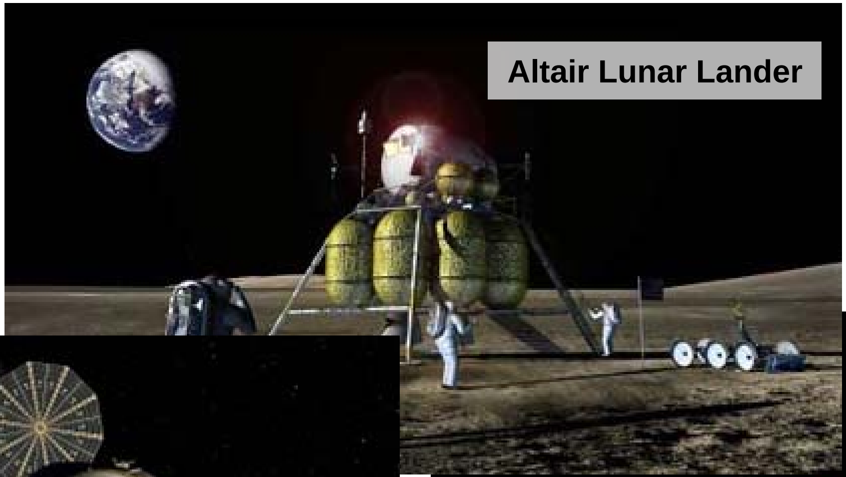
Customer Requirements and Needs

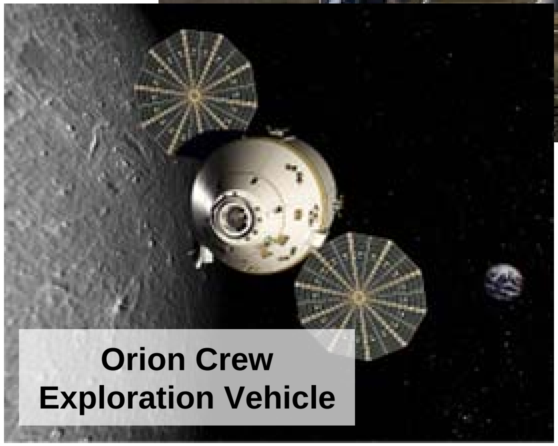
- **RHESE is a "requirements-pull" technology development effort.**
- **RHESE is a "cross-cutting" technology, serving a broad base of multiple project customers within Constellation.**
  - Every project requiring…
    - operation in an extreme space environment,
    - avionics, processors, automation, communications, etc.

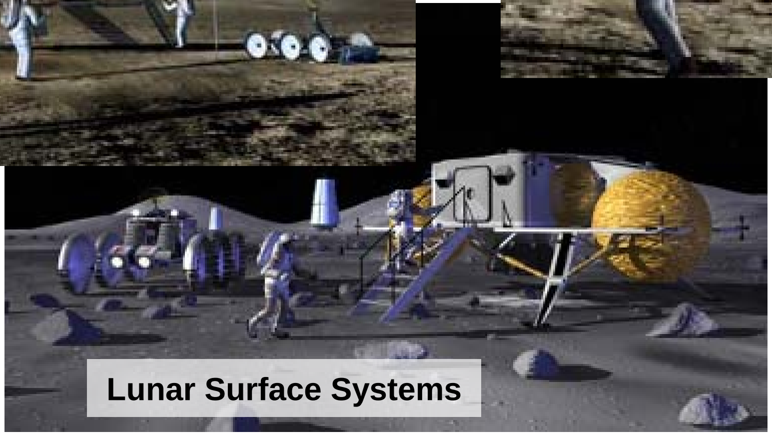
    …should include RHESE in its implementation trade space.
- **Constellation Program requirements for avionics and electronics continue to evolve and become more defined.**
- **RHESE will develop products per derived requirements based on the Constellation Architecture's Level I and Level II requirements defined to date.**
- **RHESE is actively working CSAs with all Constellation customers.**

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.







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

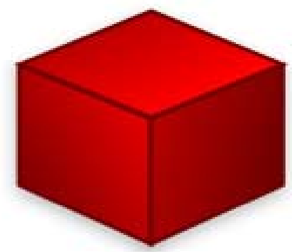
- **Primary Objective**
  - A computational tool to accurately predict electronics performance in the presence of space radiation in support of spacecraft design
    - Total dose
    - Single Event Effects
    - Mean Time Between Failure

    (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

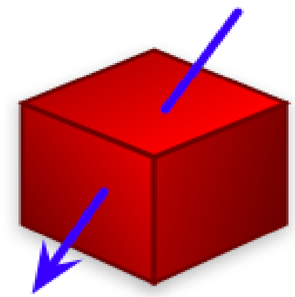
Update the Method for SEE Calculation

CREME96

Device/Circuit/System Virtualization



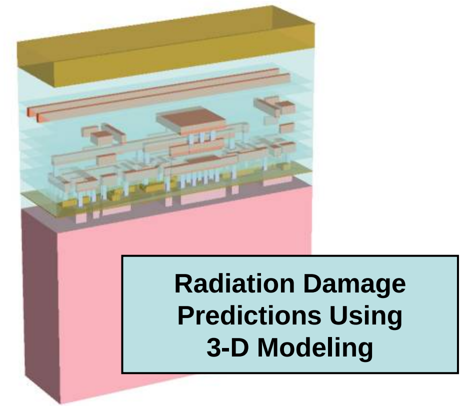
Radiation Event Generation

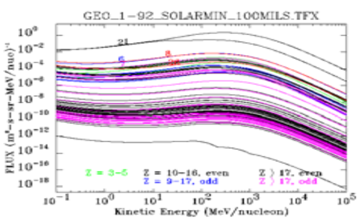


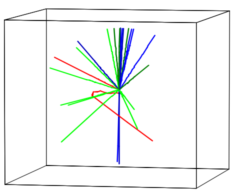
Response Prediction

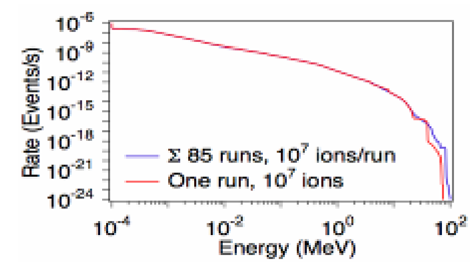
Integral over path length Distribution + critical charge

MREE









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

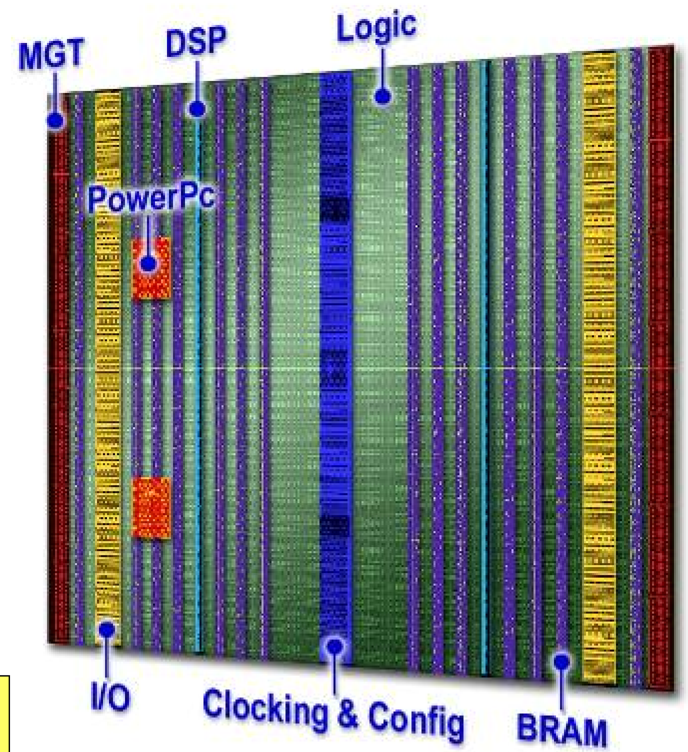
SIRF
(Single-Event Immune Reconfigurable FPGA)

- **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

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

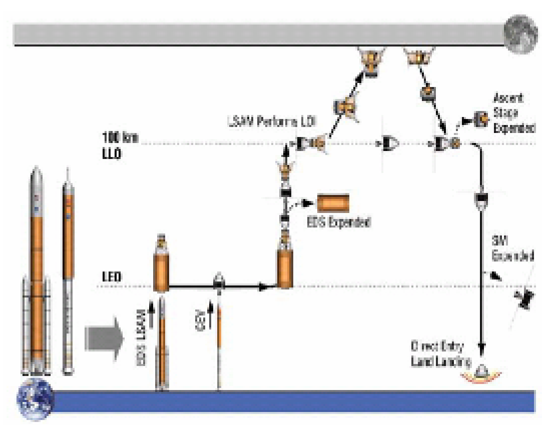
- **Columnar Architecture enables resource "dial-in" of**
  - Logic
  - Block RAM
  - I/O
  - DSP Slices
  - PowerPC Cores



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

HPP Drivers

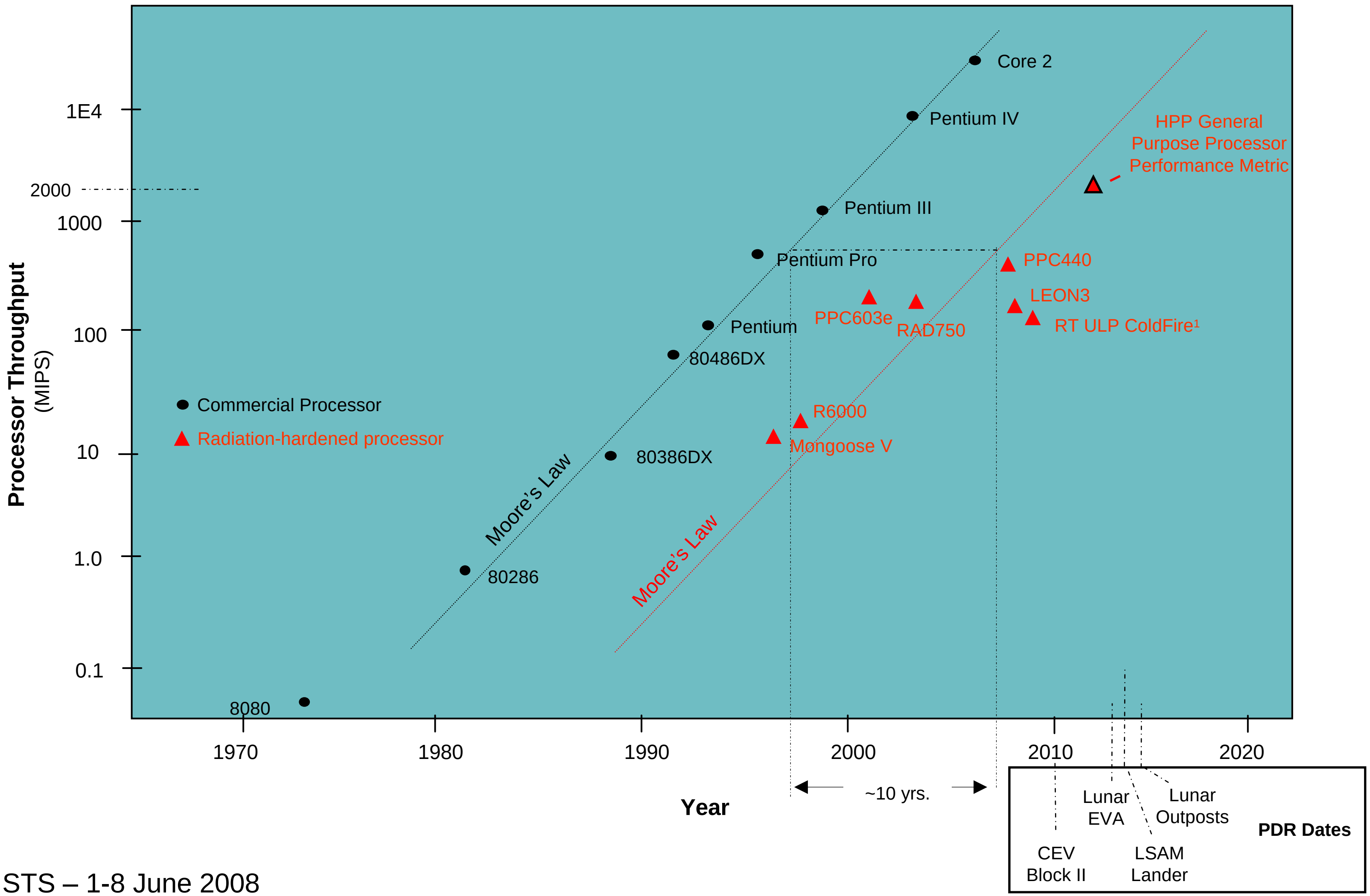
- **Problem:** Exploration Systems Missions Directorate objectives and strategies can be constrained by computing capabilities and power efficiencies
  - Autonomous landing and hazard avoidance systems
  - Autonomous vehicle operations
  - Autonomous rendezvous and docking
  - Vision systems



HPP Technical Approach

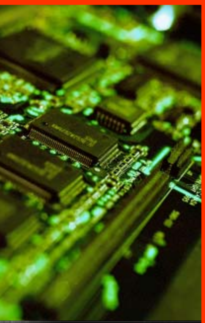
Multi-generation Performance Lag

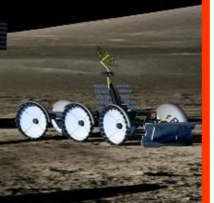
- Radiation-hardened processors lag commercial devices by several technology generations (approx. 10 years)
  – RHESE High performance Processor project full-success metric for general purpose processors conservatively keeps pace with historical trend (~Moore's Law)



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





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

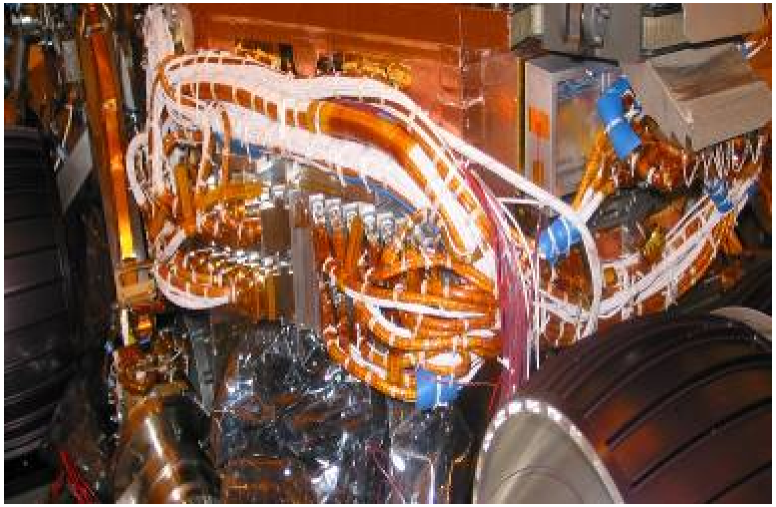
Many Different Circuit Needs:

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

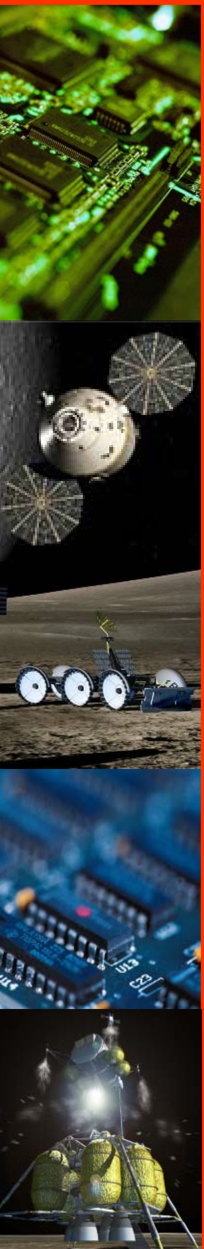
→ **Highly Mixed-Signal Flavor**

Current Rovers / Robotics

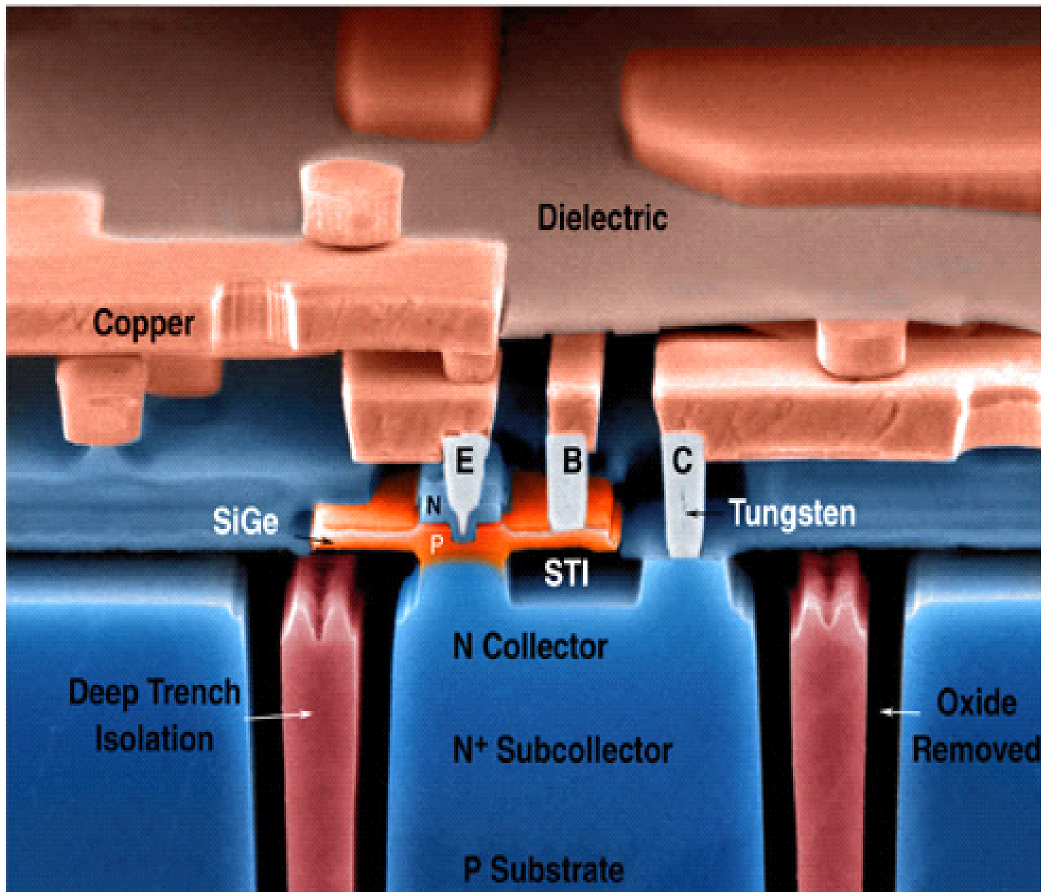
Requires "Warm Box"



SiGe Technology



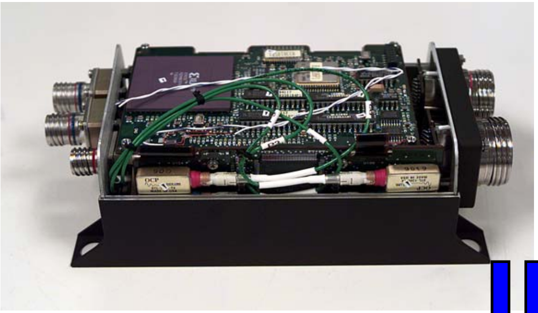
- **SiGe HBT + CMOS + full suite of passives (Integration)**
- **100% Si Manufacturing Compatibility (MOSIS Foundry)**
- **Wide-Temperature Capable + Radiation Tolerant**



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)

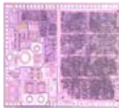


The X-33 Remote Health Monitoring Node, circa 1998 (BAE)

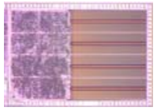
Our Project End Game:
The SiGe ETDP Remote Electronics Unit, circa 2009

REU in connector housing!

Analog front end die



Digital control die



Conceptual integrated REU system-on-chip SiGe BiCMOS die

Specifications

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

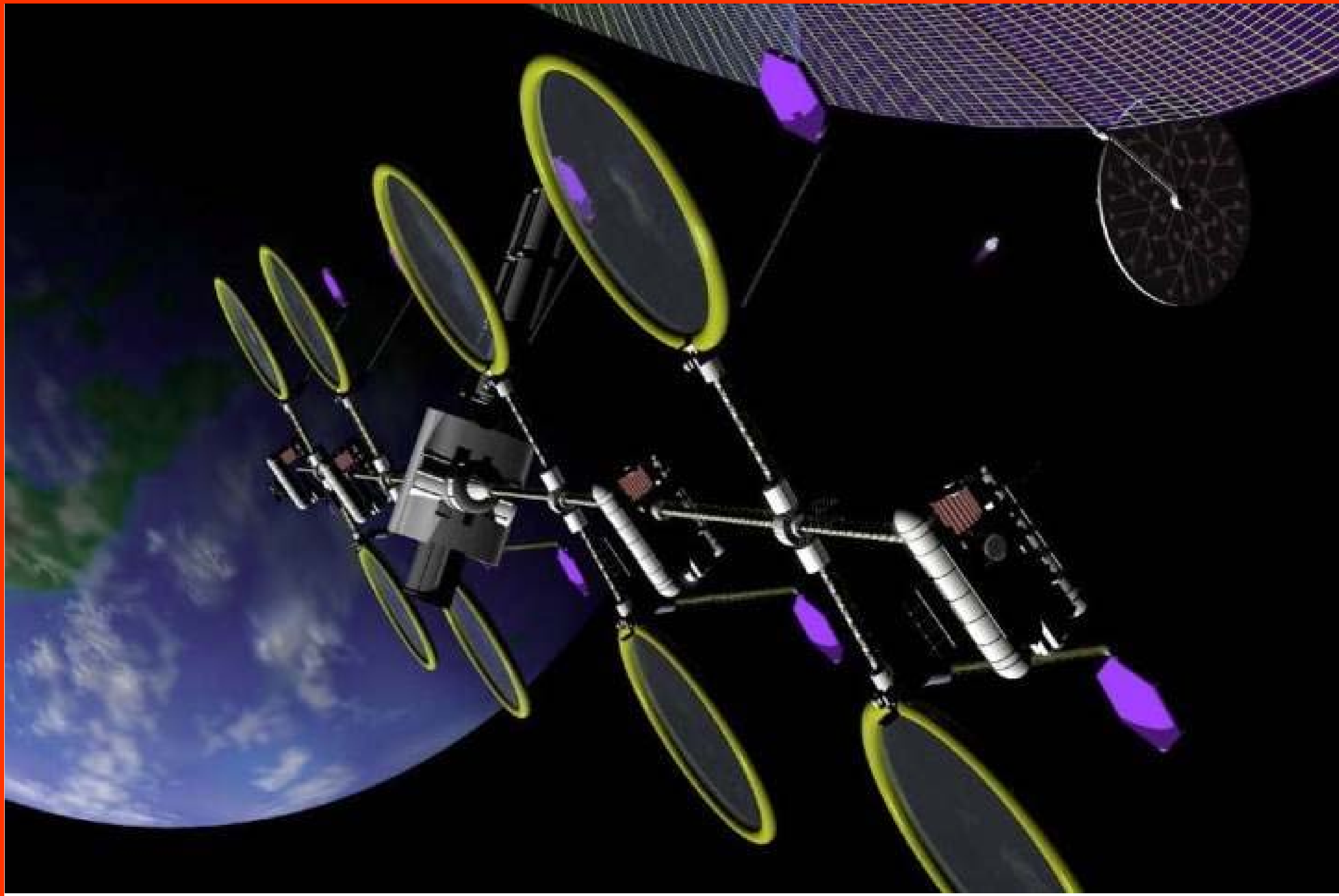
Our Goals

- 1.5” high by 1.5” wide by 0.5” long = 1.1 cubic inches
- < 1 kg
- < 1-2 Watts
- -180^{o}C to +125^{o}C, rad tolerant!

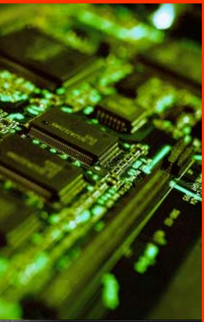
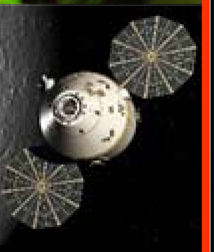
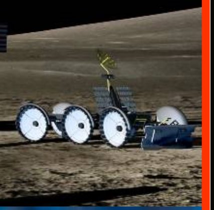
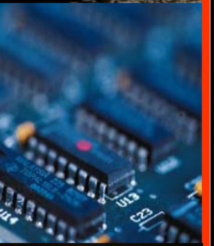
Supports MANY Sensor Types:
Temperature, Strain, Pressure, Acceleration, Vibration, Heat Flux, Position, etc.

Use This REU as a Remote Vehicle Health Monitoring Node

A notional Solar Electric Propulsion (SEP) System – an Earth-Moon System "Solar Clipper" – in operation, transporting large space systems to GEO

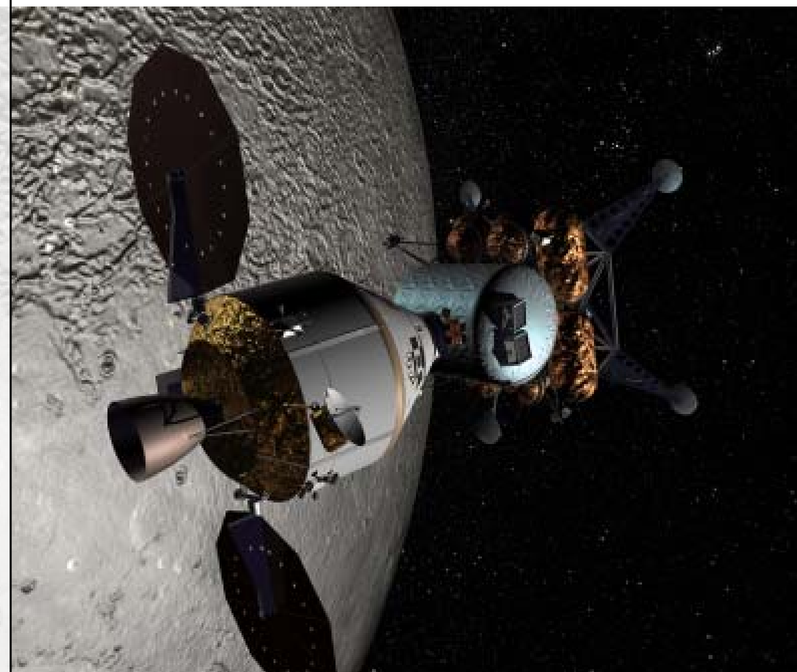


A notional In-Space Cryogenic Propellant (ISCPD) System – a "Depot" – in operation, providing space resources to Earth Neighborhood Missions

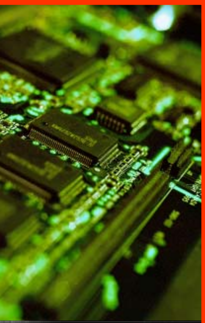





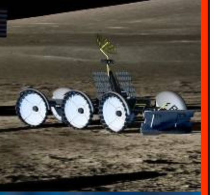
RHESE Summary

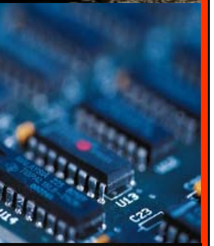
- RHESE's products are developed in response to the needs of **multiple Constellation program elements.**
- An avionics application-dependent trade space is defined by:
  - Radiation Hardening by Architecture using COTS processors, and
  - Radiation Hardening By Design using Rad-Hard processors.
  - Considerations include performance requirements, power efficiency, design complexity, radiation
- Radiation and low temperature environments currently 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.
  - The NEDD bases much of its radiation environment data on CREME96 output.
- 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).