Radiation Capability Responses to RFI #NNH09ZDA008L

Europa Jupiter System Mission
Instrument Workshop

July 15-17, 2009

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Sandia National Laboratories
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Sandia National Labs: Radiation Capabilities for the Europa Jupiter System Mission

Highly-reliable radiation-hardened microelectronics required for nuclear weapons are well suited for mitigating the harsh EJSM radiation environment. For more than 50 years, Sandia has been responsible for the development, design and maintenance of several thousand parts found in any given nuclear weapon system, including radiation-hardened microelectronics. In support of this mission, Sandia National Laboratories has a significant role in advancing the state-of-the-art in microsystems research and development. The microsystems incorporate radiation-hardened microelectronic devices and components designed to withstand total ionizing doses exceeding 1Mrad(Si). In order to withstand this level of radiation, Sandia applies its expertise in radiation effects (on-site and off-site testing), radiation reliability physics, wafer-level reliability, device and process modeling, COTS (commercial off the shelf) parts qualification, failure analysis, packaging, and rad-hard by design techniques. In addition, Sandia offers a fully qualified silicon-on-insulator (SOI) radiation-hardened complementary-metal-oxide semiconductor (CMOS) integrated circuit technology realizing digital, analog, and mixed-signal circuits designed in our accredited Trusted Design Center. These capabilities can greatly assist and support the radiation risk mitigation necessary for the EJSM to be successful in the harsh planetary environment.

Capabilities and Expertise Applicable to EJSM

Our radiation-hardened CMOS process is the foundation of Sandia's rad-hard microelectronics program. There are two efficient and effective avenues to design in this technology: one is using the structured application-specific integrated circuit (sASIC), called the ViArray, and the other is through Sandia's Multi-Product-Wafer (MPW) program. The ViArray is a metal-via configurable, fabric-like structure requiring only one reticle to fully define circuit function. Using the ViArray, product delivery cycle times are greatly reduced in comparison to custom ASICs, first pass yield is more likely and product development is more cost effective (one reticle, fewer wafers, faster cycles of learning). Low power applications benefit from unused transistors in the ViArray, which minimizes power consumption, static current, and photocurrent effects. Sandia's MPW services combine a number of different integrated-circuit (IC) designs on a single reticle set. Sharing mask and wafer resources reduces the cost per design and makes it more cost effective to produce ICs in low quantities. Sandia National Laboratories' MPW program offers access to its Trusted Design Center and its ISO 9001:2000 certified, high-reliability ASIC production facilities.

The Radiation Physics, Technology, and Assurance department at Sandia National Laboratories maintains 4 gamma ray radiation sources, including two ^{60}Co sources and two ^{137}Cs sources; these are routinely used for radiation qualification of Sandia and commercially fabricated ICs, as well as for basic studies of the physical mechanisms responsible for radiation effects in semiconductor devices. Three Aracor 4100 X ray irradiators are especially well suited to wafer-level radiation studies. Single-event effect testing is typically performed off-site at large heavy ion or proton accelerator facilities. The department is working on an MOS radiation sensor, the RadFET that is more integrable than typical dual-dielectric dosimeters, with sensitivities and device characteristics (including no requirement to be biased during exposure) that can be tailored to meet an array of real-world applications – such as the EJSM. Since it does not need to be biased except during reading, the component is inherently excellent for low power applications – another key advantage for the EJSM.

Sandia has expertise in the design, development and production of radiation-hardened power electronics and has delivered rad-hard DC-DC converters for space-based systems. Sandia is currently developing rad-hard, very low on-resistance and gate capacitance, novel power MOSFETs for the design of high-efficiency, high-frequency switching converters to provide reduced mass and volume space

power systems that deliver high-current, low-voltage power regulation. In addition, Sandia is developing radiation-hardened, high voltage (>20V) CMOS silicon-on-insulator (SOI) technology for the design and development of space-system power electronic controller integrated circuits.

Sandia has the capability to design, grow, fabricate and test THz quantum cascade lasers for use as a local oscillator at frequencies between 2-5 THz. We have experience in integrating these lasers with rectangular waveguides, making and testing integrated THz circuits, and using the lasers as local oscillators. We can reliably produce lasers with greater than 1 mW output, but we have not optimized packaging or heat sinking. The devices are reaching the maturity level required for a research instrument for space missions and we are in discussions with space related institutions to work out the space related issues.

The Advanced Microsystems Packaging Department actively engages in advanced packaging research and development, and packages and assembles a diverse suite of components, including: MEMS; compound semiconductors; optoelectronic and advanced photonic devices; micro-sensors; RF devices; and analog, digital, and mixed signal high-reliability application specific integrated circuits (ASICs). The packaging department has a proven record of successfully engaging in Class S/V assembly for past space missions (e.g., Galileo, and various satellite projects), and is currently a recognized leader in tin whisker mitigation strategies. Sandia's Component Information and Modeling organization maintains a staff of component engineers with experience in the selection and qualification of COTS electronic components for high-reliability applications. This capability would be useful for up-screening COTS for the EJSM when rad-hard components are unavailable. The organization has several decades of experience supporting space and weapon programs.

Sandia has a strong foundation in device physics and reliability physics. Several auto-probers are used to perform reliability tests such as gate oxide integrity and hot-carrier degradation from -55°C to 300°C.The ability to test large sample populations in parallel reduces the time required to obtain meaningful statistics. This capability can be extended to perform reliability predictions on irradiated parts; this is critical for determining the longer term viability of the EJSM subsequent to its primary goal. Device characterization and model generation in the mK range are also in progress. Defect localization and identifying the nature of defects are the important information provided by the Failure Analysis (FA) Department. Sandia is a leader in developing many advanced FA techniques, in particular laser-based techniques for static and dynamic investigations of silicon integrated circuits (ICs).

Ability to Deliver

Sandia's Microsystems and Engineering Sciences Applications (MESA) Complex is designed to integrate the numerous scientific disciplines necessary to produce functional, robust, integrated microsystems and represents the center of Sandia's investment in microsystems research, development, and prototyping activities. Our customer base includes: Nuclear Weapons NNSA/NA10, Non Proliferation NNSA/NA20, DARPA, Department of Defense, and Homeland Security. MESA specializes in developing and delivering low-volume, high-consequence, high-trust, custom products:

- Strategic radiation-hardened custom integrated circuits (ICs);
- Digital/analog/mixed-signal/RF ICs, Trusted products and designs; 5-level MEMS (Micro Electro Mechanical Systems – i.e., sacrificial surface micromachining including the first space-qualified MEMS product; Qualified COTS; Failure analysis/reliability physics; Advanced packaging; Specialized sensors;
- MESA has delivered over 30,000 Trusted microsystem components to Sandia's national-security customers since 2006.

Request for Information: NNH09ZDA008L (Radiation Capabilities for the Europa Jupiter System Missions)

1.0 **Submitter**: Northrop Grumman Electronics Systems (NGES), Advanced Technology Laboratories (ATL), Baltimore, MD; POC: Michael Fitzpatrick, 410-765-7469, m.fitzpatrick@ngc.com

2.0 **Capabilities Statement**: NGES has been developing and producing state-of-the-art microelectronic circuits since the late 1960's for critical defense and aerospace systems. These devices include a number of radiation hardened Application Specific Integrated Circuits (ASICs) as well as standard products for DOE, DOD, and NASA applications. The NGES ATL facility has a very long history of providing radiation hardened heritage (TRL 9) components over the last 40 years and has the required capabilities to support EJSM spacecraft applications.

3.0 **Description of Capabilities**: Attached to this capabilities summary sheet you will find an overview of our ATL facility and general capabilities. Also, you will find the first page of several standard product component datasheets that describe devices (more in Section 4 below) that are in production today which fill needed functional slots for the EJSM electronics and possess the required radiation hardness and low power to needed for ultimate mission success. Due to the seven (7) page limitation for this response, only the first page of the datasheet is provided. Full datasheets for these products can be found at http://www.es.northropgrumman.com/by_capability/electronics/microelectronics/index.html or by contacting the RFI submitter POC.

4.0 **Maturity Level of Technologies**: The maturity levels for the standard radiation hardened products with front-page datasheets attached are discussed below: NGCL3571 and NGCP3580 Radiation hardened analog MUXes – Both of these devices are currently in production. The NGCP3580 is being used in an Aeroflex standard product family of multiplexor multi-chip modules The NGCL3571 is TRL 9 with NASA and AF (SBIRS High) flight heritage. The W28C64 and W28C256 radiation hardened EEPROMs are TRL 9 with flight heritage on a number of DOD systems including AEHF, NPOESS, GPS, etc. and are also designed into several NASA programs including JWST and LWS. In addition, these EEPROM devices have been used in other DOD contractor standard product lines (INUs and Star Trackers) which have been delivered to a multitude of flight systems. The W28C0108 1Mb EEPROM is TRL 8 with flight hardware expected to ship by the end of 2009.

5.0 **Past Experience**: As indicated in section 1.0 above, NGES ATL has been delivering state-of-the-art radiation hardened microelectronics to the DOE, DOD, and NASA community for over four decades. The extensive use and space heritage of the standard products described herein is evidence of our capabilities and commitment to the United States military and aerospace community.

The Northrop Grumman Advanced Technology Laboratories (ATL)

Figure A1 Northrop Grumman's ATL in Baltimore, MD

The mission of the ATL is to provide affordable, *discriminating*, high technology microelectronics and solid-state devices that meet customers' requirements and cannot be purchased readily from the commercial marketplace.

The ATL is conveniently located near the BWI Airport in Baltimore, MD. Over 200 highly trained employees staff this facility that is ISO 9001 certified for integrated circuit design, maskmaking, wafer fabrication, and test, assembly, and screening. The fabrication facility, consisting of over 21,000 feet of class 100/10 cleanroom area, houses a 4-inch GaAs and a 6-inch silicon line. This foundry is also one of the few in the United States to receive the DoD's highest level (Category 1A) of accreditation as a Trusted Foundry.

The ATL does over $30M in annual integrated circuit business and has been supplying state-of-the-art devices to the military and aerospace sectors for over 35 years. Last year alone, the ATL delivered over 500,000 production devices for use in critical defense systems.

The ATL offers "One-Stop-Shopping", with capabilities starting at conceptual design through delivery of fully screened hi-rel integrated circuit products. The design cycle is fully automated using Mentor and Cadence (silicon) and Cadence and Agilent-Eesof (GaAs) EDA software. An in-house MEBES system is used for "quick-turn" maskmaking. Multiple processes (CMOS; CMOS/SONOS; Bipolar; BiCMOS; TO & ITO CCD processes; SiGe) are supported on the silicon fabrication line as well as the GaAs (PHEMT; MESFET; HBT; MHEMT) line. For a number of these processes, customer design libraries and on-site training is available, if the customer wishes to do their own design. Testing of up to 144-pin silicon devices at speeds of 125MHz is supported as well as 100GHz wafer probe for GaAs devices. Devices can be packaged in a variety of ceramic package styles (FP, LCC, PGA, and DIP) as well as being supplied as Known Good Die (KGD). Full screening and QCI testing is available from commercial to Class-S flows.

Figure A2 The ATL Offers "One-Stop-Shopping" by Offering Design, Maskmaking, Wafer Fabrication, Test and Assembly, and Screening Under one Roof

By offering many processes, and variants thereof, the ATL can provides a very flexible foundry capability that supports a wide range of device types (digital, analog, mixed-signal, memories, visible sensors, RF, as

well as MMICs) with a wide range of performance (feature sizes ranging from sub-100 nm to several microns) that can operate over a variety of voltages (< 1 volt to over 100 volts). Because of this flexibility, almost any type of integrated circuit device requirement can be addressed.

In addition to providing a variety of ASIC devices, the ATL also provides a wide portfolio of standard products. In the GaAs area, these include families of MMIC phase shifters, attenuators, drivers, and power amplifiers that operate at frequencies ranging from 10GHz to over 100GHz. In the silicon RF area, a family of L-band and S-band silicon and SiGe pulsed power (up to 1000 watts) devices are available. In the memory area, the ATL manufactures the only family (64K, 256K, and 1M) of radiation hardened EEPROMs available today. In the silicon mixed-signal area, high performance ADCs, radiation hardened high voltage multiplexers, regulators, power conditioning circuits, and a mixed-signal tile array are available.

To sustain advanced capabilities into the future, during 2002 and 2003, the ATL underwent a major internally funded modernization program. As part of that program, the facility was upgraded to support feature sizes down to 0.35 micron. In 2008 and 2009 the facility will again be upgraded to support processes down to 0.18 micron. In addition, using a state-of-the-art direct write EBEAM system, R&D can be conducted at feature sizes below 100 nm.

Figure A3 A Major ATL Facility Modernization Insures State-of-the Art Capabilities for Military Integrated Circuit Development & Production

In addition to supporting production product development and manufacture, the ATL also houses a state-of-the-art R&D capability whose charter is to develop next generation materials and devices. Extensive R&D activity is underway in a number of key areas including wide bandgap semiconductors (SiC and GaN); heterogeneous integration (wafer bonding); advanced MMICs (MHEMT); MEMS; nanotechnology; superconducting electronics, and advanced E/O materials. This focus on the future will insure the most advanced integrated circuit technologies will be available for emerging military systems.

In summary, the ATL has been producing and providing hi-rel microelectronic devices to critical military systems for over 35 years. These devices have supported a wide spectrum of *unique* system requirements. Being part of a major defense company, the ATL is committed to being a *trusted* supplier of these critical microelectronic devices for the system life cycle. This commitment is significantly longer than the life cycle of a typical commercial (COTS) device which greatly reduces DMS issues and keeps many of our nations critical DoD systems functioning at peak performance without missing a beat.

May 22, 2009

Response to Request for Information: NNH09ZDA008L

Northrop Grumman Electronic Systems Radiation Capabilities for the Europa Jupiter System Mission

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Cage Code:	Baltimore: 97942, Azusa: 70143
Number of Years in Bus.:	50 years (Space)

Executive Summary

Northrop Grumman Systems Corporation, Electronic Systems Sector (NGES) is pleased to submit this capability statement regarding Radiation Capabilities for the Europa Jupiter System Mission (EJSM). The Space & ISR Systems Division (SISD), with headquarters in Baltimore, MD and facilities in Azusa, CA, is a world leader in developing space-based sensing systems for civil and military applications. Over the past five decades, SISD has designed, developed, integrated, tested, and provided operational support for more than 100 visible, infrared and microwave space-based instruments. These missions have allowed us to assemble a staff of experienced design, fabrication and test personnel and develop world-class facilities that will be leveraged in our collaboration to develop instrumentation within the harsh radiation environment expected for the EJSM spacecraft

Relevant Space Payload Experience:

Space Based Infra-Red System (SBIRS-High): SBIRS-High is a TRL-9 space surveillance early warning system designed to provide missile warning, missile defense, technical intelligence, and battlefield characterization. The system includes geosynchronous earth orbit (GEO) and highly elliptical orbit (HEO) payloads with cryogenically cooled short- and medium-wave infrared sensors. With the HEO sensors in a Molniya orbit, they operate through a harsh

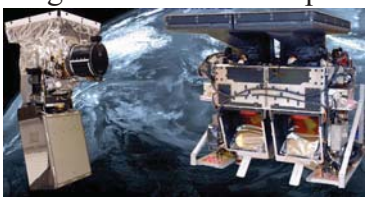

Figure 1. SBIRS Sensors

radiation environment daily, and the total system has a classified nuclear event survivability requirement.

Figure 2. Orbview 3 Payload

Orbview 3&4: NGES designed, built, integrated and tested the high-resolution panchromatic and multispectral OrbView-3&4 imagers, which included optics, focal plane assemblies, focal plane electronics and digital processing electronics. Integration and test facilities were also provided. NGES has multiple development and production contracts for Charge Coupled Devices (CCD), AP/ADCs, Level Shifters, and related technologies.

Microwave Sounders: NGES has designed, developed and manufactured millimeter wave instruments for NASA, NOAA, and the Air Force for over 45 years, including the Advanced Microwave Sounding Unit (AMSU-A, TRL9) and the Advanced Technology Microwave Sounder (ATMS-TRL8) instruments. SISD offers industry leading expertise facilities, test equipment in place from on-going ATMS work.

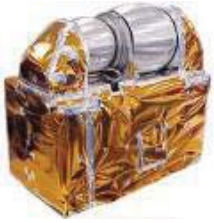

Figure 3. ATMS

Figure 4. Space Radar

Space Radar: NGES built the original SEASAT, Shuttle Imaging Radars A and B, and was the selected payload provider for the DoD/NRO Space Radar Program. Over $400M of investment was applied to develop a multi-channel high-resolution radar electronics unit (TRL 6-9) that can be leveraged for the outer planets mission. SISD signed a Space Act Agreement with NASA GSFC in 2008, to leverage Department of Defense (DoD) Space Radar Sensing Technologies for Earth and Planetary Science Applications.

NGES understands the engineering challenges associated with development of space payloads in high radiation environments. Our engineers participated in the recent Outer Planet Workshop held in Pasadena, and we recognize the radiation environment will drive many instrument teams to specialized detectors, analog devices, memory, and active RF components not found in the commercial industry. We have significant in-house device foundry capability to support the development and fabrication of the specialized devices required by science instrument teams. SISD has successfully combined in-house foundry, design, assembly and test capabilities with the best technology and products available from industry partners and subcontractors. The Space & ISR Systems Division represents a "one-stop-shop" for Science Teams looking to develop unique instruments for the Europa Jupiter Outer Planets Flagship mission. NGES looks forward to the opportunity to support a PI-led Outer Planets Instrument team.

Response to Request for Information
Radiation Hardness by Design with Commercial Microelectronics

Boeing Solid-State Electronics Development (SSED)
P.O. Box 3707, MC 42-57
Seattle, WA 98124-2207

EXECUTIVE SUMMARY

Over the past 20 years, The Boeing Company Solid-State Electronics Development (SSED) organization in Seattle, Washington, has established a world-class application-specific integrated circuit (ASIC) development center with several hundred successful ASIC design projects completed. SSED develops integrated circuit products for programs throughout the company as well as for external customers. The organization has the required resources and prerequisite expertise to complete the design and development of digital and analog radiation-hardened ASICs and transition them into mission-scale production.

SSED provides high-payoff capability to defense and aerospace programs that require high-performance, complex digital, analog, and RF system-on-chip (SoC) functionality (Figure 1). This functionality includes ultra-low power consumption, high reliability, and radiation hardness. The SSED-maintained ASIC development infrastructure includes experienced personnel, industry-standard ASIC project management and control processes, advanced integrated design automation tools, libraries and intellectual property (IP), test and characterization facilities, and fabrication and packaging sources. This validated infrastructure is ready for production development of virtually any type of ASIC.

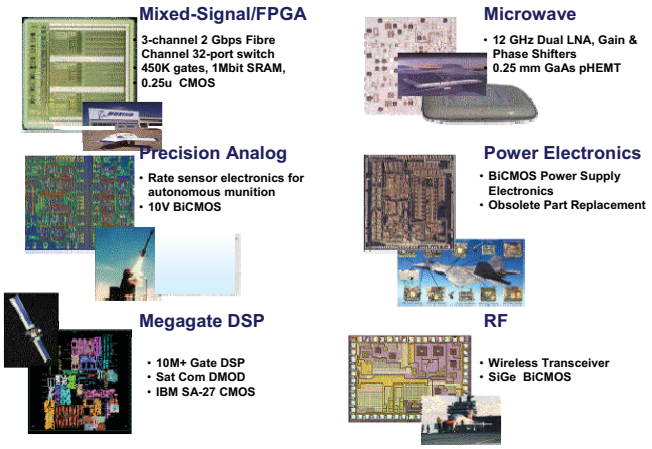

Figure 1. SSED Diverse System-on-Chip Capability

SSED engineers (a staff of more than 40 ASIC specialists) have extensive experience in design, modeling, fabrication, packaging, test, qualification, and production support for a wide range of advanced digital, analog, and RF ASICs. SSED ASIC products are in production on most Boeing commercial airplanes and on numerous production DoD and space systems.

The SSED organization has completed designs in SOI (12S0), CMOS (9LP, 9SF), GaAs, SiGe (8HP, SBC18H2), InP, bipolar, and other semiconductor processes—fabricated at more than a dozen foundries. SSED has strategic partner relationships with multiple foundries, including the IBM Corporation, and it is a frequent user of the Government's Trusted Foundry Access Program.

Most team members have, at minimum, DoD Secret clearances. All proposed design, fabrication, packaging, and test facilities are located within the continental United States and are fully capable of supporting ITAR-controlled and classified work.

Response to Request for Information
Radiation Modeling, Simulation, and Test for the Europa Environment
The Boeing Company
5301 Bolsa Avenue, Huntington Beach, CA 92647

EXECUTIVE SUMMARY

The Boeing Company is pleased to submit this request for information (RFI) response highlighting our experience and capabilities in modeling, simulation, and testing of electronics and avionics for extreme radiation environments. In the design of our commercial and military aircraft and spacecraft platforms, we place special emphasis on understanding and mitigating the effects of radiation, and we have developed the required modeling and simulation tools, test facilities, and expertise for analysis and mitigation of radiation effects. These capabilities at Boeing are directly relevant and applicable to NASA missions in the Europa environment.

Boeing pursues an integrated system approach to analyzing and mitigating radiation effects. First we evaluate, by simulation, the ambient environment expected during the planned mission, including temperatures, radiation, pressures, and sporadic events (e.g., solar flares). The computer-aided design of our systems includes definition of material properties, used in the ray-tracing Modified Elemental Volume Dose Program (MEVDP) code. From these, we develop a quantitative estimate of the primary radiation that penetrates to the interior of the spacecraft and associated secondary effects. For the most critical locations in the spacecraft, the energy deposition pattern of impinging high-energy radiation particles is modeled accurately using Monte-Carlo radiation transport codes (e.g., NOVICE). Energetic interactions between impinging particles and the target materials in the spacecraft (and the resultant stopping ranges) are modeled by radiation transport tools (e.g., the Stopping and Range of Ions in Matter [SRIM] tool).

This approach provides us with a good estimate of the radiation conditions expected on structural and functional materials, and on electronic components, and it allows us to choose the particle beam test conditions that replicate these conditions with high fidelity. Radiation transport codes are also applied to simulate radiation effects of single-energy particle beams used in tests, which further validates that the chosen test facilities indeed replicate the relevant environments encountered during the space mission.

In the extreme, radiation incident on electronics can cause permanent defects in the semiconductor crystal or cause trapped effects that degrade the electrical parameters of the device. More common are transient charge-clouds induced in one device (or a neighboring cluster), which translate into single-event upsets (SEU) that cause temporary malfunction and loss of data. Technology computer-aided design (TCAD) simulation tools can provide good simulation of these effects as a function of time after the impact of one incident particle. However, numeric complexity of the simultaneous equations solved in TCAD limits this approach to single devices or small circuits. For larger circuits, TCAD results are translated into a single-event strike model for the device, which is then applied in the Simulation Program with Integrated Circuit Emphasis (SPICE) tool as a time-dependent artificial current source. This approach allows us to simulate medium-size circuits, albeit with reduced accuracy. Complex digital circuits that are particularly affected by SEUs (such as in digital signal processors) are modeled by dedicated software tools.

This approach enables us to evaluate the radiation effects mechanisms at multiple levels to correlate with hardware test results and to implement a multilayered approach of mitigation—at the technology level (radiation-hardened by process), at the device level (radiation-hardened by device topology), and at the circuit level (radiation-hardened by circuit design).

For more than 20 years, Boeing has developed in-depth expertise, tools, and facilities for the modeling, simulation, test, and evaluation of radiation effects. We also utilize the major cyclotron facilities in the United States and have maintained a long-term collaboration with the Institute for Space and Defense Electronics (ISDE) at Vanderbilt University, a world-leading research center on radiation effects. Recent examples of our activities in technologies, methods, and processes for radiation-hardened electronics include development of radiation-hardened electronic technology in the foundry at HRL Laboratories in Malibu, California, and development of radiation-hardening-by-design (RHBD) technologies for DARPA, in collaboration with BAE Systems and Vanderbilt University.

Our models for space environments and our simulation tools are supported by the specialized expertise of Technical Fellows at Boeing. The models are upgraded as new data and new models become available from research activities at NASA, DoD, and Boeing. Boeing Radiation Effects Laboratory (BREL) in Kent, Washington, has test facilities that replicate space radiation environments, including cobalt-60 (^{60}Co) sources for preliminary assessments; the dynamitron for producing accelerated electrons, protons, and low-Z ions, in pulsed and dc-beam modes; neutron generators; and large-volume vacuum test chambers for accelerated radiation, ultraviolet, and thermal tests. The Extreme Environments Test Facility at Boeing Huntington Beach, California, includes a helium cryostat for medium-sized subsystems (up to 1 ft^3), which can also be adapted for radiation tests. Boeing also has an established Nano-Sat program, which includes the CubeSat Test Bed, and has an ongoing activity focused on establishing a platform for testing radiation effects aboard a cubesat in the Van Allen Belts.

Boeing personnel at the Boeing Satellite Development Center in El Segundo, California, and BREL have performed single-event effect (SEE) tests at many major cyclotron facilities in the United Sates (e.g., Brookhaven, Texas A&M, UC Davis, Berkeley, Sandia). We have also developed the tools and infrastructure required for computer-based device control, high-speed data acquisition, and automated analysis of results compared with the predictive simulations.

The effects of temperature and radiation are interrelated. Cold temperatures typical of the ambient environment at Europa certainly affect the formation and the dissipation of charge-clouds generated by the impacting radiation particles. For the past 5 years, Boeing has been part of the development team for the Silicon Germanium (SiGe) Electronics for Extreme Environments project, led by Professor John Cressler from Georgia Institute of Technology. Funded under the NASA Radiation Hardened Electronics for Space Environments (RHESE) program, the team develops SiGe electronics that can operate at cryogenic ambient temperatures, without warm boxes. This program includes a robust activity for simulation and testing of radiation effects, in particular at low temperatures. Activities include ^{60}Co tests at liquid nitrogen temperatures; beam tests performed on SiGe integrated circuits in the portable cryogenic dewar built at Vanderbilt University; long-duration exposure of SiGe components to low Earth orbit space radiation in the NASA Materials International Space Station Experiments (MISSE); and using the ModLyng software platform to simulate SiGe application-specific integrated circuits, including models of radiation effects, developed at Lynguent, Inc. Boeing plans to use these tools and facilities beyond the SiGe program to test and evaluate the effectiveness of our RHBD processes.

In summary, Boeing follows an integrated approach, combining modeling, simulation, testing, and validation at multiple levels—from a single transistor to a complete spacecraft system. We believe that this approach, coupled with our existing capabilities and infrastructure, are directly relevant and applicable to NASA missions in the Europa environment.

Boeing Radiation Effects Lab (BREL)

http://www.boeing.com/assocproducts/radiationlab/

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(206) 544-0329

The Boeing Radiation Effects Lab (BREL) is pleased to offer our services in the area of radiation effects on electronics including our major radiation test facilities as well as our expertise in radiation environment modeling and shielding design, effects analysis, and design hardening support.

Created in 1963 to support the Minuteman ICBM program, BREL is the largest radiation test lab in private industry and is comprised of several major accelerators as well as multiple isotope irradiators. In addition, Boeing lab personnel routinely utilize outside national facilities for additional radiation testing. For over 45 years, BREL has been meeting government requirements for radiation hardness design, test, qualification, and assurance in the areas of nuclear and space radiation effects.

Radiation Test Facility for Effects Simulation & Testing on Electronics/Materials

A summary of our radiation test facilities regularly used for radiation effects studies is shown below.

In House Test Lab Capability:

Total Ionizing Dose	• Co60 irradiators:
	  • Gammacell220RA
	  • Gammacell220Excel
	  • Shepherd 484
	• Dynamitron accelerator

Neutron Single Event Effects	• 14 MeV Neutron Generator
Low Energy Combined Effects	• Custom test chamber (e-, p+, UV, and solar)
Dose Rate	• 10 MeV linac • FX-75 Flash X-ray

Outside Testing Experience:

Heavy Ion Single Event Effects	• Lawrence Berkeley Lab • Texas A&M
Proton Single Event Effects or Displacement Damage	• UC Davis • Indiana University • TRIUMF
Neutron Single Event Effects	• Los Alamos Weapon's Neutron Research facility • TRIUMF
Neutron Displacement Damage	• White Sands Missile Range

Radiation Effects and Analysis Expertise

Engineering expertise is routinely applied to address customer's needs to help define environments, ensure proper radiation simulations, establish optimal effects measurements, as well as suggest design mitigation or hardening approaches. Some specific examples of areas of expertise are listed below.

Modeling and Analysis

- Digital Microcircuit SEE Analysis/Rate
- Space Radiation Environment Modeling
- Survivability/Vulnerability Analysis
- Radiation Transport
  - MCNPX transport modeling
  - Cosmic Ray transport
  - Graded-Z shield design

Radiation Effects on Devices/Materials

- Total Dose ELDRS
- Degradation of Solar Cells
- Darkening of Optical Coatings
- Breakdown of Polymeric Materials
- Darkening of Thermal Control Coatings
- Synergistic Effects of Combined Radiations
- Spacecraft ESD Simulation and Effects

EJSM Applicability

Several key areas of expertise may be of special value for the EJSM mission. These include:

Material Surface Damage Effects

A mature test capability for material surface damage effects in BREL's Combined Radiation Effects Test Chambers (CRETCs). Multiple test chambers for combined effects exist at BREL with varying capabilities that include: test articles as large as 18 inches across, in-situ reflectance spectroscopy measurements, and in-situ electron-proton beam spectrum measurements.

Graded-Z Shield Design

The high total dose levels given for EJSM behind aluminum shielding may be dominated by a high energy electron environment from the Jovian radiation belts. Such an environment is more weight effectively shielded by a "Graded-Z" shield design. This three layer shield of Low-Z/High-Z/Low-Z materials maximizes electron attenuation with minimal Brehmsstrahlung x-ray production. Such shields offer significant weight reduction for electron rich environments.

Shielding Produced Secondary Radiation Effects

BREL utilizes Los Alamos' MCNPX radiation transport code for shielding design and analysis that includes secondary radiation generation within shielding material. High energy cosmic rays, as sell as high energy electrons and protons, will create significant secondaries of all types, especially neutrons. BREL is currently developing light-weight shielding design tools using MCNPX.

Maturity Level

BREL has been in continuous operation for over 45 years. Many government programs have been supported with nuclear and space radiation effects support as described above. This testing has developed an extensive component database and index with over 1500 entries available for BREL engineers to:

- Identify components previously tested
- Locate existing test data or test reports
- Provide quick reference to similar components previously tested
- Allow efficient software and hardware development for new test items
- Support survivability/vulnerability assessments of circuits and subsystems

Investments

BREL continues to support diverse programs and benefits from continuous investments that include:

- Use of Boeing's General Purpose Test Equipment pool of company-wide inventory of data acquisition and measurement equipment of the latest bandwidth and sophistication
- Facilities upgrades (amounting to many millions of dollars over the years) of:
  - Optical spectroscopy
  - Beam characterization and dosimetry
  - Test chamber upgrades
  - Analog, Digital, and Mixed-Signal IC automated testers
  - Multi-channel, high bandwidth portable controller/data acquisition for SEE testing
  - Accelerator upgrades, control, and safety systems

Program Experience

Major programs supported include NASA MISSE 1 thru 7, GPS, National Missile Defense (GMD), International Space Station, Inertial Upper Stage, Air Launched Cruise Missile, B-1B, B-2, B-52, Minuteman and Peacekeeper missile systems as well as many classified military programs. BREL performs testing for many outside customers such as Hughes Electronics Corp, Aerojet, TRW, Motorola, Spectrolab and others.

INTRODUCTION

1.0 RADIATION HARDENED NON-VOLATILE MEMORY

Non-volatile memory IC technology, with excellent radiation tolerance, is a continuing NASA technical need. The Europa Jupiter mission has an acute need for a non-volatile memory that can withstand >200 krad (at the die level), have no single event latchup and provide "no SEFI" (Single Event Functional Interrupt, aka hangs) performance. New innovative, rad hard space capable non-volatile memory is a pressing need. The industry has pursued multiple rad hard R&D activities to try to meet these needs, without success, including:

1. MRAM at Honeywell Solid State/Freescale and NVE Corp (1 Mbit)
2. FRAM at Ramtron and Celis Semiconductor (1 Mbit)
3. Chalcogenide memory at Ovonyx Inc. and BAE Systems (2 Mbit ECC corrected, 4Mbit no ECC)
4. Rad hard EEPROM for embedded applications at Peregrine (1 Mbit)
5. Low density NVRAM at Raytheon for Trident D5 (1 Mbit)
6. RHBD FRAM at NxGen/Celis under NASA SBIR (1-2 Mbit)

None of these initiatives meet what NASA would really prefer: a modern, dense and radiation hardened non-volatile memory. Modern and dense refer to memories that are in the size of "Gigabit", not "Megabits", with a 512 Mbit part likely being acceptable. Space Micro proposes to design and build a radiation hardened flash integrated circuit, using Radiation Hardened-by-Design (RHBD) techniques that will meet Europa's radiation requirements. Space Micro is teamed with Arizona State University's (ASU) Fulton School of Engineering design team to develop the resulting rad hard flash IC. We term our flash IC the "RH-eFLASH". Details are described in the proprietary "Technology Description" section herein.

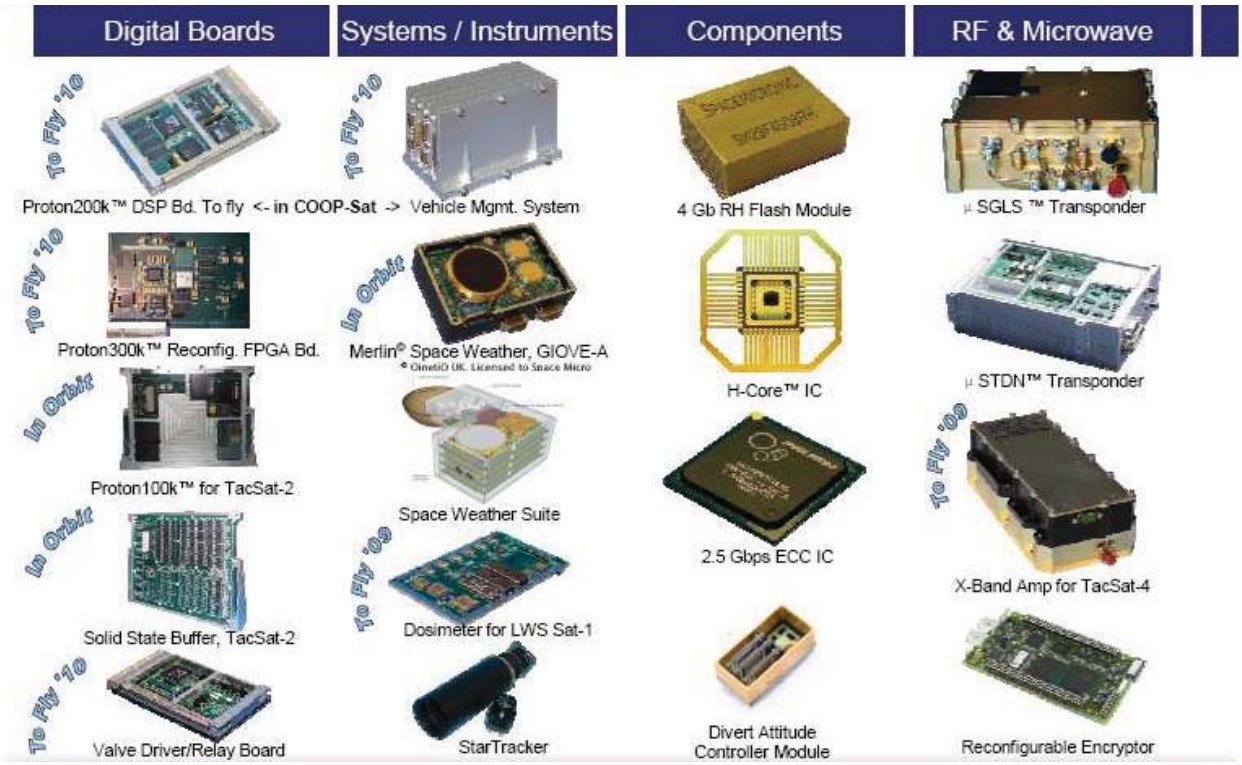
Space Micro Inc is a manufacturer of radiation hardened components, boards and subsystems. Our organization specializes in designing and manufacturing very difficult satellite electronics, all radiation hardened and built to survive the requirements of satellites and launch vehicles. For example, Space Micro built the first fully rad hard computer that has >1,000 MIPS performance and is currently shipping flight computers with >4,000 MIPS performance. We have developed a 4 Gbit radiation hardened flash product, the SM29F4G, which has the basic performance needed for the Europa mission, with a single exception. This exception is important, as its total dose tolerance is a respectable 100 krad, but this is not sufficient for Europa. Other related rad hard IC products are our RH-eDRAM, which is a fully rad hard SDRAM (and DDR2) memory integrated circuit, which is currently under development with Air Force funding. A list of some of our developments is shown in Figure 1.

Space Micro has the capabilities to design and manufacture the RH-eFLASH integrated circuit, plus a memory module stacking multiple die and/or a memory board (solid state buffer). This design will follow the overall design and manufacturing methodology as our RH-eDRAM and our SDRAM based solid state buffer.

Fig 1. Space Micro Rad Hard Projects

Product or Design	Customer	Project Description
Linearized 10-Channel X-Band Power Amp	NRL-OSC	TacSat 4 (Delivered for Flight)
Dosimeter	NASA	Living W/ Star Program (Delivered for Flight)
Proton100k development	AFRL	Development of SEU mitigation - TTMR
Proton100k Flight Unit	AFRL TacSat 2	TacSat 2 Imaging Payload (In Orbit now)
Rad Hard Image Processer & 8 GB Buffer	AFRL TacSat 2	TacSat 2 Imaging Payload (In Orbit now)
Proton200k Flight Unit	Goodrich ORS-SAT-1	Classified Imaging Payload (for flight in '10)
Proton200k Flight Unit	AFRL Coop-Sat	Avionics Suite w/ GPS, IMU (for flight in '10)
Proton200k Controller	ATK for DOD	Multistage, adaptable controller
Proton200k Flight Unit	QuickReach Rocket	Signal Processing Node - Proton200k
Proton200k & Flight Experiment	PRT/MDA	Microelectronics Test Bed Experiment
Proton100k Flight Unit	NASA Space Station	RH Medical Flight Computer
Rad Hard Valve Driver	QuickReach Rocket	cPCI valve & relay driver card
Proton100k Flight Unit	Galilio Avionica	ESA ISS RH Computer
Proton200k Flight Unit	Lockheed Martin	ANGELS Nanosat C&DH Computer
MiniSGLS Transponder	Lockheed Martin	ANGELS Nanosat Radio (NRL design)
Hardened Core RH IC	NASA/MSFC	SEFI mitigation in COTS Microprocessors
Command-Control Avionics System	Air Launch	Proton200k based avionics rack
Rad Hard Reconfigurable FPGAs	NASA/GSFC	FPGA rad hard techniques - Xilinx FPGA
Rad hard high speed ECC chip	AF Rome Labs	Space hardened Integrated Circuit
Rad Hard Flash Memory	DARPA	2 Gbit Rad Hard Flash Memory
Radiation Sensor	NASA AMES	Resetable & Programmable Rad Sensor
Rad Hard level shifter IC for space	AFRL, Kirtland AFB	Space hardened Integrated Circuit
Rad Hard Star Tracker	AFRL	APS based image sensor and Proton200k SBC
Reconfigurable Microwave Array IC for Space	AFRL, WPAFB	Space hardened Integrated Circuit
Rad Hard Divert Attitude Controller System	MDA	RH DACS for rockets
Dose Rate Proton200k SBC	MDA	Hardening Proton200k SBC to weapons specs
Weapons Hardened Dual-Core PowerPC SBC	MDA	4,000 MIPS commercial processor based SBC
JTRS Filter	AFRL	RF Filters for JTRS radios
Universal Transponder	NASA Glenn	Universal transmitter/Receiver

2.0 SPACE MICRO RADIATION HARDENED PRODUCTS (data sheets on Space Micro Web)



Space Micro has developed numerous radiation hardened products, qualified for satellite and launch vehicle use. Shown below are some products/projects that are relevant to the NASA Europa mission

Rad Hard Flash Module

The SM29F4G radiation hardened flash module was developed under Space Micro IR&D and DARPA funding. This module contains our "HF-Core™" controller and multiple flash integrated circuits. The SM29F4G is a 4 gigabit flash unit, designed to have a standard NAND flash interface and is capable of 100krad, no SEL, no SEFI and EDAC corrected SEU, with standard flash performance. The unit is currently being built as a SiP module into Space Micro's Proton200k computer and is scheduled for flight in early 2010 on multiple Air Force missions. The unit can be stacked, using space qualified stacking technology, and can fit into a 0.9 x 0.6 x 0.45 inches module size form/fit/function the same footprint as a commercially available 4Gb 48-lead TSOP Flash Memory.

Fig 2 SM29F4G RH Flash

Rad Hard Single Board Computer – Proton200k

The Proton200k™ is the space industry's fastest space computer/processor card available, featuring 4,000 MIPS and 1GHz performance under 90% common space orbit radiation exposure and operating at 7 Watts peak power. Fast and low power payloads such as imaging and video missions need on-board processing for the massive amount of acquired sensor data. The de-facto RH space processor boards typically yields 200 MIPS, and is not at all capable of such duties.

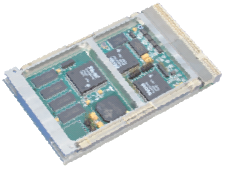


Fig 3 Proton200k™ RH DSP SBC

Rad Hard Solid State Buffer

Space Micro's Solid State Buffer is a 64 Gbit radiation hardened board, based on radiation tested SDRAM and radiation hardened electronics design. This board uses a dual port bus configuration, with a 2 Gbps high speed interface and a 32 bit, 133 MHz PCI interface. The SSB was developed for the Air Force and has successfully flown in Tacsat2. Another version is currently in development for ORS Sat-1 and is scheduled to be launched in early 2010.

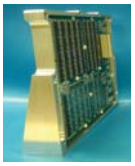


Fig 4 Rad Hard 64 Gbit Solid State

Rad Hard FEC CODEC Integrated Circuit

Space Micro has successfully designed and manufactured a 2.5 Gbps forward error correction CODEC, that includes high-speed EDAC and the "refresh hardening" technique. The resulting integrated circuit was manufactured on 0.13um TSMC foundry, combining our knowledge to RHBD, process selection, EDAC and "refresh hardening". This effort was conducted for AFRL, under contract number FA8750-05-C-0119 and resulted in a RHBD IC similar to this proposal, except the error correction is done a high-speed communication link instead of stored Flash memory.

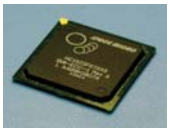


Fig 5 Space Micro's Refresh Hardened FEC CODEC

1. EXECUTIVE SUMMARY | NON-PROPRIETARY

Lockheed Martin Nanosystems (LMN) is a leader in the development of carbon nanotube nanotechnology electronic solutions for future space applications. One of the major benefits of our technology is that significant total dose hardness has been demonstrated for both memory (NRAM™) and logic electronic technologies. For the Europa Jupiter System Mission (EJSM), this capability will result in memory devices that meet the shielded design environment, but in addition could also meet the requirement for the JEO 2008 reference environment without shielding.

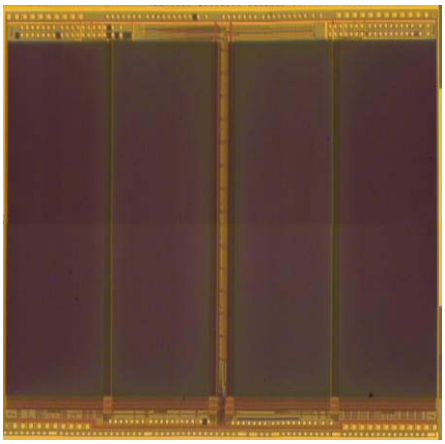


Figure 1: Optical image of 4Mb NRAM™

The ramifications for the EJSM system are profound: reduction or elimination of shielding, less electronic redundancy, and reduced layout penalty all resulting in lower mass and power consumption. No other nanotechnology company has been able to match our progress made in the development and manufacturability of nanoelectronic devices, specifically NRAM™, fabricated in three Class 1 semiconductor foundries.

LMN has strived to insert NRAM fabrication processes into standard CMOS process flows, taking advantage of existing process modules wherever possible or making modifications within the process capabilities of existing modules. The advantages of the LMN approach for the EJSM program are several; ease of scale up to meet the production needs for space qualified hardware, lower unit production costs, and alternative rad-hard memory technologies. Table 1 highlights the TRL achievements for Memory and Logic.

TRL Definition Level	NRAM™	CNT Based Logic
TRL 4 Component/subsystem validation in laboratory environment: Standalone prototyping implementation and test. Integration of technology elements. Experiments with full-scale problems or data sets.	2003	2005
TRL 5 System/subsystem/component validation in relevant environment: Thorough testing of prototyping in representative environment. Basic technology elements integrated with reasonably realistic supporting elements. Prototyping implementations conform to target environment and interfaces.	2004	2005
TRL 6 System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space): Prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application.	2006	2009
TRL 7 System prototyping demonstration in an operational environment (ground or space): System prototyping demonstration in operational environment. System is at or near scale of the operational system, with most functions available for demonstration and test. Well integrated with collateral and ancillary systems. Limited documentation available.	2009	Not complete

Table 1: Summary of TRL level and date of achievement for NRAM™ and Logic

CNT Fabrics

Lockheed Martin Nanosystems can create CNT based nanoelectronic devices by depositing (spin coating) a CNT fabric on a suitable substrate. Figure 2 presents a (a) diagram of the spinning process for the creation of a monolayer conducting fabric and the resulting (b) CNT fabric produced over a trench grating, structure that simulates a basic NRAM™ device. The electrical properties of this fabric can be tailored for the desired application of the nanoelectronic device.

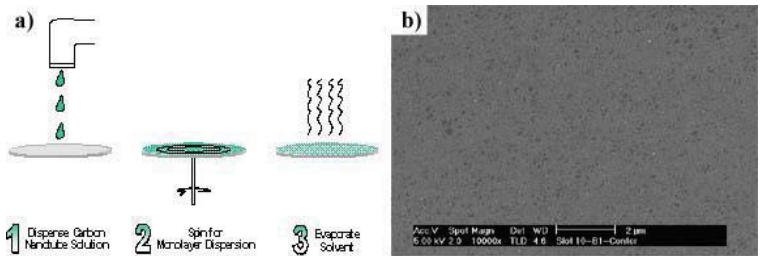


Figure 2: (a) Process for the spin coating of a CNT solution on a substrate to produce a monolayer CNT fabric. (b) SEM image showing a CNT fabric spun-on a wafer with grating trenches etched into the surface.

Discussion of Previous Experience

Lockheed Martin Space Systems is a world class developer of systems for space applications. LM Nanosystems was acquired by Space Systems and are integrating our technology within their processes to produce space qualified technology. On both the NRAM™ and Logic programs we are making full use of Space Systems expertise to assist us in developing reliability and radiation characterization plans to meet the specification for space qualified hardware such as is required for the EJSM program.

Lockheed Martin Space Systems Company has been a supplier of radiation hardened space systems, including NASA deep space missions to Jupiter, for years. As the spacecraft bus supplier for NASA/JPL's JUNO New Frontiers Jupiter mission, Lockheed Martin has extensive recent experience in the design, analysis and verification of systems, subsystems and components that must operate in the Jovian radiation environment.

The ability to model and analyze the design to provide dose predictions at any location in the spacecraft has been developed for JUNO to enable high confidence verification of the design and processes used. In fact, joint activities between JPL and Lockheed Martin mission assurance, avionics, and systems engineering have produced strategies and processes for JUNO design and verification which resulted in an "Excellent" evaluation by the JUNO Critical Design Review Board, with the associated comment "JUNO is the most prepared spacecraft in the radiation control area of all missions we have reviewed" (April 2009).

Lockheed Martin experience in hardware design and development for Jovian missions also includes the JUNO magnetometers as well as the Atmospheric Structure Instrument (ASI), the Nephelometer (NEP) and Net Flux Radiometer (NFR) for the Galileo probe mission to Jupiter. Lockheed Martin's role was(is) to design and build the instrument in conjunction with a university science partner and the system integrator to provide the science investigation with a product that delivers the required science data while withstanding the Jovian radiation environment.

Lockheed Martin looks forward to the opportunity to work with NASA once again on the Europa Jupiter System Mission to provide solutions to this challenging deep space design problem.

Lockheed Martin Radiation Hardening and Test Experience, Capabilities, and Facilities for the Advanced Stirling Radioisotope Generator Controller and Space Systems Electronics

Solicitation Number:	NNH09ZDA008L - Request for Information
Solicitation Title:	Radiation Capabilities for the Europa Jupiter System Mission
Release Date:	April 24, 2009
Response Date:	May 22, 2009

Submitted to:

Planetary Science Division
Science Mission Directorate
National Aeronautics and Space Administration
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May 22, 2009

This response to RFI Solicitation Number NNH09ZDA008L establishes the survivability technical approaches that Lockheed Martin has developed and will implement to ensure that the system performance of the Advanced Stirling Radioisotope Generator (ASRG) Controller will not degrade beyond specified performance boundaries while operating in the natural space radiation environments.

Lockheed Martin Space Systems Company has been a dependable supplier of radiation hardened space systems, including NASA deep space missions to Jupiter. As the spacecraft bus supplier for NASA/JPL's JUNO New Frontiers Jupiter mission, Lockheed Martin has extensive recent experience in the design, analysis and verification of systems, subsystems and components that must operate in the Jovian radiation environment. The ability to model and analyze the design to provide dose predictions at any location in the spacecraft has been developed for JUNO to enable high confidence verification of the design and processes used. Joint activities between JPL and Lockheed Martin mission assurance, avionics, and systems engineering have produced strategies and processes for JUNO design and verification which resulted in an "Excellent" evaluation by the JUNO Critical Design Review Board, with the associated comment "JUNO is the most prepared spacecraft in the radiation control area of all missions we have reviewed" (April 2009).

The Lockheed Martin experience in hardware design and development for Jovian missions also includes the JUNO magnetometers as well as the Atmospheric Structure Instrument (ASI), the Nephelometer (NEP) and Net Flux Radiometer (NFR) for the Galileo probe mission to Jupiter. Lockheed Martin works with a university science partner and the system integrator to provide the science investigation with a product that delivers the required science data while withstanding the Jovian radiation environment.

The ASRG Controller hardened design is accomplished by implementation of heritage Lockheed Martin survivability processes, resulting in components/systems meeting mission performance requirements in space radiation environments. Lockheed Martin has extensive experience (over 30 years) in radiation effects simulation, testing and implementation on spacecraft. Lockheed Martin makes use of an extensive historic radiation effects database to arrive at the proper choice between electrical parametric derating, shielding and mission performance. Where data is not available, Lockheed Martin's in-house facility is capable of performing cost effective tests ranging from radiation effects characterization tests to flight hardness assurance. Lockheed Martin’s methodology and expertise has been successfully applied on multiple programs for in-house and partner components. These capabilities can be made available to support partner EJSM instruments providers.

The ASRG (see Figure 1) consists of two advanced Stirling convertors packaged in beryllium housing. The generator utilizes two radioisotope General Purpose Heat Source (GPHS) modules to provide thermal energy to operate the Stirling convertors. A heat source support system maintains intimate contact between GPHS and the convertor to facilitate heat transfer into the convertor. A gas management system

consisting of a pressure relief device (PRD) and a gas management valve (GMV) are mounted on the outside of the generator housing. The GMV allows for management of the internal cover gas during ground operations and the PRD provides a barometrically actuated method for venting the cover gas during the launch sequence. The externally mounted Controller synchronizes the two ASCs, provides operational control strategies, rectifies AC power to DC power, and provides the capability for power output control and safeguarding of the ASCs within an allowable operating range.

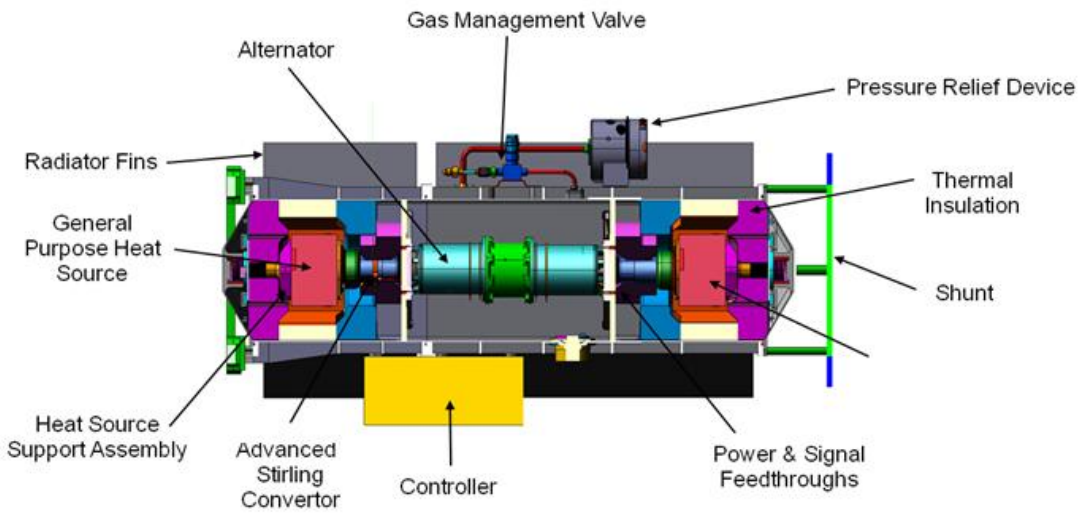

Figure 1. ASRG cut away view

Radiation hardening techniques may include special process procedures and constraints, circuit designs and system adaptations to achieve the desired level of radiation tolerance. The radiation hardness requirements are a function of operational environment, device performance and mission requirements. Figure 2 outlines the methodology employed by Lockheed Martin to assess the hardness of a given design for a particular mission.

The strength of our design approach for ASRG Controller system survivability and protection is grounded in our legacy processes for survivability engineering and protection of power control electronics that have been successfully executed for high radiation environments. Lockheed Martin is an ISO 9000 company that employs standardized processes for the survivability methodology shown in Figure 2. Free field environments will be evaluated using the NOVICE Monte Carlo radiation transport model to determine the necessary shielding required at the piece part level. In addition to a heritage radiation effects database stretching back into the 1980s, Lockheed Martin has the equipment and staff capable of executing in-house ionizing dose characterization testing at our Valley Forge facility.

As necessary, radiation testing will be executed through the Lockheed Martin Radiation Test Laboratory located in King of Prussia, PA. Lockheed Martin personnel have extensive experience in the test and evaluation of semiconductor piece parts and electronic circuits for military, civil (NASA) and commercial programs. Laboratory

operations cover ionizing dose, neutron, and single event effects testing. Test procedures conform to the appropriate Military Standards as applicable. Tailoring is done – as needed – to cover specific applications.

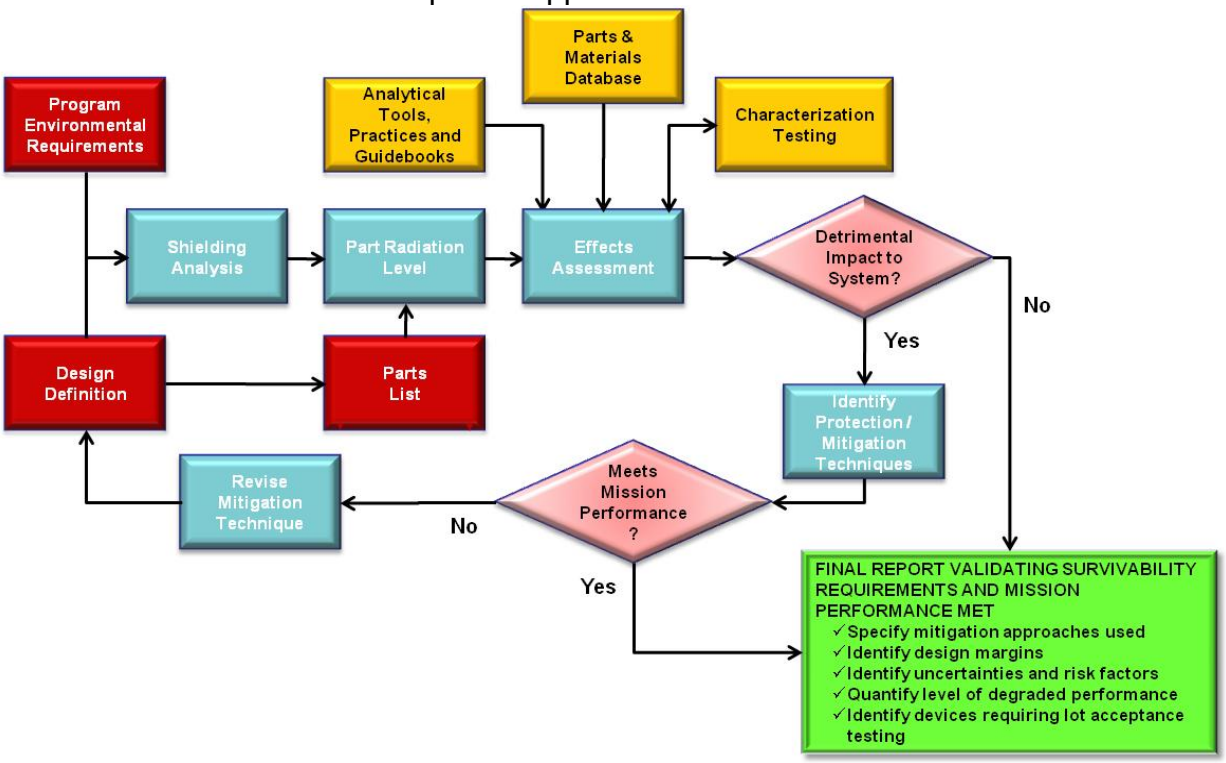

Figure 2. Radiation Design Evaluation Process.

Total dose exposures are done on-site using either of two Gammacell 200 Cobalt 60 irradiators. Enhanced Low Dose Rate Sensitive (ELDRS) parts will be tested using the Sheppard Model 484 Cobalt 60 irradiator located in Newtown, PA. Bulk damage / neutron testing is done off-site at either Penn State University's TRIGA reactor or White Sands Missile Range Fast Burst Reactor. Single event effects testing is performed at a variety of facilities across the country (Brookhaven National Laboratory, Indiana University, etc.). The Laboratory has a full suite of instrumentation and data processing equipment to execute pre- and post-exposure electrical parametric characterization of test items. A fabrication shop is also available for building custom bias boards and test fixtures.

The RFI defines the dose depth kernel seen in Figure 3 and that the minimum die-level part performance is expected to be 100 krad(Si). The current design of the ASRG Controller utilizes multiple components – with different radiation electric parametric performance levels. Table 1 shows the nominal performance levels for the device technologies identified. At this time, the majority of semiconductors meet the minimum dose requirement. It is the intent of Lockheed Martin to select, characterize and define the performance of each unique device type to the highest radiation performance level

possible while still meeting the mission goals. This process is executed to reduce and optimize the shielding weight of the Controller.

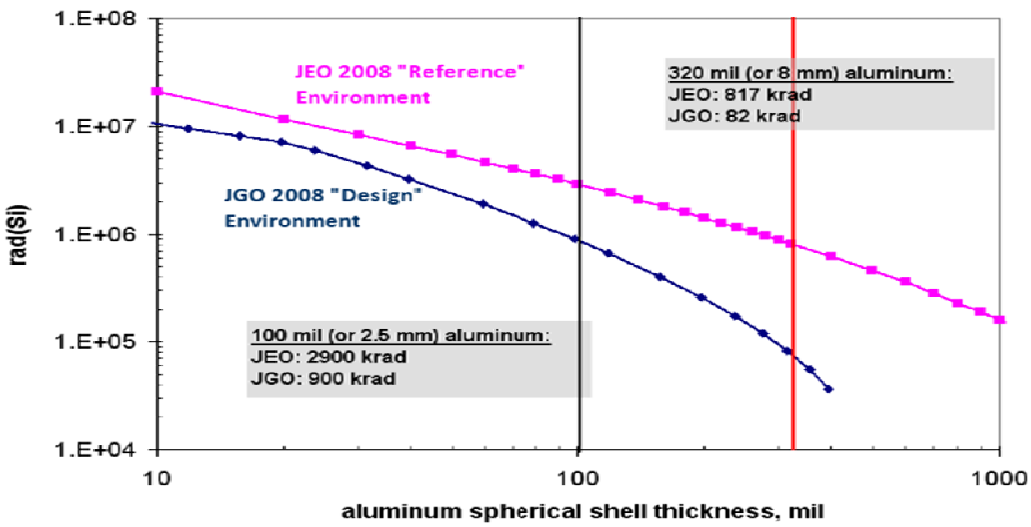

Figure 3. Ionizing dose depth kernel.

Table 1. Semiconductor Hardness Levels.

	Total Ionizing Dose (TID)	Displacement Damage
Diodes (multiple)	≥ 500 krad (Si)	≥ 1E13 n/cm^2
Transistors (multiple)	≥ 100 krad (Si)	≥ 1E12 n/cm^2
MOSFETs (multiple)	≥ 300 krad (Si)	≥ 1E12 n/cm^2
Digital Devices (multiple)	50 to 100 krad (Si)	≥ 1E12 n/cm^2

ASRG Controller survivability requirements are a flowdown of the free-field environments into derived environments, verification approaches and test/analysis methodologies to ensure a hardened system. Figure 4 shows the flowdown from external radiation environments to specific threat implications and mitigation techniques. The implementation of the hardened design is predicated on the overall mission requirements of ASRG Controller, the individual component requirements and the environment. These environments and threats are flowed down to individual piece parts, circuits and subsystems such that performance characteristics may be developed and a threat-hardened design implemented which meets all requirements.

While the RFI total ionizing dose typically produces graceful degradation of semiconductor performance, there are other natural space radiation environments and

events that may be detrimental to performance. Figure 4 identifies natural space radiation environmental impacts of concern to a design include:

- Bulk damage. Electrons and protons produce damage by ionizing dose and bulk damage. The spectra of the free field environments will be evaluated to define the amount of damage due to bulk effects.
- Deep electron charging. The Jovian radiation environment is dominated by high energy, penetrating electrons which are capable of producing sufficient charge generation on floating metal such that sudden discharges may produce catastrophic failure. An analysis of the environment produced behind the radiation shields will determine the necessity for modifying standard boards to accommodate ground paths.
- Single Event Effects (SEE). SEEs are the results of charged particles having enough energy to penetrate the shielding afforded by the vehicle and subsequently depositing a sufficient quantity of energy in the form of charge within the sensitive region of a digital device to affect the operation of that device. SEE is transient in nature and can manifest it as both hard and soft errors. Devices with hard errors are catastrophic and not permitted for space flight. Devices with soft errors must be assessed and their impact to the mission tolerated.

As part of the Lockheed Martin systems engineering approach, the impact of both ionizing dose and the preceding effects will be assessed during part selection. Based upon the results of the survivability analysis and component design detail, electronic circuits and components will be assessed for the effects of degradation (ionizing dose and bulk damage) as well as single event effects. The results of these analyses will be used to achieve a design which complies with mission and survivability requirements. Vulnerabilities identified by analysis and/or test will be removed by implementation of dedicated hardened design techniques which are joint efforts between survivability specialists and designers.

In conclusion, Lockheed Martin has experienced personnel capable of design, test execution and trade space assessment of deep space radiation effects on electronics. Lockheed Martin looks forward to the opportunity to work with NASA once again on the Europa-Jupiter System Mission to provide solutions to this challenging deep space design problem.

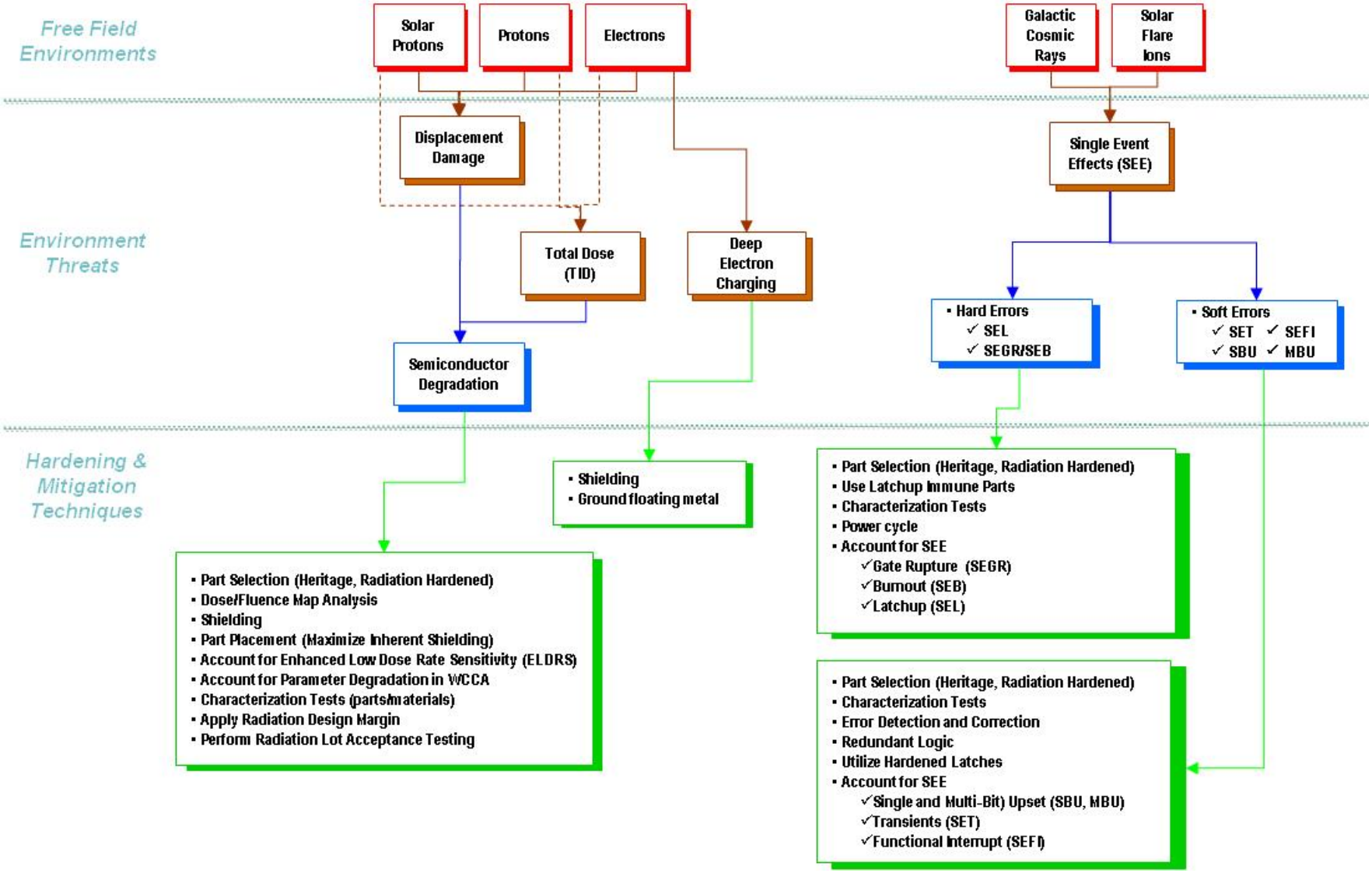

Figure 4. Natural Environment Design Impact.

RHESE Project Response to EJSM RFI

A. Name of submitter and contact information:

Dr. Andrew S. Keys, NASA Marshall Space Flight Center
Project Manager for the Radiation Hardened Electronics for Space Environments (RHESE) project
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B. Capabilities and qualifications:

NASA's Radiation Hardened Electronics for Space Environments (RHESE)[1] is a technology development project within the Exploration Technology Development Program (ETDP) that works to mature the current state-of-the-art in radiation hardened electronics and avionics, providing high performance devices robust enough to withstand the radiation and temperature levels of the space environment. The primary customers for RHESE technologies are the multiple mission elements of NASA's Constellation Program (CxP), including the Orion Crew Exploration Vehicle, the Earth Departure Stage of the Ares V launch vehicle, the Altair Lunar Lander project, Lunar Surface Systems elements, and Extra Vehicular Activity elements. RHESE is working closely with each of these customers to satisfy their needs for radiation-hardened electronics that can endure the natural environment's ionizing radiation as defined in the CxP Natural Environment Definition for Design (NEDD). For an external review of the ETDP and its multiple technology development projects, including the RHESE project, reference the recently released report from the National Research Council[2].

It is a given condition that the natural radiation environment specified for CxP elements within the Earth-Lunar system is less severe than that natural radiation environment specified for the EJSM within the Jovian system. However, because the hardening process and design approaches to developing rad-hard electronic technologies are similar for both environments, it can be argued that the development efforts RHESE is making for CxP are directly applied to the needs of EJSM. Leveraging technology development efforts between Exploration missions and Science missions makes good use of limited technology development funds.

C. Respondent's applicable expertise, services, components, facilities, or technologies:

The individual technology development tasks that comprise the RHESE project are broad-based and diverse, but all carry the common goal of providing the customer with the ability to endure the extreme space environment with hardened electronics and avionics. Each task is briefly described here.

- **Model of Radiation Effects on Electronics (MREE)** is managed by NASA's MSFC and implemented by Vanderbilt University. The MREE task is focused on developing an updated model of radiation effects on electronics and the environments within which they operate. The previous model, Cosmic Ray Effects on Micro Electronics 96 (CREME96), has been for years the industry standard modeling tool for estimating single event effects (SEEs) in electronics. However, over the past thirteen years since its release, the state-of-the-art in microelectronics has continued to advance toward architectures that incorporate smaller feature sizes and more complex electronic structures that often include heavy metals – all of which make electronic architectures more susceptible to SEEs and radiation induced failures. The CREME96 model is deficient in accounting for the small complex features and sensitive volumes common to modern electronic architectures. It is therefore the goal of the MREE task to develop a more physics-based approach to SEE prediction that will provide accurate results for modern electronics parts. The MREE tool can be applied to model electronics within the Jovian environment as well as CxP mission element electronics within the Earth-Lunar environments. Initial release of the modeling capability is currently scheduled for October of 2010. NASA investment to date: ~$2.450M.
- **Single Event Effects (SEE) Immune Reconfigurable Field Programmable Gate Array (FPGA) (SIRF**) is an effort that is sponsored in part by NASA's GSFC, managed by AFRL Kirtland, and implemented by the Xilinx Corporation. The SIRF task has the goal of radiation hardening by design the Xilinx Virtex 5 FPGA architecture. FPGAs are becoming increasingly common in spacecraft avionics architectures, so this radiation hardened version of the Virtex 5 architecture is highly anticipated by spacecraft designers. Release date of the final version is currently scheduled for late 2010. NASA Investment to date: ~$1.200M.
- **High Performance Processors (HPP)** seeks to address the growing need within the spacecraft community for a radiation-hardened, high performance, low power processor. The task is currently assessing two promising processor architectures; the radiation hardened general purpose On-board Processing Expandable Reconfigurable Architecture (OPERA) processor by Tilera, and the Hyper-X processor from Coherent Logix. An assessment of performance and environmental hardness will lead to a late 2009 downselect between these processors for use in CxP platforms – in particular for use as the flight processor that executes the Altair Lunar Lander's autonomous landing and hazard avoidance system algorithms. HPP is managed by NASA's GSFC. NASA investment to date = ~$2.430M.

• **Reconfigurable Computing (RC)** seeks to reduce the need for dedicated processor systems and triple module redundancy voting schemes onboard complex spacecraft. Three areas of focus have been identified for the RC task; internal modularity, external modularity, and fault detection and mitigation. The first focus area involves ability of the core processor to emulate any form of computing resource as needed to serve all of the capacities required. The second focus area enables the first by providing a capability to interface resources to any target system by adapting communication standards, physical and electrical interconnections, and other parameters of the host system to hook up to the computing resource. The final focus area allows the detection of an internal fault and autonomous isolation and recovery from the fault without required external involvement. RC is managed by NASA's MSFC and implemented in part by NASA's LaRC. NASA investment to date: ~$1.300M.

• **Radiation Hardened Volatile and Non-Volatile Memory** are required for manned and unmanned space vehicles. The RHESE memory task is working to identify and test the memory products of several of today's leading memory providers. One of the latest memory technology developments is based on a Silicon on Insulator (SOI) device architecture. Because of total dose tolerance and absence of a latch-up mechanism, SOI has emerged as the technology of choice for radiation hardened electronics. In addition to silicon and SOI based memory devices, there are several other potential candidates which are to be evaluated within this task, including ferroelectric-based, silicon based, carbon nanotube based, magnetoresistive based, phase change, and SOI based devices. These different technologies will be assessed and tested for their tolerance to the environmental extremes to be encountered by in the space environment. NASA investment to date: ~$0.600M.

• **Silicon-Germanium (SiGe) Integrated Electronics for Extreme Environments** has as its goal the development and demonstration of extreme environment electronic components required for CxP mission elements with distributed architecture using low-cost, commercial SiGe Bipolar junction transistors within Complementary Metal Oxide Semiconductor (BiCMOS) technology. The SiGe BiCMOS offers unparalleled low temperature performance, wide temperature capability, and optimal mixed-signal design flexibility at the monolithic level. The approach to implementing this task is to demonstrate system-critical SiGe BiCMOS mixed-signal integrated circuit components capable of operating reliably from -180°C to +120°C while under radiation exposure. This particular SiGe development effort culminates in the development and test of a flight-ready remote electronics unit (REU) system prototype that serves as a general purpose, extreme environment ready, sensors and control interface system. Tests will include radiation characterization to a total dose of at least 100 krad, life testing at the temperature extremes (-180°C and 120°C), and over-temperature part and package thermal cycle testing. The final radiation and thermal tested REU system prototype is scheduled for delivery in September of 2009. This SiGe task is managed by NASA's LaRC and implemented by a team as led by the Georgia Institute of Technology. NASA investment to date: ~$8.530M.

D. Past experience and capability in designing, developing, and delivering technologies for space missions:

Even though the RHESE project is primarily a technology development effort, the project has been successful in providing avionic hardware that has either flown on a space mission or is currently scheduled to fly. For purposes of testing the SiGe technology in the low-Earth orbit environment, multiple flight experiments are underway. Located on the Materials on International Space Station Experiment (MISSE)-6 experiment as currently mounted on the exterior of the International Space Station (ISS) are passive, unpackaged SiGe chips that function as a voltage reference. These circuits were protectively coated against atomic oxygen damage and tested prior to flight. Upon the retrieval of the MISSE-6 experiment, these circuits will be recovered and actively characterized for operation and radiation-induced performance degradation. In addition to this passive SiGe circuit, an active, packaged SiGe-based control circuit will fly as an integrated portion of a Boeing Thermal Protection System (TPS) materials payload mounted on the MISSE-7 experiment.

MISSE-7 will also carry a flight experiment provided through RHESE's HPP task. The experiment consists of four rad-hard Hyper-X processor cards as developed by Coherent Logix, Inc. and mounted on a backplane with a rad-hard Aeroflex LEON-3 controller card. The experiment is designed to flight test the radiation hardness of the processors in the low-Earth orbit over an extended period of time.

Finally, RHESE's Memory task is preparing to fly a ferroelectric transistor-based memory block aboard an upcoming FASTSAT satellite mission. The memory testing experiment is developed to actively determine the accuracy of hardened memories within a low-Earth orbit environment.

E. References

[1]A. Keys, J. Adams, J. Cressler, M. Johnson, M. Patrick, "*A Review of NASA's Radiation-Hardened Electronics for Space Environments Project*," AIAA-2008-7673, AIAA SPACE 2008 Conference and Exposition, San Diego, CA, Sep. 9-11, 2008.

[2]National Research Council, *A Constrained Space Exploration Technology Program: A Review of NASA's Exploration Technology Development Program*, 2008, URL: http://www.nap.edu/catalog/12471.html [cited 22 May 2009].

RHESE Reconfigurable Computing EJSM RFI Response

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Technologies

Through the umbrella efforts of NASA's Radiation Hardened Electronics for Space Exploration (RHESE) Reconfigurable Computing Project, our team has been working towards the development of a radiation-mitigation technique for use in Field Programmable Gate Arrays (FPGAs). Specifically, the technique is based upon the synthesis of four technologies to overcome hard latchups in modern SRAM-based FPGAs:

- Hardware resident micro-kernel, as exemplified by Dr. Andrews' HybridThreads project
- Dynamic TMR 'Many-Core' processor arrays, as exemplified by Dr. LaMeres' projects
- Partial dynamic reconfiguration of an FPGA using the Xilinx ICAP
- Integrated Radiation Sensor for spatial location of radiation strikes

The combination of these technologies will result in a many-core, tile-based, heterogeneous computer architecture that will be able to integrate both TMR-identified and environmental information to intelligently detect, avoid, and recover from radiation strikes through dynamic relocation of both TMR processors and custom circuitry. Figure 1, below, illustrates this concept.

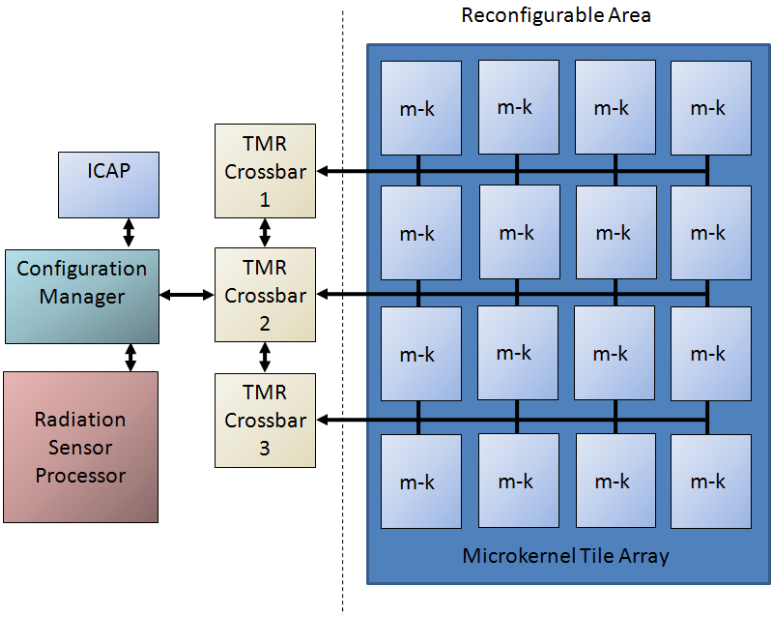

Figure 1

In this figure, the areas labeled "m-k" represent a multiplicity of soft IP circuitry (i.e. FPGA circuitry), such as a "Many-Core" implementation of the MINIX kernel built upon HybridThreads. The use of a "Many-Core" implementation provides the team an avenue to further explore the ability of dynamic partial reconfiguration to survive not only single effect events (SEE) but multiple effect events (MEE) which occur when single or multiple heavy ion strikes cause multiple simultaneous SEE. It is anticipated that this research will result in an FPGA-based architecture that will additionally be capable of surmounting related bulk effect issues such as Total Ionizing Dose (TID).

Initial radiation testing of the above integrated architecture is planned at the Pacific Northwest National Laboratory (PNNL). Further heavy ion testing will be performed at other DOE facilities (anticipated is the light- and heavy- ion capable 88" Berkeley Cyclotron).

This work has been intentionally oriented towards the Xilinx Virtex-5 FPGA in anticipation of the delivery by Xilinx of their "SEU Immune Rad-Hardened FPGA" (SiRF), a radiation-hardened version of their commercial Virtex-5 FPGA. As discussed in the following sections, the separate technological pieces of this project have been realized in either a laboratory or commercial environments (i.e. TRL 2-3).

HybridThreads

The University of Arkansas HybridThreads Project is a real-time embedded operating system that allows programmers to run threads, simultaneously on the CPU and FPGA fabric. HybridThreads allows programmers to design HW/SW systems using threads as building blocks by abstracting the HW/SW boundary. In order to accomplish this in an efficient manner, OS primitives which are the "language" that threads use to communicate were implemented as soft-IP cores so that both software- and hardware-based threads are able to access operating system services uniformly. HybridThreads has been operational since 2004.

http://hthreads.csce.uark.edu/wiki/About_Hthreads

TMR Many-Core Processor Array

This Montana State University project consists of 64 picoBlaze soft-IP processors implemented on a Xilinx Virtex-5 FPGA to control a basic set of peripherals. At any given time, three of the 64 processors are running in triple modular redundancy (TMR) mode to avoid and recover from a single event upset (SEU). SEUs are induced in the system using a simple push button. The remaining 61 processors are internal spares which are used when it is determined that a hard failure has occurred on one of the active three processors. Upon a hard failure, the faulted processor is flagged as unusable, and a spare processor is brought online to complete the TMR circuit. Locations of hard failures are tracked so that the system does not attempt to reuse that region of the FPGA in the future. For the demonstration of this system, a PC-based graphical user interface (GUI) is used that allows a user to indicate a hardware failure in one or more of the 64 processors on the FPGA. This student project was successfully demonstrated in April 2009.

http://sites.google.com/site/ee492rtc/

Dynamic Partial Reconfiguration

Using the Internal Configuration Access Port (ICAP) found on recent Xilinx FPGAs, system designers have the ability to reconfigure, or reprogram, a portion of the FPGA while the remainder of the FPGA remains operational. When operating under the control of a circuit, such as a soft-IP processor, this allows the chip to "self-reconfigure". This capability has existed in Xilinx FPGAs since 2002.

http://www.xilinx.com/itp/xilinx7/books/data/docs/dev/dev0036_8.html

The ICAP will be used to manage the configuration memory in the FPGA, allowing the system to respond to radiation events with localized reconfiguration. This capability will be initiated when a tile failure or damaging radiation event is detected. ICAP device drivers for both Linux and uClinux have been developed at both The University of Queensland and Virginia Tech. These will be modified for use with the MINIX microkernel architecture.

http://www.itee.uq.edu.au/~listarch/partial-reconfig/archive/2004/10/pdf00000.pdf
http://www.ccm.ece.vt.edu/~nsteiner/icap/

Integrated Radiation Sensor

Radiation sensors are well known. One current and relevant research effort is occurring at Montana State University where they are developing a gridded layered radiation sensor that will be coupled with an FPGA to provide real-time spatial information of radiation strikes. This sensor uses a double sided strip detector (DSSD) based upon a large area p-n diode. The electrodes in the radiation sensor are broken up into narrow strips running orthogonal to each other on both sides of the substrate, each of them being read-out with a separate electronic channel. The location of an ionizing particle is given by the position of the intersection of the strips receiving the signals from the front and back electrodes. This project is currently underway.

RFI: Lynguent COTS Capabilities for the Europa Jupiter System Mission

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Abstract

Model-Based Design (MBD) is a proven methodology for system design. In this brief we show how MBD can be used to evaluate **response of systems that contain commercial-off-the-shelf (COTS)** components **to the radiation and temperature environments of space**. We examine the current state of the art in component libraries, describe how a model can become an executable datasheet, examine the barriers to a wide adoption of MBD for COTS-based systems, and show how tools from Lynguent, Inc. can be used to build a **model suite of COTS components that are radiation and extreme temperature aware**.

Capabilities and Qualifications

Lynguent is a provider of tools and services to enable modeling of devices, circuits and systems from basic electrical behaviors and incrementally improving model fidelity with thermal, mechanical, and radiation effects. Lynguent's commercial offerings include the ModLyng™ Integrated Modeling Environment (IME), designed to provide users of all levels of expertise the ability to easily generate models for multiple simulators and design environments. Lynguent also provides toolkits to enable specific modeling and analysis capabilities, such as a Radiation Toolkit for custom space-bound circuits and systems and the Event Driven Analog (EDA) Toolkit for complex system validation.

Lynguent's staff includes experts in the fields of modeling and simulation (engineering staff averaging over 15 years experience in the field), as well as specific expertise in the area of modeling and analysis for radiation, including single event transient (SET), dose rate, and total ionizing dose (TID). This world-renowned expertise is led by Martin Vlach, the inventor of the Saber® simulator and MAST hardware description language; Ernst Christen, the chief architect

of the industry standards VHDL-AMS language; and Alan Mantooth and Jim Holmes, who have led research and development projects in modeling and modeling tools for a combined 35 years.

Applicable Technology and Expertise

To effectively explore Jupiter, Europa and Ganymede, spacecraft developed for EJSM must be designed with advanced sensing and analysis capabilities. Such capabilities, in turn, will require utilization of electronics that are flight proven, whether commercial-off-the-shelf (COTS) components rated for the estimated total dose exposures and flux rates or custom ASICs designed for extreme environments. All technologies applied or developed must be proven to survive the combined thermal, mechanical and radiation effects associated with the mission. Thus, ensuring that devices will perform within specification for this extreme environment will require extensive simulation and will require well characterized electrical device models whose behavior is consistent and predictive of the effect of radiation and extreme temperatures on performance.

Model-Based Design

A Model Based Design methodology relies on models and simulation to explore the design space of systems that are built as aggregates of COTS components and integrated circuits. MBD tools enable lower-cost system development and cost versus lifetime assessment, shorten development time, and extend flight-proven technology to broader applications. To effectively deploy MBD, accurate models of all components of the system must be available, and those models must describe all effects of interest to the system designer. In the context of the EJSM, this means that the component models must describe not only the base behavior, but also the effects of the space environment that may not be commonly available for COTS components, such as TID and temperature.

The accurate extreme-environment enabled models of COTS may be developed in a multistep process that builds on previously created generic models:

1. Develop the base generic model of a class of components, for example A/D converters, by graphical composition from basic electrical effects.
2. Add parameters to the generic model that reflect the specific behavior of a particular component, e.g. AD7888. The parameter sets are developed so that the simulated component behavior accurately matches the datasheet description of the COTS component.
3. Graphically add generic extreme environment behavior from a library of effects.
4. Add parameters to the generic extreme environment effects. These parameters can be based on measured or simulated (e.g. by TCAD) response of the component to extreme environment conditions.

This process has been extensively investigated and proven by Lynguent in two SBIR Phase I and II awards, (*Model-based Design Tools for Extending COTS Components to Extreme Environments*, and *High Efficiency Compact Modeling of Radiation Effects*) and the results of those investigations have been incorporated into Lynguent's commercially available toolset. The process of predictive Rad-Hard By Design (RHBD) modeling is described in a companion submission under this RFI: "Lynguent Radiation Capabilities for Europa Jupiter System

Mission." Decomposing the process of creating a model into repeatable steps makes it scalable for several reasons:

1. The domain expertise of creating both the base generic models and the extreme environment effects can be encapsulated in a set of *reusable* libraries.
2. The Lynguent toolset enables domain experts, who usually are not simulation experts, to encapsulate their knowledge using an easy-to-understand mathematical language.
3. Many effects can be reused across entire classes of components.
4. The development of the models by composition from predefined libraries can be done in parallel by personnel who need not have the specialized domain expertise.

The current state-of-the art of COTS-based design consists of component libraries that may be used in a Printed Circuit Board (PCB) design environment, and a separate set of component models libraries. The component libraries contain information such as schematic symbols, land patterns, links to printed (i.e. PDF) datasheets, but notably they do not contain any models that can be executed in a simulator. These component libraries tend to be run by 3rd party organizations (i.e. not the component manufacturers), and are available either for proprietary tools (ActiveParts for OrCAD from Cadence Design Systems) or for a broader selection of tools (supplyframe.com). The component libraries tend to be comprehensive, with millions of parts from thousands of manufacturers represented. In contrast, the model libraries are typically available from the component suppliers, are not linked to the component libraries, and are much smaller. Some of them (such as those available from TDK) support several popular simulators, while others (e.g. Texas Instruments, Tina simulator) are available for only one simulation environment, which leads to a relatively narrow application space. Model libraries of common components are also available from simulator vendors. Such models are captive to the vendor tools.

To successfully apply MBD to systems that contain COTS components, models of the required components, extended with extreme environment effects, are necessary.

Executable Datasheets

The current method of describing a COTS component is to publish a printed (i.e. PDF) document that describes selected behaviors relevant to the class of the component. In order to determine that a model of a particular component accurately reflects the published datasheet information, a method of simulating a model in such a way that the results can be directly compared to the datasheet is required. This method, called an **executable datasheet**, must encompass the following capabilities:

1. Define a set of testbenches for each class of components.
2. Define a set of procedures that when applied to the combination of a testbench and the component in a simulator produces simulated data.
3. Extract numerical information from the published datasheet so that it can be numerically compared to the simulated data.
4. Compare the simulated and published datasheet information.

5. Produce printed (i.e. PDF) datasheet information for the model, for human interpretation.
6. Make this methodology applicable to multiple simulators.
7. Make this methodology scalable to thousands of components.

This methodology is available in the commercially available Lynguent toolset. Testbenches can be easily created from libraries of effects and managed by the library navigator. Procedures to execute simulation of each testbench in different simulators are enabled by simulation plugins (Fig 1). Comparison of results is enabled by Python scripting and APIs, and generation of reports and printed datasheets has been automated. The methodology is scalable, since regression testing procedures can be written and executed on simulation farms.

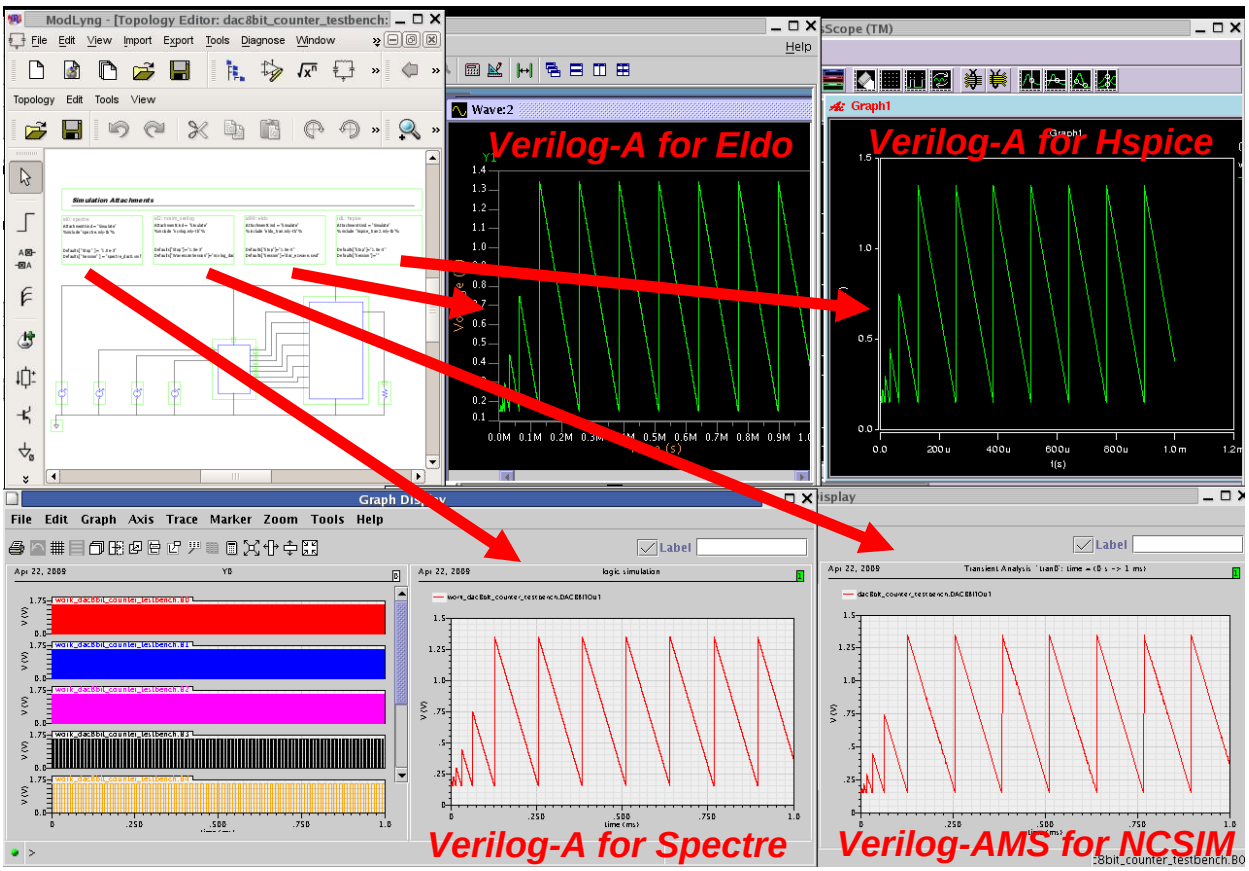

Fig 1. A single model and testbench (left) may be automatically evaluated in four different simulators with Lynguent toolset (Shown: 8 bit Wilkinson DAC).

Model Repository

A model repository is a database of models. A worthy goal for the various electronics that will be designed for EJSM is to have a model repository of the approved COTS components that are qualified for use in the missions. One outcome of Lynguent's collaborations with chosen electronics design contractors could be the creation of this repository for EJSM. And, this can be

extended to include integrated circuits custom designed for the program. The repository must support the following concepts:

1. Source control management to enable reliable concurrent engineering
2. Unified handling of component information, including models, for components from multiple vendors
3. Consistent and full support for all tools that will be used on the project
4. Search capability based on feature, closest equivalent, etc.

Lynguent's modeling technology is uniquely positioned to provide the foundation for such a repository for extreme-environment capable COTS models. At the core of Lynguent's capability lies the CMX model description format. An XML format, CMX enables simple revision control using readily available tools (e.g. CVS, SVN, Design Sync, etc). The ModLyng tool provides the frontend to this powerful model description format, enabling simple model creation and even reuse of existing models through import mechanisms (Fig 2). Once models are created in CMX, ModLyng is capable of generating models for multiple languages, simulators, and even simulator versions.

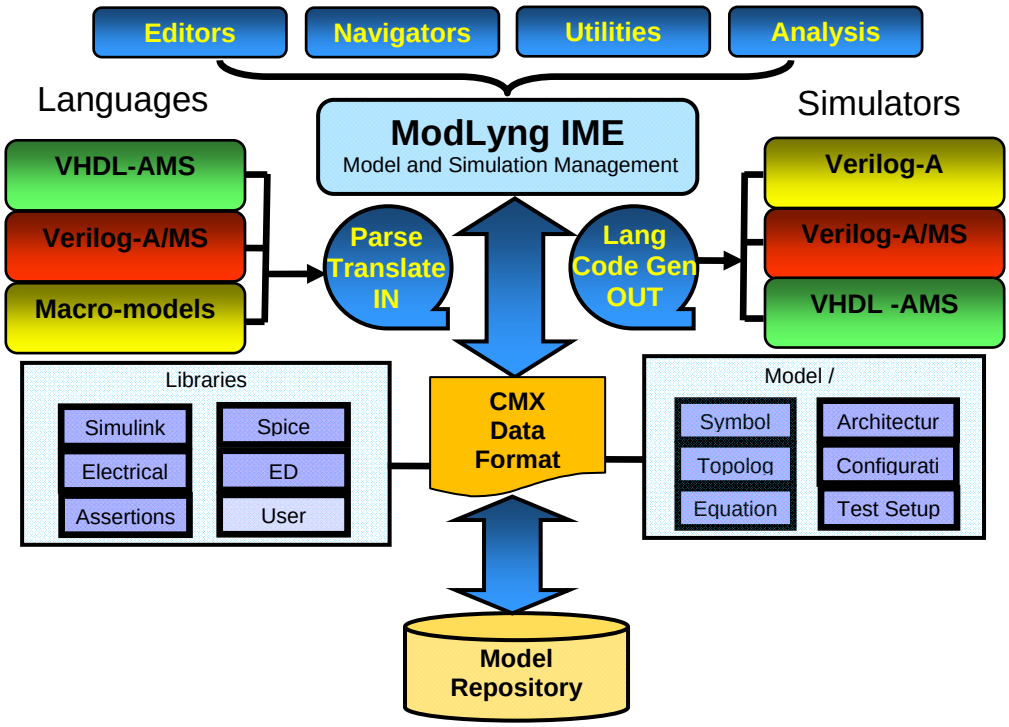

Fig. 2. Lynguent modeling capability for model repository creation.

Finally, regression testing of entire libraries of components may be accomplished through Lynguent's powerful application programming interface (API). This capability may be applied in particular to any interface (web or software) to an Extreme Environment model repository, without the need to build new model or language analysis tools. Finally, the architecture of

ModLyng is such that if new simulators or languages are needed to support repository completeness, new language interfaces may rapidly be integrated through Lynguent's unique language-neutral approach.

These tools can and should be used by any electronics design team involved in the EJSM. The Lynguent tools can allow board designers to better predict the performance of their electronics in the radiation and temperature environments of space. Even if some custom modeling is required, Lynguent personnel possess the knowledge and experience to provide those services, while also teaching the designers how to effectively use the tools and techniques for themselves. The advantages to be gained using model-based design with Lynguent's extreme environment tools (Fig. 3) are:

1. Verification of complex COTS-based electronics in a more efficient way
2. Addition of extreme environment effects to models without the need to be a radiation or thermal expert, thus enhancing the fidelity of the electronics analysis
3. Prediction of failure modes induced by thermal, mechanical or radiation effects
4. Promotion of collaboration among disparate design teams.

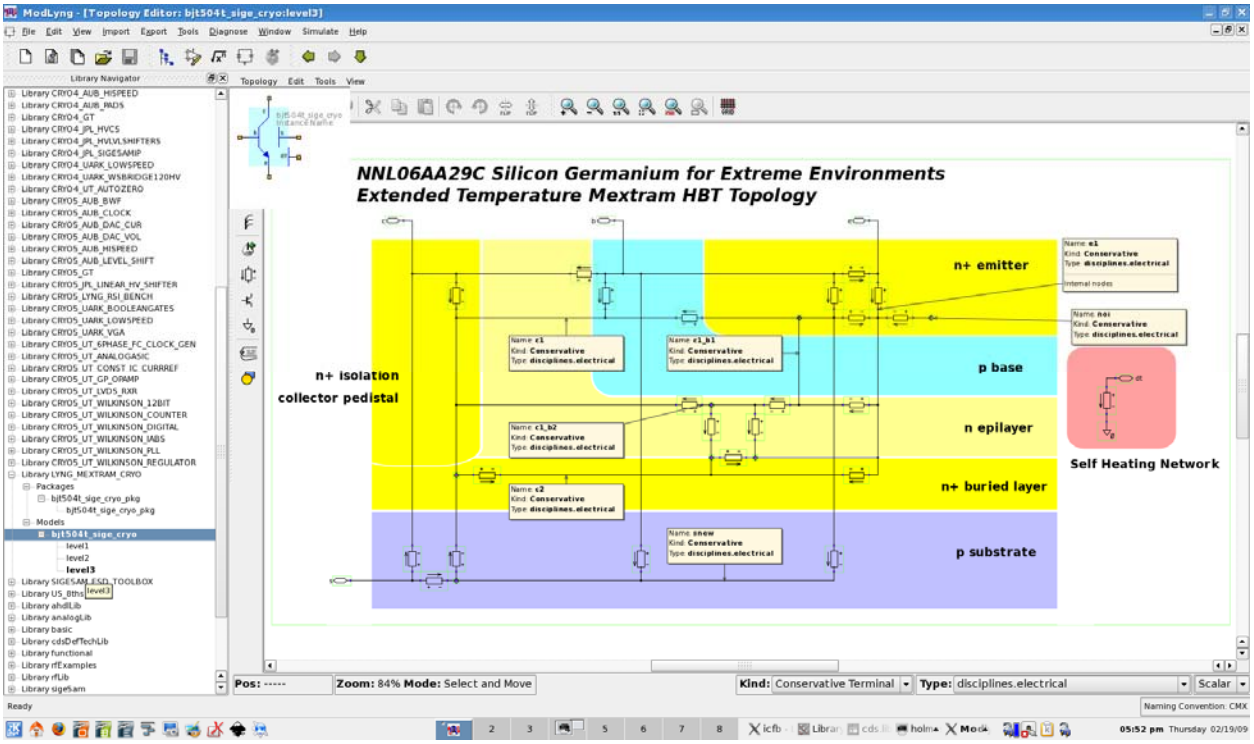

Fig. 3. Lynguent extreme environment tool.

Technology Readiness (Maturity)

Lynguent tools and technology are currently at Technology Readiness Level (TRL) 6, based on the fact that hardware designed using these tools to be rad-hard and survive wide temperature swings has not yet flown in space. Flights of hardware modeled in Lynguent tools are scheduled for 2009, leading to TRL 7. TRL 6 was achieved by validating the tools against actual radiation data taken from exposed circuitry. Fundamental observations and measurements have been made

for several phenomena at various technology nodes, tools and circuits have been demonstrated, and circuits and applications have been analyzed using Lynguent Extreme Environment tools.

Experience in Space Applications

Lynguent has completed several research programs in the last several years in space applications and radiation environments with NASA, JPL and DTRA. Most recently Lynguent completed a DTRA SBIR Phase I and II focused on modeling of single-event upset in deep sub-micron technologies (HDTRA1-05-P-0124, POC – James R Fee, Major USAF, DTRA 703-767-7455), where the behavior of charge-sharing upsets was successfully migrated from Technology CAD analysis and measured data to circuit simulation using the LynRad toolset.

Lynguent has also completed NASA SBIR Phase I and Phase II projects focused on modeling of extreme temperature effects on COTS devices and predicting end-of-life (EOL) based on failure effects that occur as a result of high temperatures (POC – Dr. Mohammad Mojarradi, JPL (818) 354-0997). Lynguent recognizes the coupling between radiation and temperature effects as a difficult issue and this work may also lay a foundation upon which tools that account for combined thermal-radiation effects can be validated.

Finally, Lynguent is nearing the end of a NASA ETDP program on Silicon Germanium Electronics for Extreme Environments (POC – Andrew Keys, MSFC 256-544-8038) which focused on the integration and validation of a complex sensor interface multi-chip-module for space applications. Lynguent's system-level validation capability developed therein will lay a foundation for migration of observed device and circuit-level radiation effects to system-level validation for the complex applications (mixed analog and digital) necessary for an applications such as the EJSM spacecraft.

These programs added together sum to nearly $2M in small business investment from NASA and DTRA toward modeling tools for extreme environments aimed at creating a model-based design methodology that can address both COTS-based board design as well as custom ASIC design.

Summary

Over the past five years Lynguent has developed unique capability in modeling tools to expedite the capture of extreme environmental effects into industry standard models and/or newly created models. This capability has matured to a point that a NASA program team has utilized it (SiGe program above) for custom ASIC design. These tools are now under evaluation by BAE Systems and Boeing, two partners in the SiGe program, for next generation design activity. EJSM will be able to leverage these tools and the expertise that has been created under previous programs to design electronic systems through a model-based methodology. Using the Lynguent tools can be the great equalizer for spacecraft design teams to utilize the same set of models – even if using different simulators. This promotes traceability, collaboration, and lowers risk.

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Abstract

This brief describes a set of hardware design tools from Lynguent, Inc. that promotes **model-based design at all levels of hierarchy from circuits through systems**. These tools include the capability to modify industry standard models with radiation effects in a simple, graphical way. They also promote easy to compose methods for model creation ranging from signal flow at the system level down to physical models of transistors. The resulting models promote collaboration between teams using different simulators because the tools support models in a wide variety of simulator languages.

Capabilities and Qualifications

Lynguent is a provider of tools and services to enable modeling of devices, circuits and systems with behaviors ranging from fundamental electrical all the way through thermal, mechanical and radiation. Lynguent's commercial offerings include the ModLyng™ Integrated Modeling Environment (IME), designed to provide users of all levels of expertise the ability to generate models for multiple simulators and design environments easily. Lynguent also provides toolkits to enable specific modeling and analysis capabilities, such as a Radiation Toolkit for custom space-bound circuits and systems and the Event Driven Analog (EDA) Toolkit for complex system validation.

Lynguent's staff includes experts in the fields of modeling and simulation (engineering staff averaging over 15 years experience in the field), as well as specific expertise in the area of modeling and analysis for radiation, including single event transient (SET), dose rate, and total ionizing dose (TID). This world-renowned expertise is led by Martin Vlach, the inventor of the Saber® simulator and MAST hardware description language; Ernst Christen, the chief architect

of the industry standard VHDL-AMS language; and Alan Mantooth and Jim Holmes, who have led modeling and modeling tool research and development for a combined 35 years.

Applicable Technology and Expertise

To effectively explore Jupiter, Europa and Ganymede, spacecraft developed for EJSM must be designed with advanced sensing and analysis capabilities. Such capabilities, in turn, will require utilization of electronics that are flight proven, whether they be commercial-off-the-shelf (COTS) components rated for the estimated total dose exposures and flux rates or custom ASICs designed for extreme environments [1]. Meeting the needs of extreme low power with sufficient processing capability may entail creating entirely new components composed of custom circuit solutions as well as integrated multi-chip modules. All technologies applied or developed must also be designed and proven to survive the combined thermal, mechanical and radiation effects associated with the Europa missions. Thus, ensuring that devices will perform within specification for this extreme environment will require extensive simulation at many levels of abstraction and, subsequently, will require not only well-characterized electrical device models but also models and behaviors predictive of the effect of radiation on performance.

Lynguent's modeling and analysis capabilities for radiation and other extreme (combined) effects include the Radiation Hardened by Design (RHBD) Toolkit for modeling the effect of radiation on standard cells of which custom integrated circuits are composed, as well as Lynguent's LynRad analysis tool for manufacturing process characterization of radiation effects on said cells.

Effectively modeling and predicting radiation effects for custom circuits and designs requires characterized process models, aware of SET and TID effects on electrical performance. While Technology CAD and Monte-Carlo approaches [2, 3] may be used as a point solution to these problems, Lynguent's RHBD-LynRad flow is completely scalable as all effects (radiation, thermal or otherwise) may be easily added directly to the models already used to model electrical behavior; the transistor compact models widely used in SPICE-like simulators [4-6]. The upshot is that **thousands of mission profiles may be executed on large systems** and cells in the time required for a single TCAD simulation.

Fig. 1 below illustrates the Lynguent modeling capability on an industry-standard SPICE model, BSIM4. ModLyng allows the addition of new radiation effects to such complex electrical models using a unique graphical interface. Through this capability, the figure illustrates how a threshold shift due to observed TID may be straightforwardly added to a characterized ASIC process model.

In the realm of single event modeling, the RHBD-LynRad flow may be utilized to characterize and extend existing PDK models in much the same manner. Fig. 2 illustrates the modeling of the effect of a single charged particle on multiple devices simultaneously, a unique capability that Lynguent has developed under DTRA funding. This is accomplished using RHBD-LynRad's physical design analysis tool to find devices susceptible (by their proximity and properties) to SET radiation effects. Enhanced compact transistor models are thus characterized by LynRad to model such charge-sharing behavior and provide a simulation capability in a SPICE simulator. Thus, for a single design of ~20 devices, **hundreds of analyses for particle strikes may be run in a matter of minutes**.

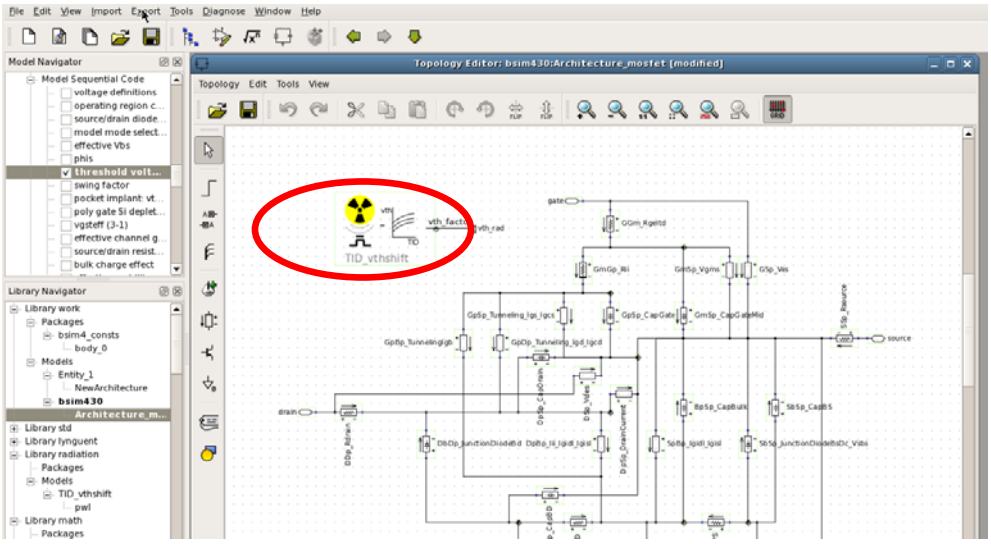

Fig. 1. Deploying TID models graphically in a process model (BSIM4 shown).

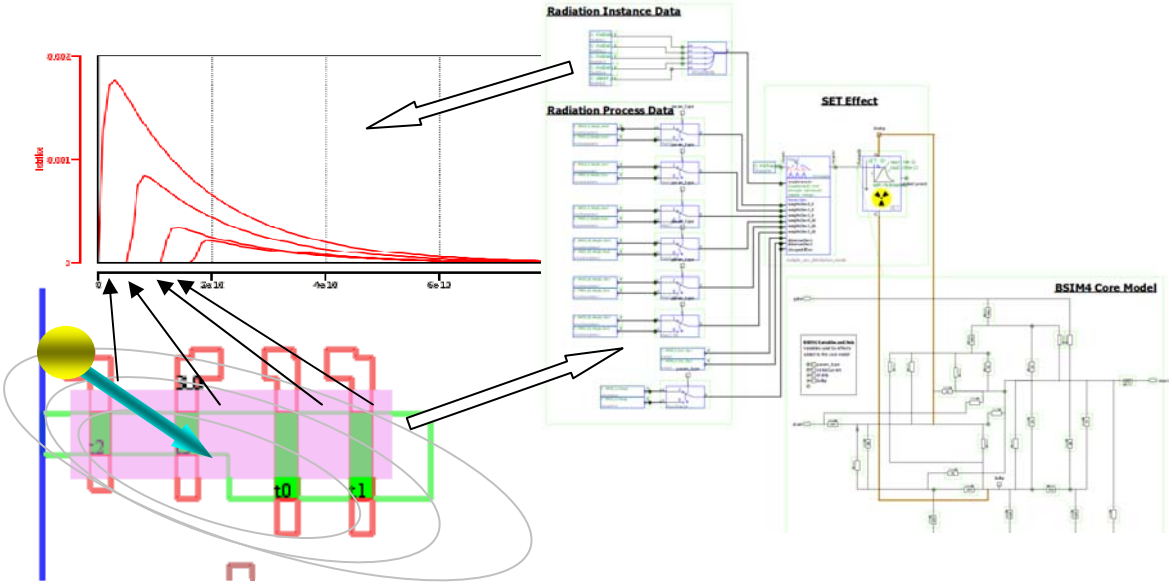

Fig. 2. Layout-aware SET modeling capability using embedded radiation models in SPICE (BSIM4) model.

The results of these analyses are the identification of vulnerable transistors in a given design – again, the **first tool to be capable of such *predictions*** at the circuit level. This data may be used to enhance the given design (modify for identified vulnerability) or, if acceptable within bounds, to model the behavior for system-level simulation of radiation-induced performance degradation.

Lynguent's industry-first modeling tools do not stop at the ability to add thermal, radiation, or stress effects to existing models. They also do not stop at the ability to easily create new models at any level of abstraction (ranging from signal flow at the top to detailed physics at the bottom of the hierarchy and several other steps in between). An example of a transcendent capability that aids the designer in conquering design complexity in ASIC design is the EDA

Toolkit. The EDA Toolkit allows analog behavior to be captured as event-driven, so that the resulting models can execute in a digital simulator. As a result, Lynguent has collaborated on a NASA program whereby an ASIC chip-set implementation of a remote health node sensor interface solution was designed by BAE Systems, University of Arkansas, Auburn University, Georgia Tech, and the University of Tennessee. Lynguent used ModLyng™ and its companion EDA Toolkit to model the chip-set with high fidelity. One ASIC in the chip-set was a mixed analog-digital sensor interface while the other was a custom digital control and data processing unit. The models produced by Lynguent's tools described the two ASICs such that they could simulated ***together*** in a single, event-driven simulator to verify the hardware, software, and firmware functionality. These two chips are rad-hard, able to survive in the environment of the moon (i.e., -180 °C to +125 °C), and replace an 11 kg existing device. Lynguent modeling tools, including the EDA Toolkit, were an indispensible key to the success of that program.

These tools can and should be used by any electronics design team involved in the EJSM. Whether they are designing board level electronics using COTS or integrated circuits, the Lynguent tools can allow them to better predict the performance of those electronics in the radiation and temperature environments of space. Even if some custom modeling is required, Lynguent personnel possess the knowledge and experience to provide those services, while also teaching the designers how to effectively use the tools and techniques for themselves. The advantages to be gained using model-based design with Lynguent's extreme environment tools (Fig. 3) are:

1. Verification of complex analog, digital and mixed-signal electronics in a more efficient way
2. Hierarchical design debugging using the EDA Toolkit
3. Traceability of design problems
4. Addition of extreme environment effects to models without the need to be a radiation or thermal expert, thus enhancing the fidelity of the electronics analysis
5. Prediction of failure modes induced by thermal, mechanical or radiation effects
6. Promotion of collaboration among disparate design teams.

Technology Readiness (Maturity)

Lynguent tools and technology are currently at Technology Readiness Level (TRL) 6 based on the fact that hardware that has been designed to be rad-hard and survive wide temperature swings using these tools has not yet flown in space. This is to happen very soon though. However, the tools have been validated against actual radiation data taken from exposed circuitry. Fundamental observations and measurements have been made for several phenomena at various technology nodes, tools and circuits have been demonstrated, and circuits and applications have been analyzed using Lynguent Extreme Environment tools.

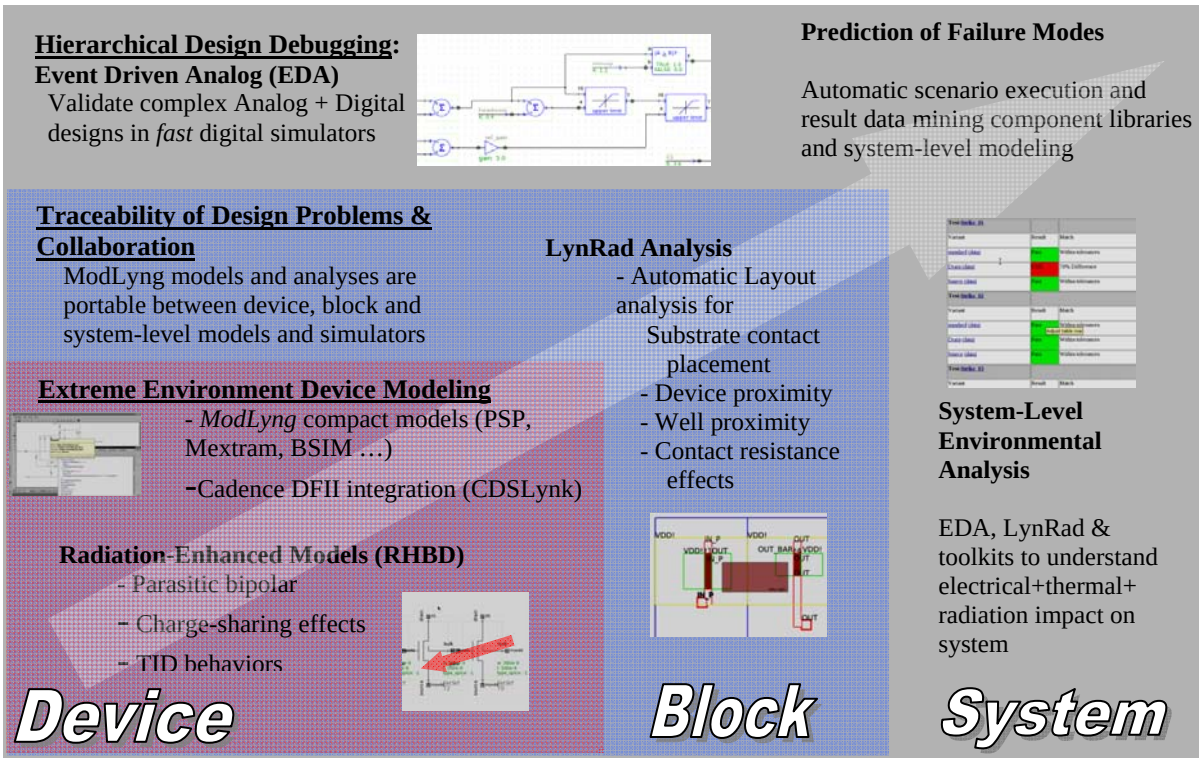

Fig. 3. Lynguent modeling and analysis capabilities for extreme environments at all levels of abstraction.

Experience in Space Applications

Lynguent has completed several research programs in the last several years in space applications and radiation environments with NASA, JPL and DTRA. Most recently Lynguent completed a DTRA SBIR Phase I and II focused on modeling of single-event upset in deep sub-micron technologies (HDTRA1-05-P-0124, POC – James R Fee, Major USAF, DTRA 703-767-7455), where the behavior of charge-sharing upsets was successfully migrated from Technology CAD analysis and measured data to circuit simulation using the LynRad toolset.

Lynguent has also completed NASA SBIR Phase I and Phase II projects focused on modeling of extreme temperature effects on COTS devices and predicting end-of-life (EOL) based on failure effects that occur as a result of high temperatures (POC – Dr. Mohammad Mojarradi, JPL 818-354-0997). Lynguent recognizes the coupling between radiation and temperature effects as a difficult issue and this work may also lay a foundation upon which tools that account for combined thermal-radiation effects can be validated.

Finally, Lynguent is nearing the end of a NASA ETDP program on Silicon Germanium Electronics for Extreme Environments (POC – Andrew Keys, MSFC 256-544-8038) which focused on the integration and validation of a complex sensor interface multi-chip-module for space applications. Lynguent's system-level validation capability developed therein will lay a foundation for migration of observed device and circuit-level radiation effects to system-level validation for the complex applications (mixed analog and digital) necessary for an applications such as the EJSM spacecraft.

These programs added together sum to nearly $2M in small business investment from NASA and DTRA toward modeling tools for extreme environments aimed at creating a model-based

design methodology that can address both COTS-based board design as well as custom ASIC design.

Summary

Over the past five years Lynguent has developed unique capability in modeling tools to expedite the capture of extreme environmental effects into industry standard models and/or newly created models. This capability has matured to a point that a NASA program team has utilized it (SiGe program above) for custom ASIC design. These tools are now under evaluation by BAE Systems and Boeing, two partners in the SiGe program, for next generation design activity. EJSM will be able to leverage these tools and the expertise that has been created under previous programs to design electronic systems through a model-based methodology. Using the Lynguent tools can be the great equalizer for spacecraft design teams to utilize the same set of models – even if using different simulators. This promotes traceability, collaboration, and lowers risk.

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[6] X. Huang, A. Francis, A. Lostetter, and H. A. Mantooth, "Compact modeling of environmentally induced radiation effects on electrical devices," *IEEE Aerospace Conference,* vol. 4, pp. 2597-2607, 2004.

I. Summary

Raytheon is pleased to respond to the NASA Request for Information "Radiation Capabilities for the Europa Jupiter System Mission (EJSM)," Solicitation Number NNH09ZDA008L. This response summarizes the radiation analysis capabilities of the Radiation Analysis Services Center (RASC), a consortium in formulation between Raytheon Missile Systems (RMS, Tucson, AZ), Raytheon Space and Airborne Systems (SAS, El Segundo, CA) and Arizona State University (ASU, Tempe, AZ). RASC is forming under the auspices of a Master Sponsored Research Agreement between RMS and ASU. Raytheon and the RASC have a broad range of unique technical expertise and capabilities that that are applicable to the EJSM including radiation shielding design and optimization, radiation transport analysis, and radiation testing.

II. Capability and Qualifications Statement

RMS brings to RASC high fidelity radiation shielding analysis via the state-of-the-art proprietary TopAct radiation analysis tool. TopAct converts standard Computer-Aided Design (CAD) drawings into MCNP(X), NOVICE, ITS, and TART input decks up to three orders of magnitude faster than traditional methods and with the full fidelity of the source CAD drawings. The resulting models are used to perform shielding analysis and optimization through computation of highly-accurate predictions of radiation effects at any point in a complex system. When coupled with detailed device modeling capabilities, this allows unprecedented capabilities to predict overall system performance under radiation conditions. SAS brings to RASC the Component Engineering Department (CED) for qualification, failure analysis, and radiation testing. CED has over 17,500 ft² of space, >$20M in capital investment, and over 100 technical staff responsible for performing radiation survivability testing, radiation environment and transport analysis, design verification testing, destructive physical analysis (DPA), microcircuit and discrete component test and evaluation activities, and failure analysis (FA). The CED supports all piecepart test, evaluation and screening, design verification testing, part qualification, radiation survivability analysis and test, environmental test, failure analysis, destructive physical analysis, non-destructive test and analysis for Raytheon programs. ASU brings to RASC extensive expertise in device level modeling, conducting radiation effects research from the physics of radiation transport and material interactions to the impact of radiation damage on the operation of electronic components at the transistor, circuit, and system level. This expertise includes TID effects, DD, ELDRS, packaging issues, and RHBD.

III. Detailed Description

TopAct provides an end-to-end translation capability. It accepts as input part files in standard STEP and Parasolid formats. A pre-processor reads in part files and analytical surface data are extracted. TopAct then computes an efficient zoning statement for part geometry and any void space. The final optimized zoning statement and surface prescriptions are output in the desired code formats. TopAct has been validated via laboratory experiment [1]. TopAct allows radiation transport analysts to fully participate with mechanical designers as a design is evolved. When translations are performed by hand, cost and schedule precludes multiple iterations. This may lead to inelegant design patches when transport calculations reveal system shortcomings. Because TopAct drastically reduces translation time, it allows designers and analysts to evolve their high-fidelity models in parallel, and to discover weaknesses early. This cooperative arrangement often leads to more elegant, efficient, superior delivered components and systems. Further data are in the Proprietary Information (PI) Section.

The CED laboratories are equipped with test and analysis equipment to perform integrated circuit (IC) test systems, and include a wafer probe station, semiconductor and microwave test systems, thermal imaging, real-time x-ray equipment (Phoenix, Fein Focus, and North Star), conformal scanning acoustic microscope, a scanning electron microscope, and energy dispersive x-ray analysis equipment (PI section). The computed radiation environment serves as input to the System Radiation Response Module (SRRM) developed by ASU. SRRM enables statistical predictions of an electrical system's response to radiation. SRRM considers ionization and displacement damage as well as transient single events. The module serves as both a comprehensive, expandable test database and simulation tool for modeling radiation effects in semiconductors, ICs, and hybrid systems. ASU has developed a unique capability for modeling radiation effects in discrete COTs applications. The approach, radiation-enabled macro-modeling, allows for efficiently simulating the radiation response of a hybrid electronic system [2]. This system level simulation facilitates design optimization prior to assembly, thereby reducing cost, shielding requirements, and supporting higher functionality design (*i.e.*, risk margin reductions). In addition to COTs system modeling, SRRM can significantly reduce the design and fabrication costs associated with hardened ASICs, avoiding expensive development of chips that will be well behind the state of the art. ASU's extensive experience in RHBD positions it well to support the design of hardened ASICs in advanced commercial flows. Moreover, ASICs designed in some trusted foundry processes (e.g. IBM) can build upon the cell libraries already developed by ASU with its industrial partners. The device modeling team at ASU will also build radiation-enabled transistor models to support design and layout of ASICs based on targeted radiation specifications. These specifications may include LET thresholds and total dose levels provided as inputs from TopAct. ASU has demonstrated this capability on numerous research activities.

IV. Maturity Level/Past Experience

TopAct was developed in 2000 when existing modeling capability could not support schedule for shielding design for the Exoatmospheric Kill Vehicle. Since that time, Raytheon has supported numerous internal and external customers reported in the Proprietary Information Section. CED is a mature capability, details of which are also reported in the PI Section. The ASU group brings decades of industry and academic research experience to RASC.

V. Application to the EJSM

Since the EJSM will be required to enter Europa orbit and operate for >2 years in the Jovian radiation environment, it will be necessary to do the best possible optimization of its design to enable system architecture, shielding design, materials choices, and component selection to ensure performance while minimizing mass and cost. RASC offers a full complement of services from academic research to industrial production to perform the radiation testing and analysis that will be required for EJSM. The demands for high functionality and performance in the extreme Jovian environment suggest the need to build more sophisticated, custom hybrid systems.

RASC can work in concert with system designers to conduct transport modeling throughout the design phase. RASC will work with EJSM designers to propose system layouts, synergistic subsystem choices, and materials options to enhance native shielding schemes such that the added shielding mass is as small as possible. Furthermore RASC analyses will enable shielding material to be added only where it is necessary, enabling a comprehensive shielding strategy.

RFI Response: BAE Systems: Space Systems & Electronics (SS&E) May 21, 2009

Submitted By: Caprio, Claudio
BAE Systems SS&E
Manassas, Va 20110-4122
703-367-2343
claudio.caprio@baesystems.com

Reference: Radiation Capabilities for the Europa Jupiter System Mission
Planetary Science Division Directorate, NASA
Solicitation Number: NNH09ZDA008L

Dear Sir/Madam

Background

BAE Systems Space Systems & Electronics (SS&E) located in Manassas, Virginia has a long proud heritage having been in the radiation hardened space business since the early 1980s. As one of the original government very high speed integrated circuit (VHSIC) contractors, we began our entry into the government semiconductor processing and ASIC design activities while we were then part of IBM Federal Systems. We were later sold to Loral (1994) as Loral Federal Systems and then to Lockheed Martin (1996) as Lockheed Martin Federal Systems/Space Electronics, finally becoming part of BAE Systems in 1999 as BAE Systems Space Systems & Electronics. During that time we have leveraged our expertise in systems engineering, hardware and software design and semiconductor fabrication (originally focusing on submarines and sonar) to provide innovative and capable solutions for space with a decades long record of success.

Manassas has a state of the art strategic radiation hardened specialty microelectronics center with a six inch semiconductor process line. Leveraging the capability to process with our proven Radiation Hardened By Process (RHBP) and Radiation Hardened By Design (RHBD) techniques we are able to provide our NASA, Civil Space, DoD Space and Missile, Classified Space, and Commercial Space the necessary products and services to meet their missions' needs. These include:

Systems architecture – we utilize our algorithm and technology knowledge to optimize size, weight and power (SWaP), key when selecting the optimal solutions for the instruments and bus for the Europa Jupiter System Mission (EJSM).

Hardware and software engineering to implement solutions based on radiation hardened (RH) ASICs, RH FPGAs, memories, high speed I/O circuitry, general purpose processors and DSPs, solid state recorders (both small and large), board support S/W packages, Start-up ROM (SuROM) code and flight S/W. We heavily leverage reuse of proven components, synthesizable logic cores, and modular software code to minimize both cost and risk.

Materials engineering design services, parts procurement, component engineering, radiation testing and a high level of understanding of what it takes to space qualify not only a technology, but a single chip module, multi-chip module, card or unit/subsystem

Within our specialty micro-electronics capability we provide the following:

On-shore trusted ASIC/memory design, wafer fabrication and test, and module fabrication and test for a number of technologies. These include 150/180/250 nm bulk CMOS, Chalcogenide (a chemistry that is not only rad hard but non-volatile, which is very important to the Jupiter Europa Orbiter (JEO) mission and its instrument providers), and Carbon Nanotubes (CNT) a new and promising technology that will provide all of the same radiation characteristics of Chalcogenide for radiation and non-volatility but provides a path for the density of Flash, EEPROMS and/or SDRAMs (both needed for high density solid state recorders (SSRs).
BAE Systems' Trusted MMIC foundry in New Hampshire produces analog RF components using GaAs and InP processes for space and avionic applications. RF components include low noise amplifiers and MMICs for SSPAs. Our cooled IR sensor foundry in MA produces SWIR HgCdTe sensor assemblies for SBIRS and is currently extending capabilities to 2048 x 2048 under the High Stare program.

We also provide low cost circuit card assembly services to the space industry. We apply our space parts purchase and quality assurance processes to acquire components and then manufacture complex circuit cards that are used in multiple space programs.

BAE SYSTEMS

Manassas, VA site

Silicon to Systems

- Leading Supplier for Radiation Hardened Digital Electronics and Space Systems
- Core Competencies
  - Semiconductor Processes & Manufacturing
  - Space Microelectronics Physics
  - Very Low Power, Fault Tolerant Digital Design
  - Multi-Million Gate ASIC Development
  - High Density Semiconductor Packaging
  - Space Computer Design & Manufacturing
  - Space Communications Systems
  - Space Signal Processing Systems
- Key Customers
  - US Aerospace Primes & Electronics Suppliers
    - Northrop Grumman, Lockheed Martin, Boeing, Orbital, Spectrum, SS/L, ……
  - US Government Technology Sponsors
    - AFRL, NRL, DARPA, DTRA, MDA, …..
  - NASA and its Labs
  - JPL, GSFC, JHUAPL, LASP, and MSFC
- ISO 9001 , 14001 and SEI 4 Certified
- About 380 People

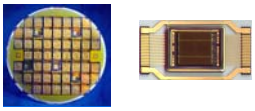
Growing Advanced Technology Organization

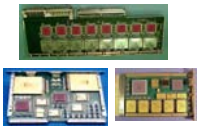
BAE SYSTEMS

Space Systems and Electronics Product Portfolio

BAE SYSTEMS

Radiation-Hardened Electronics – Silicon to Systems





Integrated Circuits (IC)

Chips

- **Memory (e.g. Static Random Access Memory - SRAM)**
- **Micro-Processors**
- **Application Specific Integrated Circuits (ASICs)**
- **Field Programmable Gate Array (FPGA)**
- **Unique (Analog, Read Out IC…)**

Boards

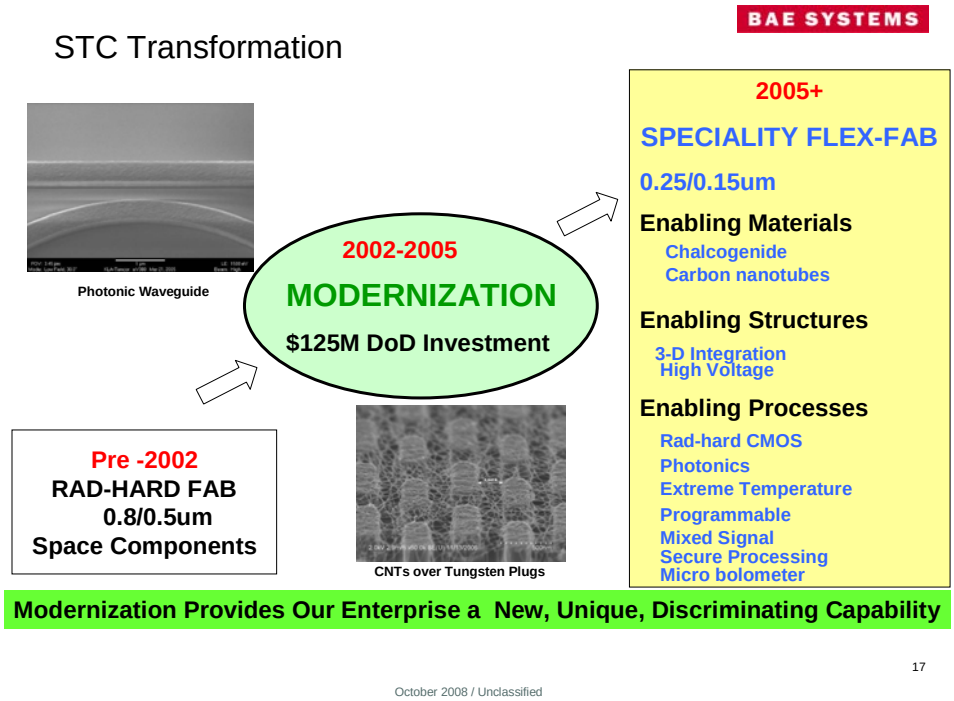
Many ICs + Frame

- **Single Board Computers**
- **Special Function**

Systems

Many Boards + Backpanel+ Power Supply + Housing

- **Digital Processing**
- **Data Routing**
- **Solid State Recorders**



<u>Uses Of Technologies and Products and relevancies to EJSM:</u>

The full breadth of BAE Systems technologies and products/services will be able to be utilized to support EJSM. For the instrument providers, our System Engineers/Architects will be able to provide a solution that optimizes science with SWaP in mind. The use of our current and future technologies and products can be inserted in a spiral evolutionary approach to insure that science is gathered and the harsh environments of the Jupiter system are kept in check. A list of the technologies and products that BAE Systems believes have relevance to EJSM and the TRL level they are currently at or will be in the future is provided in the table below. Each of the elements are either under contract today or have a funding path from the either IRAD or other Government sources. The "Rad Tolerant" technologies meet the minimum JEO requirement of 100 Krad (Si) behind 100 mils of shielding. The "Rad Hard" technologies meet the JEO mission requirement of 817 Krad (Si) with 320 mils of aluminum.

Technology or Product	Current Status	Future	Comment
Rad Tolerant (RT) 250nm RHBD Technology	TRL 9: QML Q and QML V Qualified		Flight heritage with the 132MHz RAD750, Enhanced Bridge, 4Mb SRAMs and ASICs
Rad Hard 250nm Technology	TRL 8		Magnum SRAMs have been delivered

			to multiple programs. RH25 structured ASICs have been delivered for satellite integration but the launch date is unknown because it is a classified mission.
Rad Hard 250nm Technology with Chalcogenide CRAM Technology Qual	TRL 7	TRL 8 2010 Technology V Qual YE 2010	Early chalcogenide C-RAM modules have been delivered to a technology mission; C-RAM enters into production in 2009
Rad Hard 180nm Technology	TRL 6	TRL 8 2011 QML V Qual by 2011	RH 200MHz RAD750 QML Q Qualified
Rad Hard 150nm Technology	TRL 7	Technology Qual V Qual has been completed	Golden Gate ASIC and RH 16Mb SRAM are fabricated in this Technology
RH RAD6000	TRL 9 QML	.	RAD6000 product set has flown on SIRTF, All JPL Martian Rovers, MESSENGER and STEREO plus others
RT 132MHz RAD750	TRL 9		Flown on Deep Impact, MRO, LRO, LCROSS, MiniRF and others
Enhanced Bridge ASIC (RT)	TRL 9		Flown on MESSENGER and STEREO and will be flying on SDO, LRO, LCROSS and MiniRF plus others
RH Proms	TRL 9		Commericial Satellites and Classified Missions plus JPL Mars

			Rovers and others.
RH 4Mb SRAMs	TRL 9		MESSENGER, STEREO, Classified Missions and Commercial Satellites. Will fly on LRO, LCROSS, SDO and AEHF
RH L2 Cache	TRL 6 built in RH18 180nm Technology	TRL 9 2011	Will fly in 2011 Classified Mission
RH 200MHz RAD750	RH18 Technology TRL 6	TRL 9 2011	Will fly in 2011 Classified Mission
RH 250MHz RAD750	RH 15 Technology TRL 5	TRL 6 YE 2011	
RH Golden Gate Bridge 100MHz	RH15 Technology TRL 5	TRL 6 YE 2011	This ASIC Contains a RH Spacewire with RMAP + Dual 1553
RT SpaceWire router ASIC	TRL 8: through qualification (RT 250nm technology) and inserted into LRO and LCROSS satellites	TRL 9 June 2009	SpaceWire reusable core developed jointly with GSFC; RMAP enhancement currently under design

Investments to date on the capital and process investments made to bring the Specialty Microelectronics Center from 500nm to 150nm is in excess of $ 200M (combination of BAE Systems and Government Funding). The investments that have been made to develop, and qualify the above products are in the $ 150-200M range (BAE Systems + Government).

To date BAE Systems is proud of its achievement of having over 500 Space Computers in Space from the 1750A GVSC Space Computer to the RAD6000 Space Computer to the 132 MHz RAD750 Space Computer. Notable NASA Missions include all of the JPL Rovers, STARDUST, SIRTF, Kepler, MESSENGER, STEREO and its SECCHI Payload, Solar Dynamic Observatory, MRO, LRO, LCROSS and the MiniRF Payload.

BAE Systems is proud of its past performance in developing General Purpose Processors, RH Components (ASICs, Memory Products, Non-Volatile) RHPROMs, RH FPGAs, Single Board Products (Computer, Memory/SSR Cards, I/O Cards and C&T Cards), large SSRs, Large Payload Processing Units, Digital Channelizers, Hyperspectral Instruments and products for the Warfighters (Night Vision Technologies) all of these past

experiences demonstrate our knowledge and breath in the radiation hardened technology, design, parts procurement and management, fabrication and qualification; all key to EJSM.

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Radiation Analysis and Support Capabilities of Southwest Research Institute – Space Sciences and Engineering Division

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Southwest Research Institute is uniquely qualified, as an independent research entity with broad experience in physics, analysis, and hardware development, to provide expertise, services, hardware and technologies to ensure avionics and instrumentation will survive and operate in the challenging EJSM radiation environment.

Southwest Research Institute (SwRI), headquartered in San Antonio, Texas, is one of the oldest and largest independent, nonprofit, applied research and development (R&D) organizations in the United States. Founded in 1947, SwRI provides contract research and development services to industrial and government clients. SwRI consists of 11 technical divisions that offer multidisciplinary, problem solving services in a variety of areas of the engineering and the physical sciences. Nearly 2,000 projects, funded almost equally between the commercial and government sectors, were active at the Institute at the close of fiscal year 2008 providing total revenue for this fiscal year of $563 million. More significantly, during 2008, SwRI provided nearly $7 million to fund innovative research through its internally sponsored R&D program.

At the close of fiscal year 2008, the staff numbered 3,323. This number includes professionals who hold 273 degrees at the doctorate level and 526 at the master's level. In 2008, staff members published 511 papers in the technical literature; made 345 presentations at technical conferences, seminars, and symposia around the world; submitted 55 invention disclosures; filed 41 patent applications; and received 39 patent awards.

Since 1977, the SwRI Space Sciences and Engineering division of SwRI has played a key role in NASA space physics and planetary missions. With world renowned expertise in planetary and space science, instrument design and fabrication, and avionic/data systems development, the Institute contributes significantly to understanding the space radiation environment, the solar system and the study of solar system bodies, in situ and remotely. Figure 1 is a photo of the engineering model HPCA instrument which will fly on the MMS mission.

Figure 1. Hot Plasma Composition Analyzer (HPCA) EM, part of the SwRI PI led Magnetospheric Multiscale Mission (MMS).

Using state-of-the-art computer modeling and data analysis techniques, the Space Science Department investigates the solar wind, the solar system and other astrophysical phenomena from theoretical and observational standpoints. Historically, space research at SwRI has emphasized magnetospheric and auroral physics, centering on the Earth's plasma environment and its response to the solar wind.

Complementing these activities is SwRI's space instrumentation program. SwRI-developed plasma instruments have flown on sounding rockets and satellites, including the two Dynamics Explorer spacecraft, the Upper Atmosphere Research Satellite, the Polar spacecraft and the Cassini Saturn Orbiter (See Figure 2). Other instruments include a novel energy-mass spectrograph for energetic neutral atom imaging of magnetospheric plasmas, a miniature electrostatic dual spherical analyzer for concurrent ion and electron measurements of auroral plasmas, a miniaturized optimized smart sensor (MOSS) for in situ plasma measurements, embody NASA's philosophy for future space missions.

The Space Systems Department is a leading developer of processors, command and data handling systems, and related electronics for space flight. The department has full capabilities in system and subsystem design, fabrication, and testing. SwRI processors have flown on more than 30 space missions without an on-orbit failure. Figure 3 is a photo of radiation hardened flight model avionics for the Deep Impact mission.

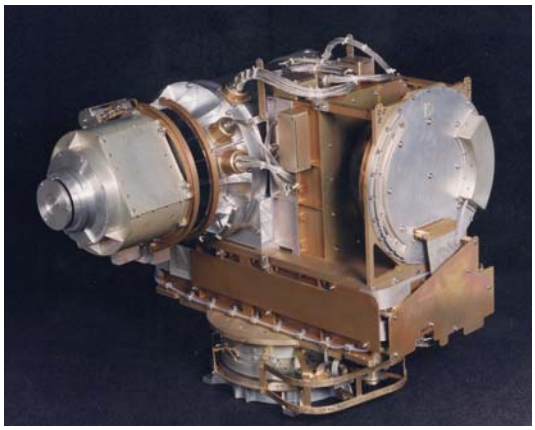

Figure 2. Cassini Plasma Spectrometer (CAPS).

Historically, SwRI was the PI institution for IMAGE, the first PI led MIDEX mission that went on to explore the interaction of the magnetosphere with the solar wind. After the very successful IMAGE mission, (ahead of schedule and under budget) SwRI has gone on to be selected as the PI institution for the New Horizons mission to Pluto, IBEX, JUNO, and MMS. As the lead institution, SwRI is responsible for ensuring that all components will survive and operate in each of the missions unique radiation environments.

Besides being the PI institution for many missions, SwRI has also provided instruments or avionics components for over 85 missions. This hardware runs the gamut from an instrument to a single board to the entire spacecraft avionics. Every mission requires the design procedures and analysis capability to guarantee that the hardware will survive and operate in the environment. In some of these missions SwRI created the models to predict the expected environment.

Over the decades, SwRI has worked closely with the radiation community. SwRI has regular communications and interaction with the radiation and parts engineers at GSFC, JPL, MSFC, and JSC. SwRI developed the electronics for the MSFC Gamma Ray Burst Measurement Instrument on GLAST, and is currently working with JSC to produce a radiation monitor for the space station and the manned missions to the moon and Mars. SwRI’s background in space-radiation effects goes well beyond parts characterization to include the knowledge, expertise, and understanding of the actual physics of the space radiation environment. SwRI is also an active participant in the space radiation related conferences. Numerous papers have been submitted to NSREC, SEE Symposiums, MAPLD, and RADECS. Each of these conferences are regularly attended by SwRI’s radiation and design engineers to keep them abreast of new developments in the community

SwRI will typically follow the radiation mitigation process from mission conception through on-orbit analysis and proof of models. At the proposal phase, SwRI will work with the spacecraft and systems engineering teams to establish the orbit and determine the radiation environment that the spacecraft will encounter. To predict the total dose and the high energy single event

effects environment requires a thorough knowledge of orbital mechanics and the intensity of the solar and cosmic environment. Without a comprehensive radiation environment prediction, the proposal cannot be accurately costed and mass/power predictions may be off. Careful modeling at the earliest stage guarantees that shielding mass is included, risks are identified and mitigated and the additional cost of radiation testing and shielding is understood and included.

Beyond the proposal and award phase, SwRI works with the entire team to establish and control the radiation aspects of the design through authoring the specifications and analysis to chairing and attending reviews. Each design from each team member must be evaluated for appropriate radiation mitigation.

Proper radiation hardened design begins at the lowest level. Over the decades, SwRI has compiled a list of tolerant technologies and devices for the designer to choose from and has staff specially assigned to maintaining this comprehensive data base by attending conferences and staying in direct contact with the community. Since SwRI designs cover all aspects of spacecraft hardware from both high and low voltage power supplies, to state of the art computers, to communication hardware, the list covers all devices for high voltage opto-FETs to radiation hardened microprocessor. Every designer is strongly encouraged to pull from this list of devices, but as everyone knows, there is always a part or two that the design requires that has not been tested for radiation effects.

All aspects of radiation effects must be evaluated when selecting a part for a space application. The most common effects are Total Ionizing Dose (TID) and Single Event Effects (SEE) which are further broken down into Single Event Upset (SEU), Single Event Transient (SET) and Single Event Latchup (SEL). TID effects can increase leakage and gradually change a devices gain and thresholds. SET and SEU are where a particle causes the output of the device to erroneously change state or have a noise spike. An SEL can destroy a device and occurs when a particle creates a false PNPN junction within the device. Other effects to consider are Extremely Low Dose Rate Sensitivity (ELDRS) which primarily affects bipolar linear devices, Single Event Gate Rupture (SEGR) which primarily affects power FETs, proton displacement damage in opto-coupler devices.

When a designer requires a part that has no radiation history, our physicists and parts engineers first evaluate the technology that the device uses. Certain foundries and technologies offer the hope of radiation tolerance while others fail miserably. After the part has been evaluated at the silicon level, the decision is made whether or not to test the device or continue to look for a more suitable replacement. Should a device be selected for radiation testing, SwRI will either work with one of the NASA centers to arrange testing or have the device tested itself.

Figure 3. Flight Prove Radiation Hardened Avionics Hardare on more than 30 missions

SwRI has ready access to a Co60 Hot-Cell that can provide a dose rate of up to 1 Mrad(Si)/hour and we are very close to the facilities at Texas A&M University (TAMU). SwRI personnel have performed radiation testing at TAMU, Berkeley, Harry Diamond, UCDavis, Brookhaven, CERN, and iThemba to name a few. Not all activity at these sources was to characterize a part, some was to calibrate radiation

instrumentation that has been developed and produced by SwRI. SwRI has characterized the radiation effects on dozens of devices such as the VIRENA ASIC, the MSA0760 MMIC, the AD648, the HV801, and the AD713. SwRI is an active participant in the current effort to qualify the Xilinx Virtex 5 for a broad spectrum of space application. Several papers have been submitted by SwRI radiation engineers on the Xilinx family.

After testing, a final report is written for the device and decisions made about its use at all or if additional shielding is required. Radiation tolerance and hardening is not solely an issue of parts selection – it is also an issue of packaging. Since every material between the particle and the device itself affords some level of shielding it can and should be considered in the environmental model. Of course, the simplest and most conservative shielding model is to take the thinnest portion of the chassis and consider that a spherical shield around the component and if the component can survive that dose without further consideration, the task is complete. However, there are times when the simplest model is not sufficient and a more detailed ray-trace model initiated. A ray trace model looks at every spacecraft component and considers it contribution to the overall radiation environment of the device in question. A good ray-trace model identifies where there is sufficient shielding and where an increase in chassis thickness or application of an aluminum or tungsten shim can provide sufficient protection for a device.

While commercially produced components are desirable due to their low cost and mission heritage – there are occasions where no commercially component is available that can do the job and an ASIC must be considered for the application.

SwRI is the PI institution for the Radiation Assessment Detector (RAD) of the Mars Science Laboratory (MSL) mission. This high dynamic range instrument will characterize the Mars radiation environment. The RAD mission's challenging power and weight constraints led SwRI to develop a mixed-signal ASIC to save over 5kg and 10W called the VIRENA (see Figure 4). The VIRENA is a first pass silicon ASIC specifically built and tested for the challenging space radiation environment. It was hardened using non-standard features at the silicon level and careful foundry selection. The TID tolerance of the VIRENA is in excess of 100kRad (Si), SEE is better than 45MeV-cm2/mg and no latch-up was observed in testing. The experience gained by SwRI while developing the VIRENA is directly applicable to any mixed signal ASIC for space instrumentation.

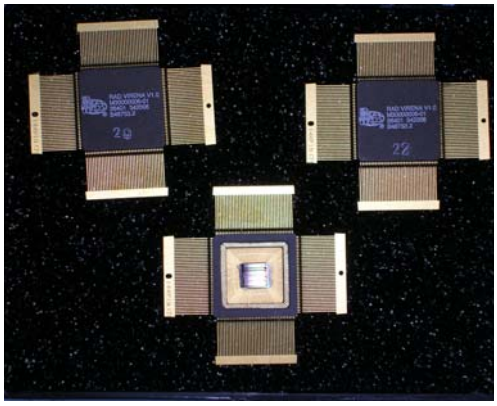

Figure 4. VIRENA ASIC for the Radiation Assessment Detector on the Mars Science Laboratory

SwRI has developed and produced a radiation hardened Command and Telemetry ASIC that performs CCSDS compliant command decoding, data formatting and Turbo encoding of the downlink. The ASIC was developed entirely under SwRI IR&D funding to serve as the core of the next generation of Command and Telemetry hardware from SwRI. This ASIC used foundry techniques and feature libraries to achieve a predicted TID of 100kRad (Si) and no latchup at >100MeV-cm2/mg. Testing is still pending.

JUNO and RBSP are two missions with very challenging radiation environments that are directly comparable to the EJSM. SwRI is producing the electronics for the UVS and JADE. Currently the shielding for the

electronics package is a titanium "vault" with walls up to 0.5" thick. The earlier design used tungsten which proved too difficult to machine and produce. Even with Ray Trace analysis the actual dose (and without the typical RDM of two) behind the wall is on the order of 15Krad for some critical components. This relatively high dose behind considerable shielding led the designers to pick components that are rad-hard to 50krad minimum. This required special attention to the usual analog bipolar components for High Dose Rate and ELDRs, and the selection of specifically rad-hard ADCs and DACs, optocouplers for HV and digital isolation functions, rad-hard memories, special filtering of high speed Low Drop Out (LDO) regulator outputs for SET mitigation. Individually shielded commercial components did not prove useful for the JUNO environment. For example, while there are many repackaged very high performance and low power ADCs on the market, it was necessary to use the rad-hard ADC 9225 from Honeywell for Juno with its power penalty of 250mW.

As part of the Radiation Belt Storm Probes (RBSP) mission, SwRI and LANL are developing the Helium, Oxygen, Proton and Electron (HOPE) spectrometer for the Radiation Belt Storm Probes — Energetic particle, Composition, and Thermal plasma (RBSP-ECT) mission study, led by Boston University. SwRI is building the electronics unit and microprocessor, writing the operating software and developing the spacecraft interfaces. To accommodate the radiation environment, the electronics are housed in a aluminum chassis with a minimum wall thickness of 0.300". With that level of shielding, components were selected that had a minimum TID tolerance of 30Krad (Si) to provide a minimum RDM of two.

SwRI is a unique institution in that it is similar to both a university and commercial industry. With that university/corporate mentality, SwRI interfaces and teams extremely well with universities providing them with the experience and resources they lack. This is particularly important in the areas of Quality Assurance (QA) and Product Assurance (PA) which includes all aspects of radiation analysis. SwRI's expertise has led to the success of several university led missions such as Swift (Penn State University), Galex (UCBerkeley) and RAD (Christian Albrecht University – Kiel, Germany). SwRI is an excellent teaming partner with the experience necessary to assist a university led payload or mission.

SwRI has produced radiation hardened hardware for many missions including IMAGE, UARS, CASSINI, Deep Space1, Orbital Express, Deep Impact, Kepler, QuikSCAT, ICESat, GPB, AcES, Coriolis, CALIPSO and many, many more (more than 85). SwRI parts engineers, design engineers, systems engineers and program managers are very well known and respected throughout the space community, and are regularly asked to participate in radiation design and document reviews for both civilian and defense missions. As the PI institution for multiple PI-led missions, SwRI has been directly responsible for the radiation performance of the entire spacecraft without incident.

SwRI's has demonstrated over three decades of exemplary radiation hardened experience spanning from flight proven hardware to the physical understanding and study of the space radiation environment. As a strong and experienced team member, Southwest Research Institute will provide services and broad expertise; guaranteeing the success of the EJSM.

RESPONSE TO REQUEST FOR INFORMATION (RFI)

NNH09ZDA008L Radiation Capabilities for the Europa Jupiter System Mission

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The ASI team presents significant expertise in all aspects of natural and induced environment modeling for space applications. Our personnel have assisted government programs in flight dynamics calculations, orbital simulations, radiation environments modeling, requirements development, laboratory testing, and validation. ASI also develops knowledge-based software for many customer requirements including: databases, orbital environment simulators, 3-D modeling tools, and radiation transport models.

ASI is under contract with the Missile Defense Agency to commercialize its Radiation-tested parts Catalog (RadCat™), and develop a series of codes for the hardening of electronics and materials which may be exposed to the natural and induced radiation environments. RadCat™ is a fully functional database, but further software tool development is underway based on the needs of our clients. These software development projects include a Radiation Hardness Assurance Toolkit (RadHAT™) for improved modeling and transport calculations, and the Radiation Test Assistant (RadTest™) for test planning and report generation.

RadCat™ currently includes over 5,000 radiation-tested or hardened parts with links to thousands of tests, test providers, and manufacturer's product listings. The database is supported by MDA with no user fee. The database is open to all U.S. persons, and should assist designers in locating radiation tested and hardened electronics parts for the high natural environment requirements presented for the Jovian mission. A sample of the database shows a limited number of vendors available for 100 krad parts and a very limited part selection when the total ionizing dose requirement approaches 1,000 krad. However, significant cost savings may be realized by the+ purchase of radiation-tolerant electronics parts where available and lot purchases for parts requiring radiation testing.

RadHAT™ is a data integrator and software director that interfaces with industry standard software such as Satellite Tool Kit (STK™), AE-8, AP-8, and outputs from CREME96. RadHAT™ also moves 3-D data from computer-aided design (CAD) models through Raytheon's Translation Optimization for Part-wise Adaptive Combinatorial Transport (TopAct™) software. The RadHAT™ and TopAct™ software converts the user's spacecraft model into the inputs required by well-established radiation transport codes such as Shielddose, MCNPx, HZETRAN, and NOVICE. This 3-D approach to modeling may allow the placement of critical, but

insufficiently rad-tolerant, components in a low-dose area without the addition of shielding. This software suite allows the use of CAD models for an accurate determination of dose for each part, and the development of requirements with less margin of error resulting in less expensive electronics parts, lower requirements for radiation testing, and less overbuild in the final product.

RadTest™ part tracking software will keep projects on schedule, on budget, and within risk. Entering the Bill of Materials (BOM) into the RadTest™ system will allow the tracking of the test requirements, aid planning for the required tests, standardize test reporting, and matches each test to the validation of the specific component tested and to its criticality in a spacecraft system so that risk can be accurately evaluated and a schedule can be maintained. RadTest™ will also allow engineers to formulate validation to match requirements specific for each element in the design.

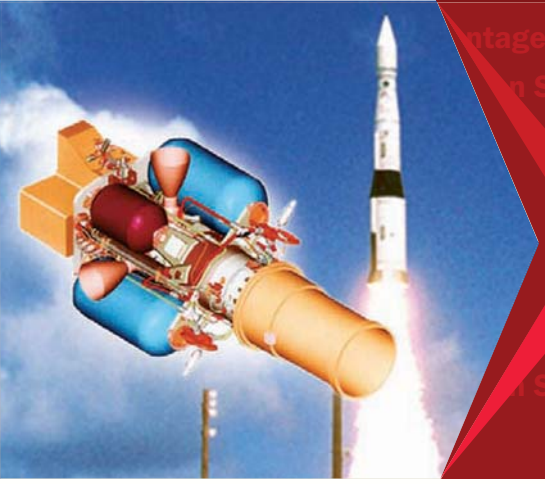
Through the use of ASI's expertise and these knowledge-based systems, the requirements definition can be made with a minimum of margin, radiation hardened parts can be chosen where available, and the validation of multiple systems can be tracked on schedule in a public database across multiple management desktops simultaneously. ASI is uniquely positioned to aid NASA in the development of a next-generation system for radiation-hardened spacecraft design.

Corporate Information

Incorporated in 1992, Analytical Services, Inc. (ASI) is a management and technical solutions company providing dedicated, professional services and support to Federal and Defense customers across the U.S. As a small, disadvantaged business under North American Industrial Classification System (NAICS) 541712 and 517110, ASI has grown to 373 employees and current three year revenues average $64.6 million. Over the past ten years, ASI has demonstrated stable and consistent growth in both employees and revenues. Corporate headquarters is in Huntsville, AL with additional field offices in Arlington, VA, Dayton, OH, and Montgomery, AL.

ASI's diverse customer base includes organizations and agencies from the Army, Air Force, Navy, Coast Guard, Department of Homeland Security, and the National Aeronautics and Space Administration (NASA).

ASI's core competencies are information technology (IT), engineering, business management, and logistics. ASI's highly technical staff has extensive expertise in integrating information systems, providing new information technologies, providing innovative IT solutions, and applying Lean Six Sigma processes to improve productivity and maximize throughout with existing staff personnel, and within existing hardware and software resource constraints. ASI is committed to providing outstanding service, innovation, and competitive costs, with minimum risks and best value to customers, ASI is helping customers improve their bottom line. Dedicated to exceeding expectations and providing high quality services, ASI is ISO 9001:2000 registered by the National Quality Association, and is planning an appraisal of CMMI Level 2/3 ratings (continuous model) in the third quarter of 2009. An award winning company, ASI has received local and national recognition.



Radiation Hardening Catalog (RadCat™)

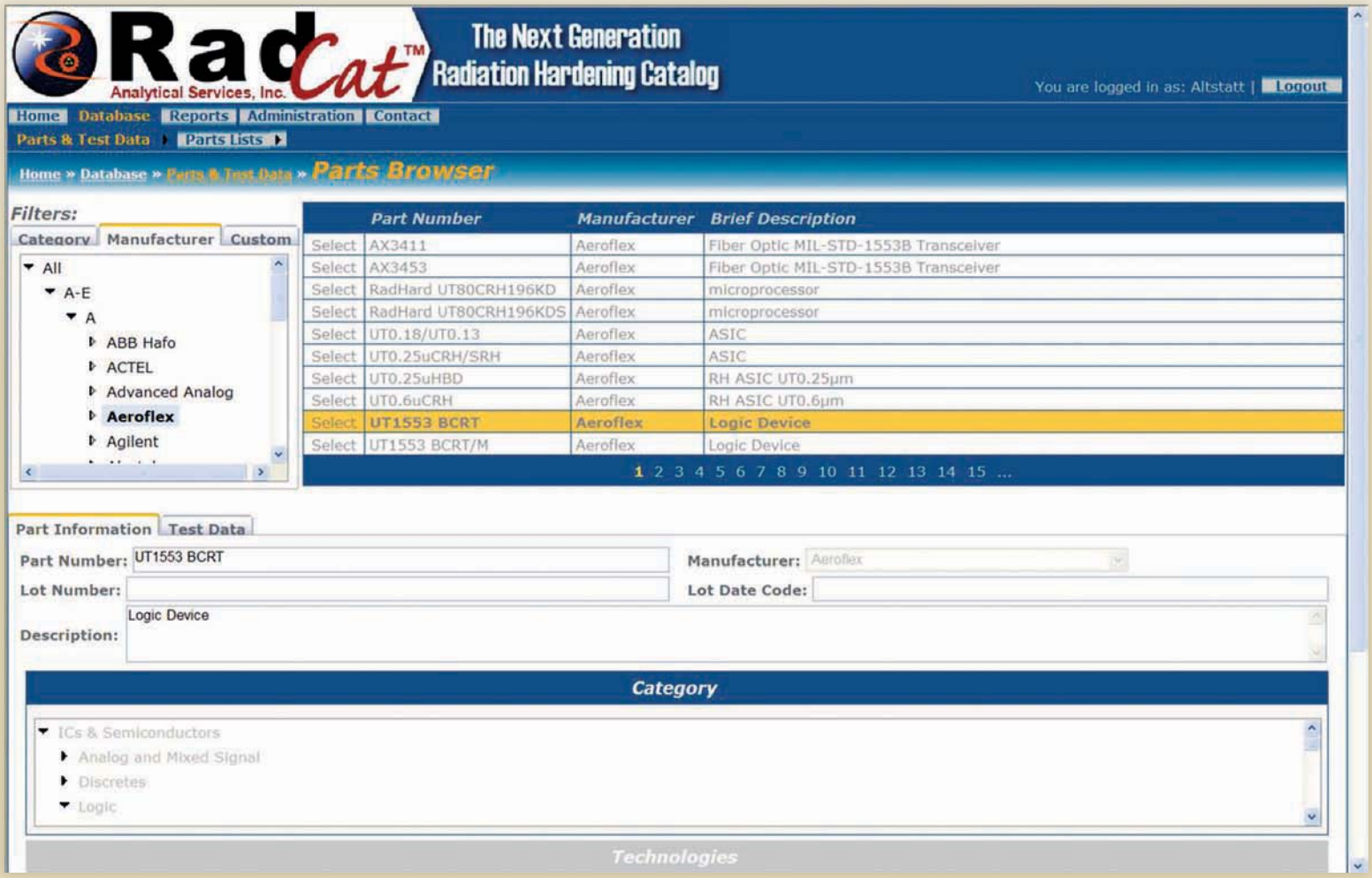
Customized Software Solutions Group
Aerospace Engineering Group

Analytical Services, Inc. • 350 Voyager Way • Huntsville, AL • www.asi-hsv.com

Penetrating radiation resulting from nuclear weapons effects--gamma rays, neutrons, and high-energy ions--presents serious design problems for the Ballistic Missile Defense System (BMDS). Such radiation can cause transient errors in electronic systems, and can permanently damage electronic components. In space environments, large fluxes of high-energy photons, protons, and heavy ions can upset flight control and guidance systems, inducing errors that could cause functional failure. Technologies, components, and systems must be radiation hardened either by design or processes to lessen these risks and address these challenges.

In the past, information from manufacturers and vendors was neither located in centralized databases nor tracked and managed in a consistent format. To enhance radiation hardening design and processes, the industry needed a modern tool that could store test and product data, reside on a centralized website location, and provide links to other radiation hardening applications.

Analytical Services, Inc. has developed RadCat™ to provide a single source, accessible to companies that have been assigned a Certification Number under the U.S./Canada Joint Certification Program System (http://www.dlis.dla.mil/JCP), for component data and test results. RadCat™ also provides access to CAD modeling software and industry-standard DoE-developed radiation transport codes. RadCat™ is an invaluable tool for the design and development of missile defense systems that will work efficiently in radiation environments.

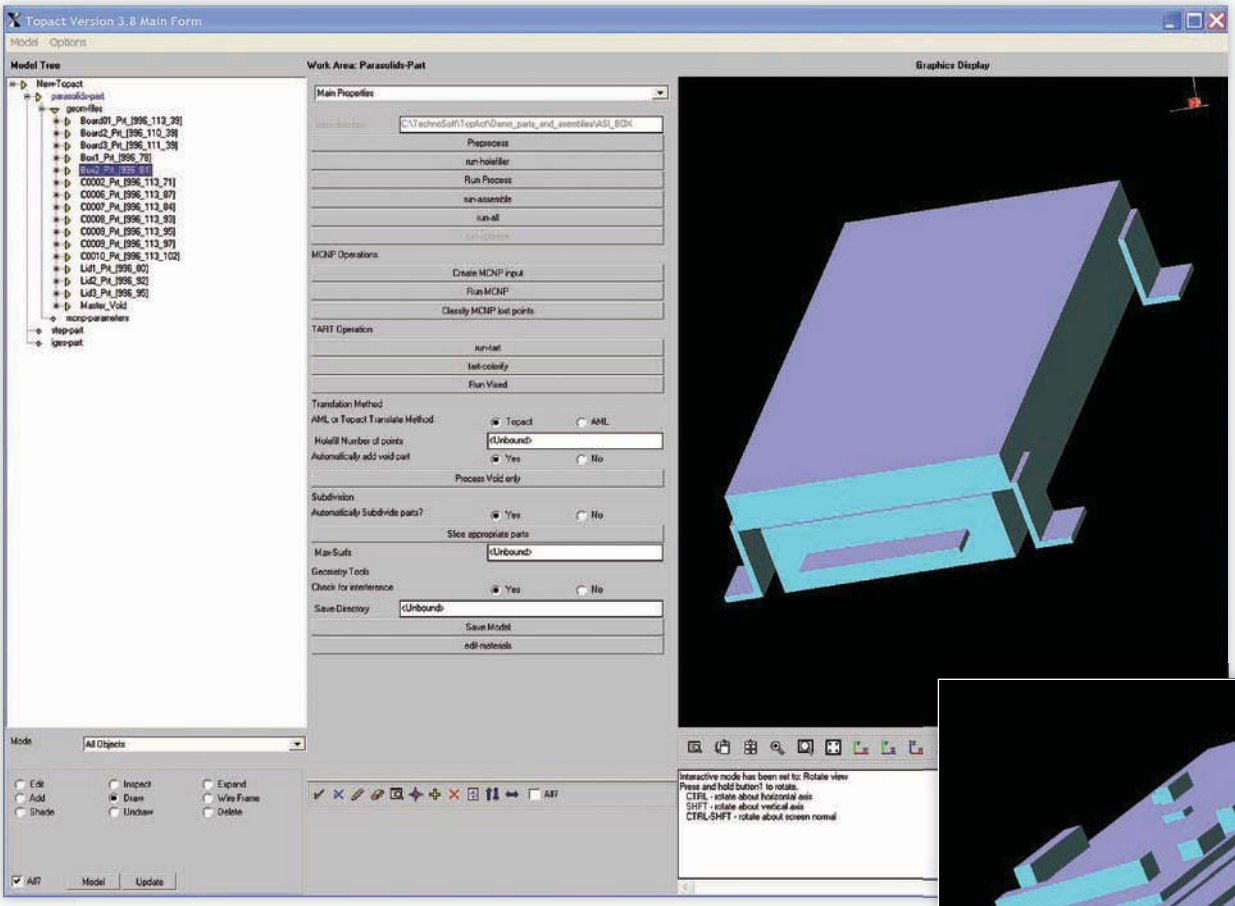


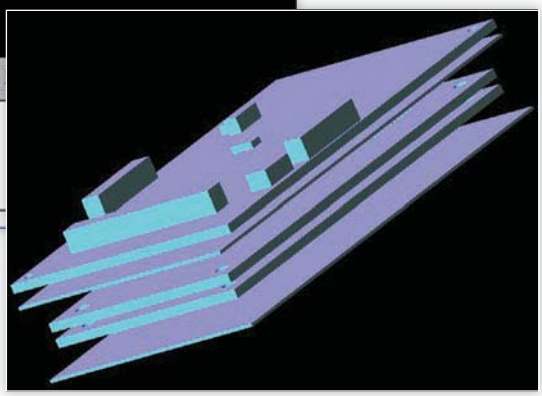
BENEFITS

- Web-based application
- Offers intuitive, secure access
- Uniquely identifies parts, components and materials for radiation transport and physical analysis
- Provides database search options and summary reports for parts, manufacturers, and test data with user defined or default search criteria.
- Includes a hierarchical authorization scheme
- Interfaces with radiation transport analysis tools, like Translation Optimization for Part-Wise Adaptive Combinational Transport (TopAct)
- Supports 3-D CAD model designs of piece parts, components, and systems.

Visit the RadCat™ website at https://www.radcat.net

For more information on RadCat™ contact: Dr. Mike Guthrie at 256.562.2115 or guthriem@asi-hsv.com or Richard Altstatt at 256.562.2127 or altstattr@asi-hsv.com





Side view of image shown above.

Corporate Office: Huntsville, Alabama
Phone: 256.562.2100 **Web:** www.asi-hsv.com
Huntsville | Montgomery | Washington DC | Dayton

Short Title: Radiation Hardened Via-Configurable Analog Arrays
Full Title: SOI Analog/Mixed Signal ASICs for Radiation Hardened applications using Mixed Signal Via-Configurable Analog Arrays

Response to RFI - Radiation Capabilities for the Europa Jupiter System Mission Planetary Science Division, Science Mission Directorate, NASA
Solicitation number: NNH09ZDA008L

Submitter/PI: James Kemerling
Company: Triad Semiconductor, Inc.
Email: jkemerling@triadsemi.com
Phone: 336-774-2150

1. Introduction

Triad Semiconductor, Inc. has developed a novel, disruptive technology in analog and mixed signal application specific integrated circuits (ASICs.) Essentially this technology provides the capability to configure an entire analog or mixed-signal ASIC with a single mask layer. In this case, the mask layer used to configure the ASIC is a via layer, hence the name via-configurable analog array (VCAA.) Although the primary focus of this technology is analog, mixed-signal devices are supported as well.

Triad's VCAA technology has been successfully introduced and proven in the commercial market sector. With appropriate funding, in partnership with Sandia National Laboratories, this disruptive technology can be migrated to Sandia's Silicon on Insulator (SOI) 0.35μ CMOS semiconductor process resulting in radiation hardened VCAAs for Aerospace and Military applications. A digital library has already been ported to this process as substantiated by Sandia's ViaArray moving to production in 2009. In summary, putting Triad's VCAA technology in Sandia's SOI process will provide the same benefits the commercial market sector enjoys to the Mil-Areo community in a proven radiation hardened process.

2. Triad Background Information

Triad Semiconductor is a fabless provider of mixed-signal via-configurable ASICs. Their proprietary via-configurable array (VCA) intellectual property allows for the creation of single mask mixed-signal ASICs by pre-configuring VCA platforms with silicon-proven analog and digital functions and then overlaying these embedded functions with a global routing fabric. Partially processed wafers containing VCA die are staged at the semiconductor foundry. A customer's design is mapped or configured onto a VCA platform by a single mask layer (the via-layer between metal-2 and metal-3 global routing fabric.) This single via-layer mask is sent to the foundry for fabrication resulting in reduced fabrication cost, reduced risk and rapid access to prototypes and production devices. Some of the benefits of Triad's VCA technology are listed below.

- **Proven analog and digital building blocks**
- **Reduced ASIC development to configuration of an array of elements.**
- **Reduced time-to-market for custom mixed-signal ICs to as little as one quarter of the time typically required to develop a full-custom mixed signal ASIC.**
- **Lowered development costs by up to 90%.**
- **Simplified design for 'System on chip' that can replace multiple components on a printed circuit board.**
- **Economical small volume production for ASICs. Annual volumes in the thousands are practical, but still competitive for volumes over one million pieces annually.**

ASIC development is a particularly difficult problem in the Government market. Especially in aerospace where size and power requirements demand single chip solutions. These systems often require mixed signal products, so FPGAs do not represent a satisfactory solution. Via configurable analog/mixed-signal ASICs offer an ideal solution to enable single-chip solutions for these specialized applications.

Triad's VCA technology has proven successful in the commercial market space as evidenced by the VCA platforms currently in production. Migrating this technology to SOI will provide the same benefits to the aerospace and military market segments.

3. Technology Overview

The key ingredients required for developing VCAA and MS-VCA platforms are cell libraries. The digital library has already been developed and proven on Sandia National Laboratories 0.35μ SOI CMOS process. Consequently, all that remains is the migration of the existing bulk CMOS analog library to SOI to be a companion to the pre-existing digital library to support via configuration of analog and mixed-signal arrays.

The currently available via mask-programmable IP blocks are listed below. The majority of these IP blocks exist in standard 0.35μ bulk CMOS technology allowing for straight forward migration to the SOI process.

CELLS

- **wideband opamps**
- **low noise opamps**
- **comparators**
- **analog switches and muxes**
- **via configurable capacitor arrays**
- **via configurable resistor arrays**

MACRO CELLS

- **programmable gain instrumentation amplifiers**
- **digitally controlled amplifiers**
- **peak detector**
- **sample and holds**
- **integrators**
- **12 bit sigma delta ADCs**
- **16 bit sigma delta ADCs**
- **10 bit DACs**
- **12 bit pipelined ADCs**
- **digital potentiometer**
- **clock synthesis PLLs**

FUNCTION BLOCKS

- **capacitive sensor interface**
- **switched capacitor filters**
- **data acquisition system**

3.1. Technical Description

Mixed signal VCAs are composed of analog and digital tiles. These tiles are arranged in a configuration suited for a particular application. The following sub-sections describe the recommended analog cells, analog tiles and a MS-VCA

platform suitable for Europa Jupiter System Mission applications. The actual analog library and initial VCA/VCAA platform will be determined in the conceptual phase of the development process.

3.2. SOI Mixed-Signal VCA Platform

Figure 1 is an example floor plan of a VCA platform that may be suitable for the Europa Project's needs. The actual floor plan will be developed in the conceptual phase of the project. This particular platform has 162 logic tiles (~ 120 k gates), 40 analog tiles, 12 I/O amplifier tiles, 3 high speed DAC tiles, 2 high speed ADC tiles and several fixed analog blocks.

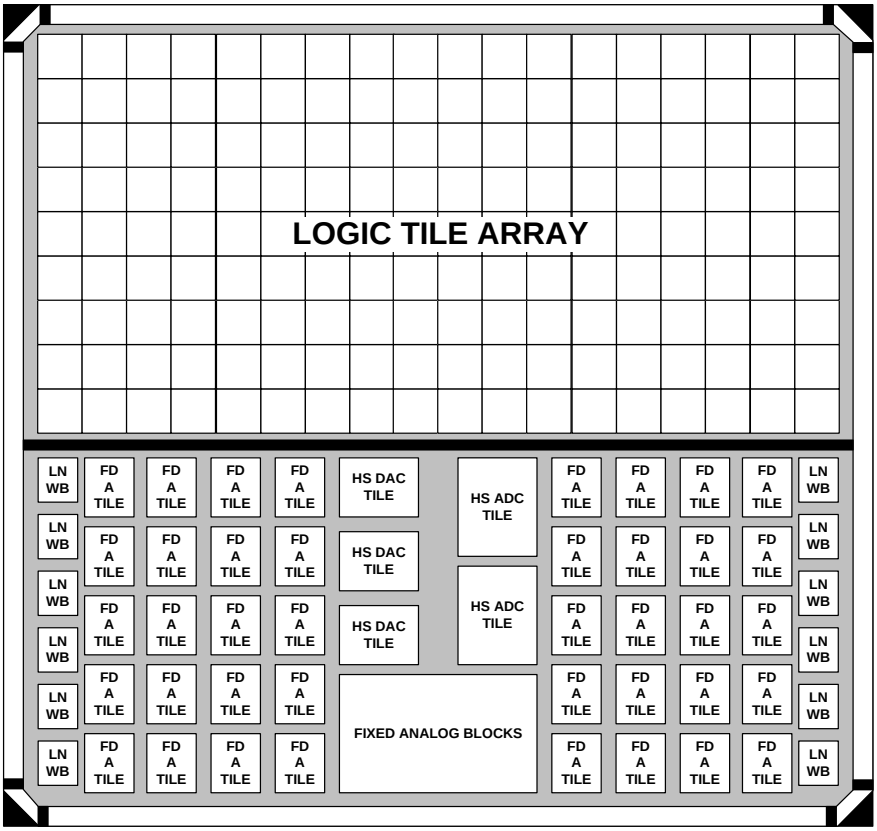


Figure 1: Example floor plan of an SOI VCA platform.

3.3. Fully Differential Analog Tile

Typically an analog tile is made up of multiple primitive cells. Figure 2 shows an example of an analog tile with two resistor arrays, two capacitor arrays, two fully differential amplifiers and one single-ended amplifier. In addition, logic gates, analog switches, and discrete transistors are included. The number of primitive elements in each array will be determined based on specified requirements. In general, a capacitor array contains approximately 200 unit capacitors with several remainders (used for non-integer ratios.) The resistor array, similar to the capacitor array, also contains several unit devices.

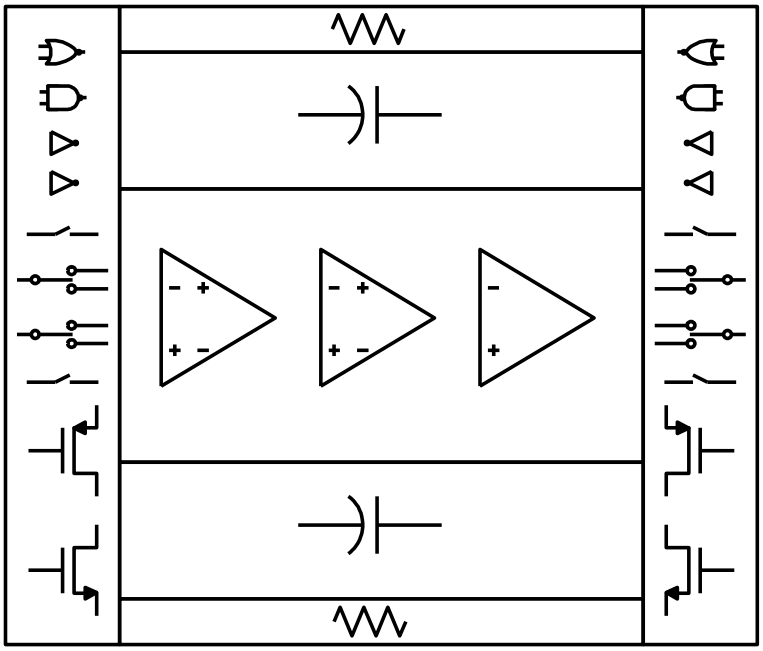


Figure 2: Fully Differential Analog Tile.

The analog tile displayed in Figure 2 is well suited for baseband analog signal processing tasks such as switched capacitor filters, continuous time filters, digitally controlled amplifiers, delta sigma modulators, analog-to-digital converters and digital-to-analog converters to name a few.

3.4. High Speed Data Acquisition Tiles

In some cases, the analog tiles do not provide an optimal solution to some larger mixed-signal circuits such as high-speed or high-resolution analog-to-digital and digital-to-analog converters. Consequently, high-speed ADC and DAC tiles are recommended for applications requiring sample rates exceeding 5 MS/s or word lengths exceeding 8 bits.

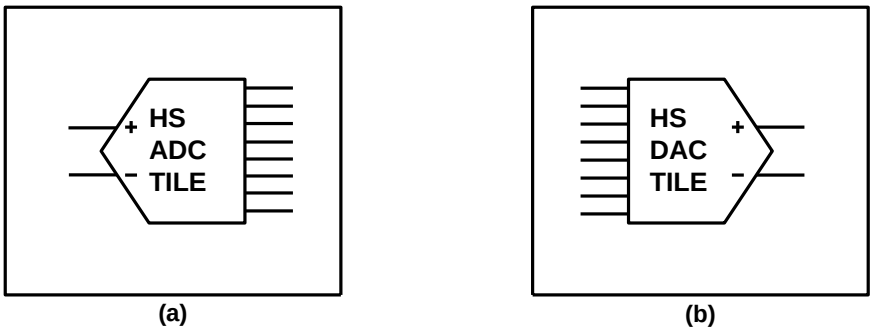


Figure 3: (a) high speed ADC Tile and (b) high speed DAC tile.

Figure 3 shows a simplified diagram for a high speed ADC tile (a) and a high speed DAC tile (b). These tiles are capable of implementing DACs and ADCs with speeds up to 30 MS/s and resolutions up to eight bits standalone, but can be cascaded to realize word lengths up to 12 bits.

3.5. I/O Amplifier Tile

Frequently it is advantageous to buffer low level analog signals coming from outside the chip as close to the input pad as possible. In addition, signals going off-chip frequently need to be buffered for driving low impedance or highly reactive loads. Hence, the I/O Amplifier Tile is recommended and can be configured as a low noise amplifier and/or a high drive, wide band amplifier.

3.6. Fixed Resources

Fixed resources can be any full-custom block which is not via-configurable. These blocks generally consist of band gap references, low speed (< 200 kS/s), low resolution (< 8 bit) ADCs and DACs.

4. Key Personnel and Bibliography of Related Work

James C. Kemerling brings 25 years of broad analog and digital signal processing and integrated circuit design experience ranging from transistor to system level. He has developed numerous low power consumption sensor interface, waveform CODEC, mobile radio, and data modem IC products during his career. Most recently he has been focused on developing Triad Semiconductor's Mixed Signal Via Configurable Array technology for which he is named the primary inventor on the patent. In addition, he has been an investigator/technical integrator on data acquisition and signal processing system for structural health monitoring applications funded by AFRL.

In the ten years prior to co-founding Triad Semiconductor, Mr. Kemerling directed the R&D activities of MX-COM, Inc. (now CML Microcircuits, USA) as Vice President of Product Development. The company designed and manufactured low power consumption mixed-signal ICs for the communications industry. Other prior employers include Kemerling-Sorrels, Inc., Aritech, Inc., General Electric/Ericsson, Lynch Communication Systems, Inc. and Rockwell International.

Mr. Kemerling earned his Bachelor of Science in Electronic Engineering from South Dakota State University in 1981 and his Masters in Electronic Engineering from the University of Nevada in 1987.

Relevant Publications and Patents

J. Kemerling, M. Turner, and R. Wender, “Structured Analog IC Design Example using Mentor Graphics tool flow”, U2U 2006.

J. Kemerling, C. Hopper, and D. Ihme, “Structured Analog ASICs using the Mentor Graphics tool flow”, U2U 2005.

J. Kemerling, D. Ihme and B. Cox, 2008 *Via Configurable Architecture for Customization of Analog Circuitry in a Semiconductor Device*, The corresponding US patent application no. 10/907,456 has been allowed and will issue shortly.

D. Ihme, J. Kemerling and B. Cox, 2008 *Configurable Integrated Circuit Capacitor Array Using Via Mask Layers*, US Patent 7335966.

Company name: B&A Engineering Systems Inc.
Point of Contact (PI): Alireza Bakhshi
Address: 440 S. Cataract Ave. Suite #H, San Dimas, CA 91773
Office# 909-305-6868
Cell# 909-524-1432
Email: alib@baengineering.com
Web-site: www.baengineering.com

COMPANY AND CAPABILITY

B&A Engineering Systems Inc. is a small business located in Southern California, Los Angeles with its primary focus on Space Flight Electronic Instrumentation design. We specialize in designing electronics in Space Radiation Hardened and Extreme Temperature environments.

We have helped our clients to develop Space Flight and Avionics electronic systems and boards from initial concept and specification to final Testing, System verification, Reliability analysis, Environmental testing support and Ground Support Equipment (GSE) development. Our designs have been used by both government and non-government entities such as NASA, Jet Propulsion Laboratory (JPL) and ATK (formerly Swales Aerospace).

Our core competency is in Electronic digital and FPGA/ASIC designs. We have extensive design experience with both radiation hardened/tolerant ACTEL (anti-fuse) and XILINX (SRAM based) FPGAs. Due to Single Event Upset (SEU) nature of SRAM based FPGAs, most of our space designs are based on anti-fuse ACTEL FPGAs, more so in mission critical applications in which an SEU can cause mission failure.

We also have been actively involved with research and testing of FPGAs to demonstrate operations beyond their normal operating temperature of -55 to +125 °C. Our studies and hardware testing had demonstrated that radiation hardened FPGAs can operate at temperatures as low as -130 to -150 °C. We are actively researching to formulate a process in which FPGAs can be modeled beyond their operating norm for back annotated HDL simulation. Such models do not exist at this time. Ability to model the FPGAs at such a harsh environment will have applicability in number of space missions such as EUROPA and MARS.

PAST PERFORMANCE

We have been involved with several of past and present JPL/NASA missions and instruments including Microware Limb Sounder (MLS), Mars Exploration Rover (MER), Ocean Surface Topography Mission (OSTM), Mars Science Laboratory (MSL), JUNO Polar lander and number of Research and Development projects.

Our main client is JPL/NASA and following are the contracts that we had or currently working on for the past three (3) years.

Subcontract no. 1284647 under JPL's NASA contract Task order no. NMO715853
Provided necessary labor, materials and facilities for the design, development and implementation of a Field-Programmable Gate Array (FPGA) code for gyroscope control and tuning digital hardware platform.

Subcontract no. 1288239 under JPL's NASA contract Task order no. NMO710979
Description: Provided necessary labor, materials and facilities for the design, development and implementation of electronics for the reconfigurable analog array-integrated circuit (an application-specific IC, ASIC) hardware platform.

Subcontract no. 1291389 under JPL's NASA contract Task order no. NMO715923
Description: Provided necessary labor, material and facilities for the design, development and implementation of a Field Programmable Gate Array (FPGA) code for JPL's Fast Lossless hyper-spectral Data Compression Algorithm (DCA).

Subcontract no. 1296037 under JPL's NASA contract Task order no. NMO710962
Description: Provided necessary labor, materials and facilities for the design, development and implementation of Proto-type, Engineering Model (EM) and Flight Electronic hardware for Micro Wave Radiometer (MWR) instrument used in JUNO Polar Orbiter.

Subcontract no. 1304963 under JPL's NASA contract Task order no. NMO710764
Description: Provided necessary labor, materials and facilities for the design, development, board layout, electronic assembly, implementation, test and integration of camera board for Mars Celestial Navigator (MCN) flight project.

Subcontract no. 1323536 for JPL/NASA Mars Science Laboratory (MSL)
Description: Provided necessary labor, materials and facilities for the design, development, implementation, test and integration of Engineering Model and Flight hardware for Chemistry & Mineralogy (CHEMIN) flight instrument used in Mars Science Laboratory (MSL) Lander.

SPACE RELATED PRODUCTS

General Purpose Space craft Interface Unit (GPSIU)

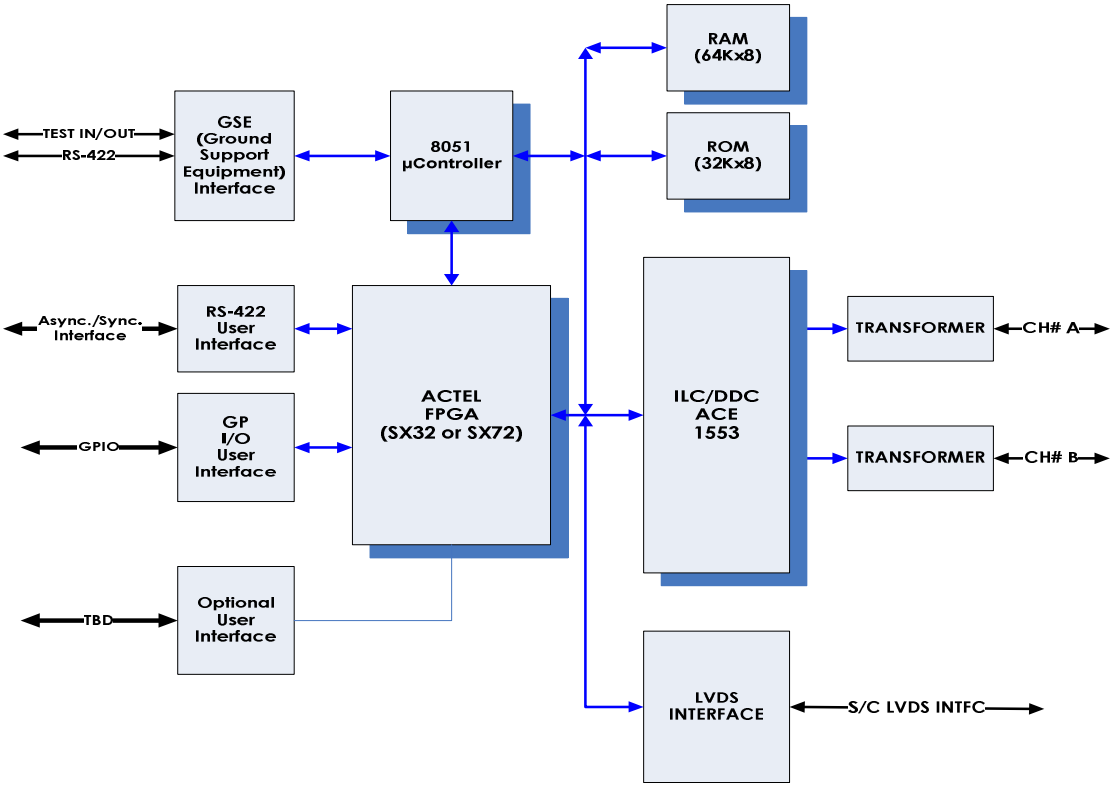
Due to our past design experience with development of space craft Command & Data Handling (C&DH) interface boards we saw an opportunity and a market for a General Purpose Space craft Interface Unit (GPSIU). Our experience has shown that C&DH interface boards poses many common features that do not required to be re-invented every time.

As a result we have designed and developed a radiation hardened general purpose board which will potentially reduce any instrument development cost and cut down the design cycle. This design is in the proto-typing stage and we are planning for space qualification by 2010.

FEATURES

1- LVDS and/or 1553 Space craft interface
2- Four Asynchronous/Synchronous RS-422 interfaces
3- Twenty General Purpose Inputs/Outputs (GPIO)
4- Ground Support Equipment (GSE) interface
5- Customer application specific customization
6- Controller with on-board RAM/ROM
7- Optional custom user interface (i.e. Space wire).

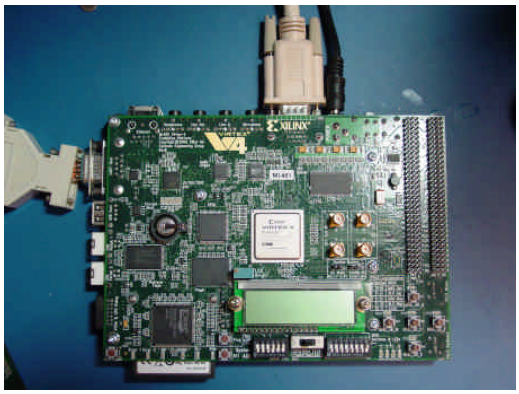
BLOCK DIAGRAM



Hyper-spectral loss-less compression IP for space

On-board lossless hyperspectral data compression reduces data volume in order to meet NASA and DoD limited downlink capabilities. The technique also improves signature extraction, object recognition and feature classification capabilities by providing exact reconstructed data on constrained downlink resources. A scalable field programmable gate array (FPGA) hardware implementation is developed. The FPGA implementation achieves a throughput performance of 58 Msamples/sec with 12 or 14 bit pixel data, which can be increased to over 100 Msamples/sec in a parallel implementation that uses twice the hardware resources.

Our FPGA implementation was benchmarked on the Xilinx Virtex IV LX25 device and ported to a Xilinx prototype board. The current implementation excluding the packer has a critical path of 17.5 nsec which dictated a clock speed of 58MHz. The critical path delay is and-to-end measurement between the uncompressed input data and the output compressed data stream. The implementation compresses one sample every clock cycle, which results in a speed of 58 MSample/sec or 58 times faster than the software implementation running on a Pentium IV machine. The implementation has a rather low device utilization of the Xilinx Virtex IV LX25 making the total power consumption of the implementation about 1.27 watts.

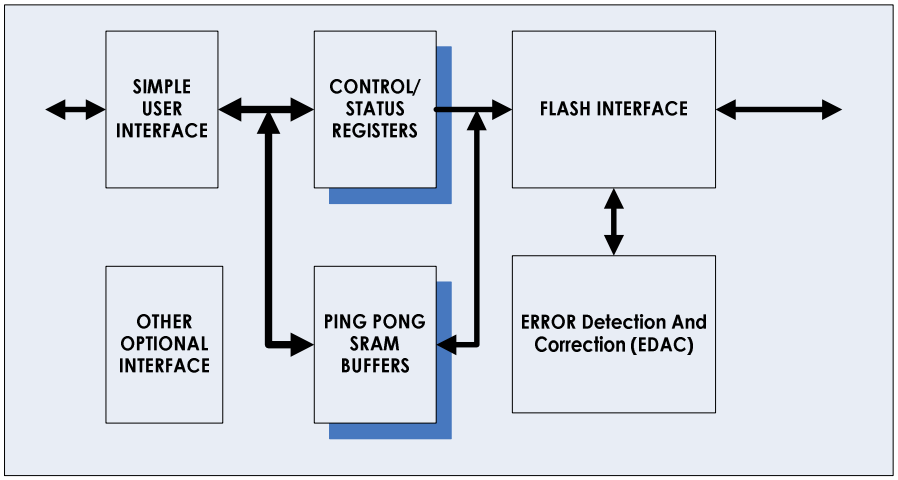


FLASH IP with EDAC designed around ACTEL Rad-Tolerant RTAX FPGA

FEATURES

1- Supports up to 2 banks of 8-bits NAND FLASH Devices
2- Each bank may contain up to 2 NAND FLASH connected in parallel for a total of 4 NAND FLASH devices.
3- Internal ping-pong buffers for continuous read data.
4- Access to the spare area (64 bytes) of FLASH area.
5- Single-bit correction and Double bit detection error correction.
6- Separate Program & Erase error bits.
7- Simple user interface.
8- Optional custom user interface.

BLOCK DIAGRAM



UTILIZATION TABLE

FPGA	COMB. CELLS	SEQ. CELLS	CORE CELLS	RAM/ROM BLOCK
RTAX2000	3778/21504 (18%)	2091/10752 (19%)	N/A	27/64 (20%)
APA1000	N/A	N/A	9467/56320 (16.8%)	54/88 (61.4%)

Memorandum For: Dr. Curt Neibur, Planetary Science Division, Science Mission Directorate, National Aeronautics and Space Administration, Washington, DC 20546

Subject: Request for information: NNH09ZDA008L (Radiation Capabilities for the Europa Jupiter System Mission).

NASA Langley Research Center (LaRC) has the capability to design, develop, test and deliver prototype radiation shielding materials and large structures for space missions. LaRC has the expertise to design and evaluate payload instrument and hardware shielding requirements. LaRC produces material sandwiches for radiation shielding effectiveness based on model predictions, tests in space environment conditions, and develops hardware. This multidisciplinary capability has the potential to support the Europa Jupiter System Mission.

NASA Langley Research Center has radiation shielding materials, modeling, and analysis capabilities with demonstrated expertise in mitigating radiation exposure risks to equipment and humans. The materials capabilities include: experimental determination of radiation shielding effectiveness and degradation evaluation by spectroscopy, microscopy, thermal analysis, and mechanical testing. Modeling and analysis skills for radiation shielding effectiveness have been demonstrated for solar particle events, galactic cosmic radiation, and trapped particle belts. Analysis products include radiation shielding effectiveness of materials in different hardware geometries, material slab depth versus dose charts, and additive shielding effects of multilayer material sandwiches. Deterministic and Monte Carlo codes have been used. In support of Jupiter moon modeling, NASA LARC scientists have modeled the trapped electron moon environments. This capability can be used to support radiation effects on materials, electronics response, instrument/sensor degradation, and payload shielding design and evaluation. The Revolutionary Aerospace Systems Concept study is an example of this effort.[1] In this study, the Hope Callisto Transfer Vehicle radiation shielding analysis was done in the trapped electron radiation belt environment. (Enclosure 1) The SAGE III analysis demonstrates LARC's ability to analyze radiation shielding effects on a sensor that is part of a spacecraft component design. The study shows the effects of radiation on a CCD detector.(Enclosure 2) NASA Langley Research Center excels at integrating material research and development with shielding effectiveness models to generate a complete radiation analysis product.

NASA Langley Research Center leads efforts in radiation testing of engineering materials for experimental understanding of shielding effectiveness. Engineering resins and composites have been tested with high energy protons and heavy ions. (Enclosure 3a) These exposures have assisted in the development of models and research and

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[1] De Angelis, G.; Clowdsley, M. S.; Nealy, J. E.; Tripathi, R. K.; and Wilson, J. W.; Radiation analysis for manned missions to the Jupiter system. Advances in Space Research, 34 (2004) 1395-1403.
[2] Wilson, John W.; Townsend, Lawrence W.; Schimmerling, Walter; Khandelwal, Govind S.; Khan, Ferdous; Nealy, John E.; Cucinotta, Francis A.; Simonsen, Lisa C.; Shinn, Judy L.; and Norbury, John W.: Transport Methods and Interactions for Space Radiations. NASA Reference Publication 1257, December 1991

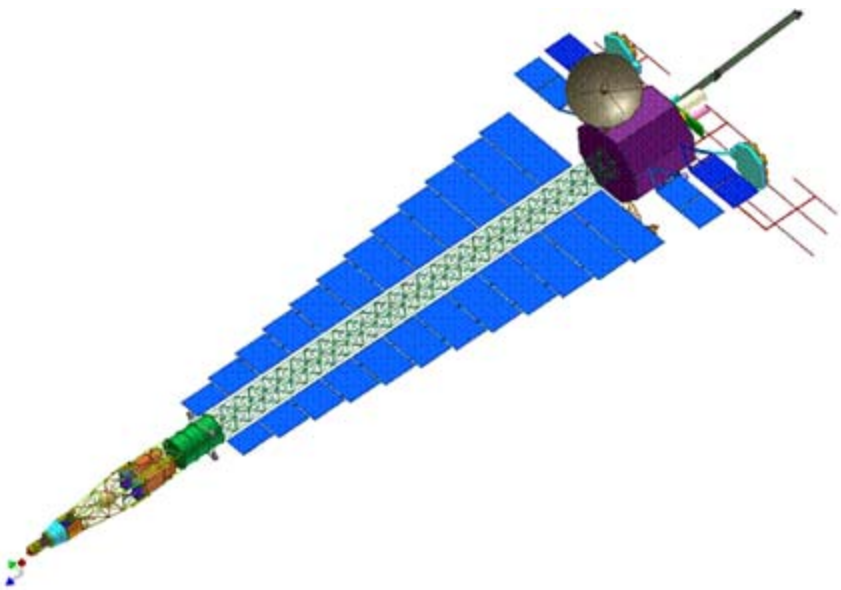
development direction. The heritage is lengthy to include resources such as the NASA Space Radiation Laboratory at Brookhaven National Laboratory, Berkeley National Laboratory, Texas A&M University, Prairie View A&M University, Los Alamos National Laboratory, and over forty years of pioneering modeling development[2]. The Materials International Space Station Experiment (MISSE) has been consistently used by NASA LARC scientists to better understand material performance in the low earth orbit space environment. (Enclosure 4a) MISSE has allowed scientists to better understand material performance in space in the atomic oxygen environment and the trapped electron radiation belt environment. NASA LARC has demonstrated the capability to model and test single event upsets in a radiation environment for microchips. (Enclosure 3b) Multimillion dollars have been budgeted over the recent years to support salaries and program investments. The modeling maturity can be best summarized as operational, because space operations at Johnson Space Center routinely use results from LaRC generated analysis tools along with current space weather forecasts to mitigate human and hardware radiation exposure for ISS and Shuttle missions.

LaRC has designed, developed, and delivered hardware ranging from structures with advanced materials to finished radiation shielding soft goods. PETI 5 a high temperature composite resin was developed during the high speed civil transport program and designed into an aircraft structure for large scale testing. (Enclosure 4b) PETI-5 and other LaRC polyimide resins have been tested for radiation shielding effectiveness with heavy ions. Many of these materials have flown on MISSE. The most recent capability has been the design, development, and delivery of the Advanced Radiation Shielding Kit for human space exploration. (Enclosure 5) Radiation shielding materials testing and modeling for solar particle events provided thickness guidance for the development of radiation shielding blankets and vest. Testing at White Sands Testing Facility has assisted with increasing the technological readiness of the prototypes. NASA LARC continues demonstrating the ability to invent, innovate and mature materials and structures.

The Europa moon mission has challenging spacecraft radiation protection requirements. NASA Langley Research Center materials and modeling collaboration is interested in communicating its radiation environment experience in support of the Europa Jupiter System Mission. If there are any questions, I can be reached at 757-864-4211 or by email: d.l.thomsen@nasa.gov.

D. Laurence Thomsen III, PhD
Materials Research Engineer

Jovian Radiation Environment Modeling Near Callisto



Piloted Callisto Transfer Vehicle

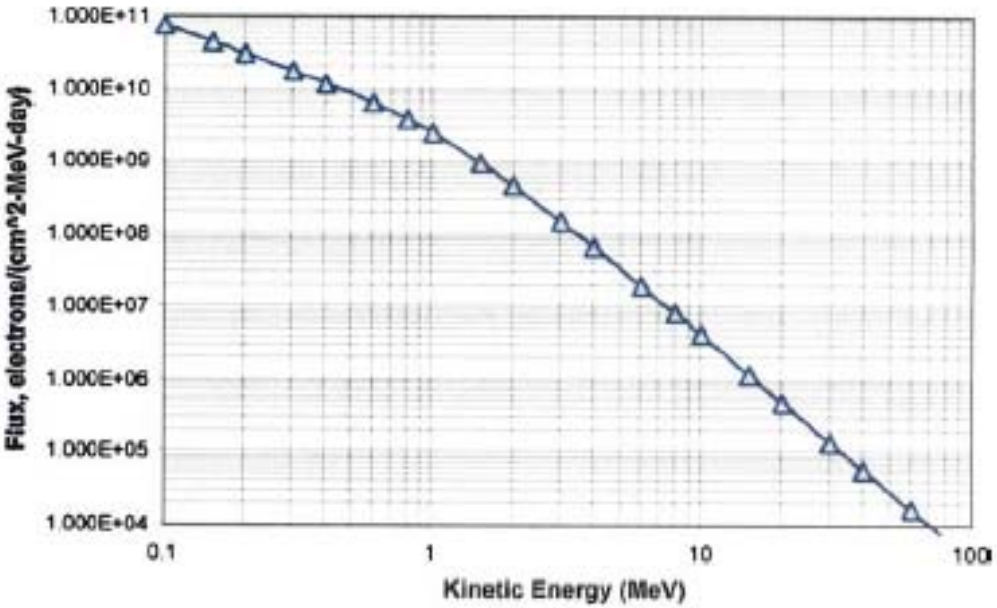
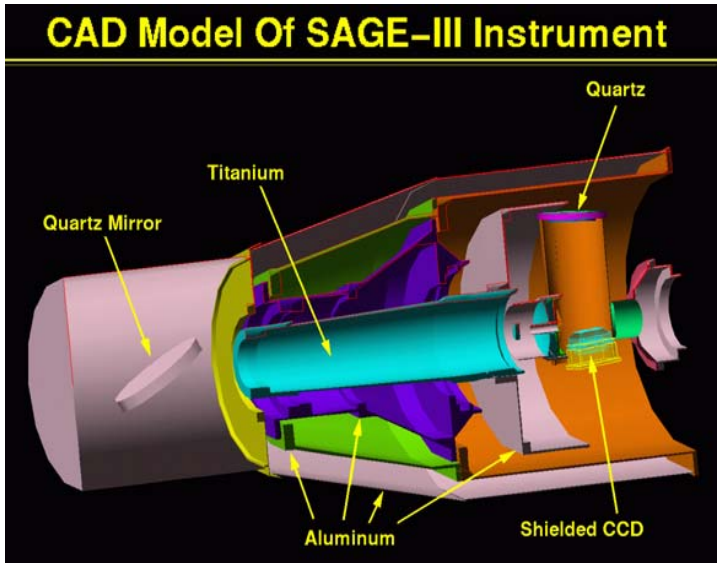


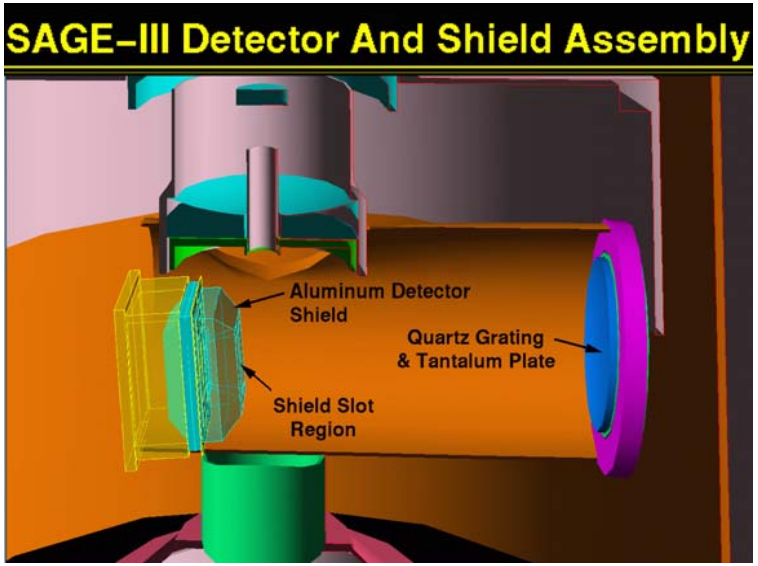
Fig. 9. Jovian electron environment near Callisto.

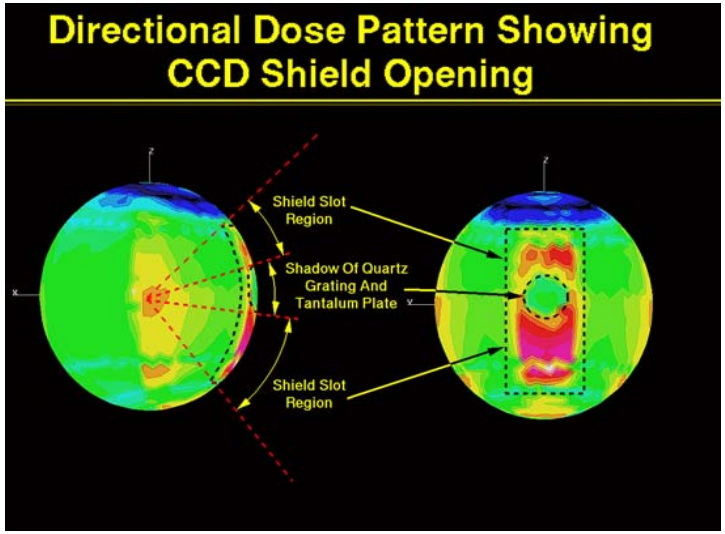
De Angelis, G.; Clowdsley, M. S.; Nealy, J. E.; Tripathi, R. K.; and Wilson, J. W.; Radiation analysis for manned missions to the Jupiter system. Advances in Space Research, 34 (2004) 1395-1403

Detailed Shield Modeling and Analysis of SAGE-III Instrument

Enclosure 2



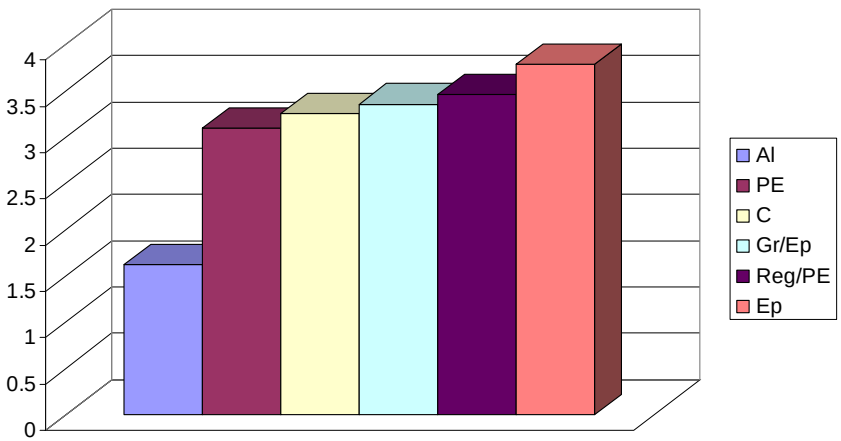




Original SAGE-III design employed tantalum shield to protect the CCD detector from penetrating electrons. The trapped proton environment produced a large number of neutrons in the tantalum shield resulting in displacement damage to the CCD detector. Replacement of the tantalum with aluminum provided adequate shielding from electrons and reduced significantly the neutron source. Understanding where the damage was coming from required development of visual analysis aids as shown on the left.

Heavy Ion and Proton Experiments

Experimental Radiation Shielding Effectiveness of Various Materials for 1.06 GeV Fe Ions

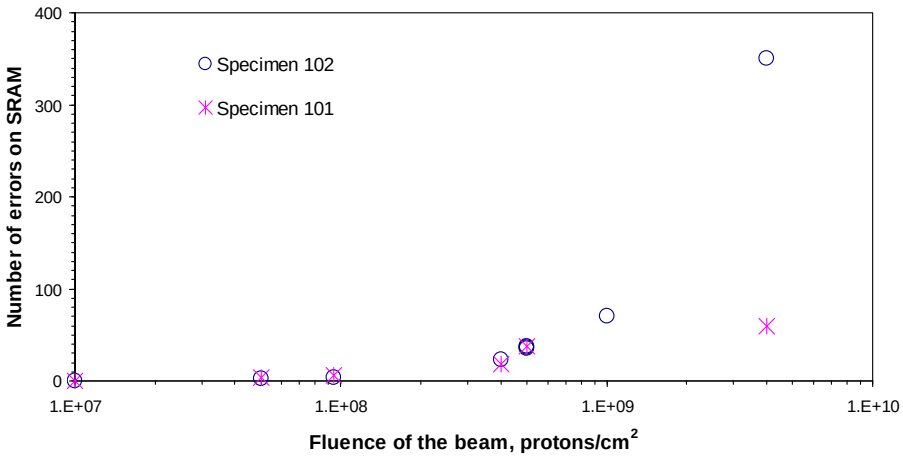


- Polymers, carbon, PMCs, and certain filled polymers better than Al
- Experiment conducted at Brookhaven National Laboratory

3a.

SEE on Motorola MCM6246-5V SRAM from 55-MeV Proton Beam

Better shielding with higher polymer content



Specimen 102: 80% regolith / 20% LaRC-SI
Specimen 101: 60% regolith / 40% LaRC-SI

Experiment conducted at Texas A & M University

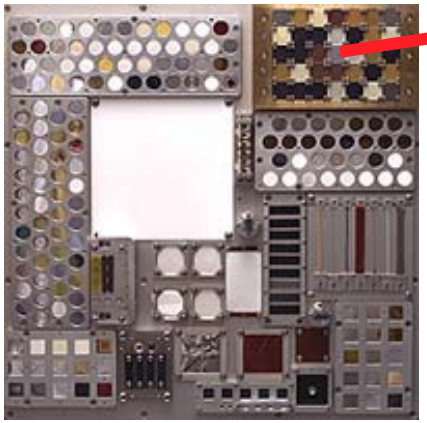
3b.

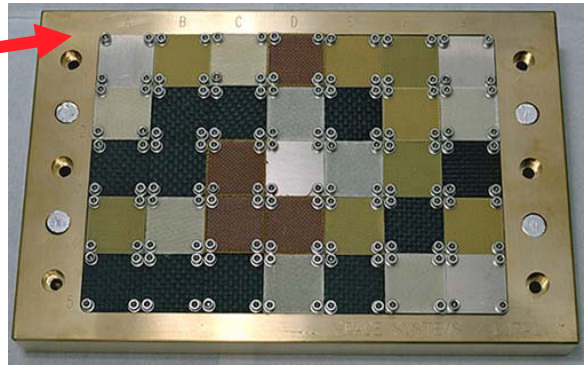
(slide courtesy Dr. S. A. Thibeault, NASA LaRC)

4a.

Materials International Space Station Experiment

MISSE 1 - UV





35 Low Z / high Z / low Z layered radiation shielding materials with 4 thermo - luminescence detector (TLD) stacks - - Space Systems Loral and Physical Sciences, Inc.

4b. NASA LARC Advanced Materials R&D

Maturation of PETI-5:
Requirements Driven High Performance Adhesive and Composite Matrix Resin

- About 20,000 pounds of IM7/PETI-5 unidirectional tape prepared in the HSR program
- Performance at 350°F for 60,000 hrs (previously unattainable)
- Technology patented and licensed to 4 companies

PETI-5/IM7 Skin Stringer Panel (6 ft x 10 ft)

10 Speen Street
Framingham, MA 01701
www.dafca.com

National Aeronautics and Space Administration (NASA)
Planetary Science Division, Science Mission Directorate
Washington, DC 20546

Attention: Dr. Curt Niebur
CC: Tsun-Yee Yan – Program Manager, Solar System Exploration Technology Office

Re: Request for Information - Radiation Capabilities for the Europa Jupiter System Mission
Solicitation: NNH09ZDA008L

Submitter Information:
Primary Interface: Jim Nash – DAFCA Director of Sales
Contact Information: Phone (508-663-3306) | Email: jim.nash@dafca.com

Dear Sirs,

DAFCA proposes the use of its distributed programmable instrumentation fabric in two primary applications: pre-deployment system testing and post-deployment real-time monitoring. DAFCA's embedded instrumentation is capable of real-time hardware monitoring, analysis, and stimulus generation. This instrumentation is used in the pre-deployment testing phase to dramatically improve testing coverage and testing methodologies to ensure the electronic systems are free from defect and are systematically proven to withstand single-event effects and other specified error conditions. In the post-deployment application, the instrumentation is used as an embedded background real-time monitoring system that can provide detection and early warning notifications of potentially disruptive events which, if not counteracted quickly, might produce more severe or even catastrophic effects. DAFCA's real-time stimulus logic can also help respond to or counteract certain disruptions.

DAFCA has developed design automation tools and embedded programmable instrumentation IP that is inserted into RTL (Verilog and VHDL) designs to provide real-time visibility, analysis, and control of functional behaviors not visible through any other means. The IP is compact and reprogrammable; it is designed to be distributed throughout the entire hardware subsystem, and ideally is applied to key components in the design to provide comprehensive system-wide visibility. This technology was initially developed to improve silicon validation and debug methodologies for large semiconductor devices whose internals are not otherwise visible when the chip is operating in an embedded system. By providing real-time embedded visibility, analysis, and control in this most realistic environment, engineers are able to test hardware (and software) more efficiently and robustly, systematically verify functionality, and quickly debug complex problems. And the fact that the embedded logic can inject functional stimulus, fault conditions, and pseudo-random errors greatly improves the quality of the testing process and the reliability of systems under test.

Most recently, DAFCA developed post-deployment applications with these same instruments. In such field applications, the instruments are managed by hardware or software controllers. Whereas hardware-based control can provide basic instrumentation-management features, more sophisticated use of the embedded instrumentation can be realized through software control. In either configuration, the primary function of the instrumentation is to provide real-time monitoring. By reprogramming the instruments "on-the-fly," a wide range of monitoring functions can be implemented to provide a high degree of coverage. When the monitors detect potentially disruptive events, alerts are transmitted to a specified resource such as a processor. The program (e.g., bitfile) loaded into the programmable instrument to define its function (for example, bus-fault monitor) is typically designed pre-deployment. However, to the extent that the system can be upgraded in the field, new

programmable functions can be uploaded as well. In this way, the programmable instrumentation provides the flexibility to guard against unanticipated upsets.

Both the pre-deployment and post-deployment applications will provide significant benefit to the Europa Jupiter System Mission. In the pre-deployment phase, the application of DAFCA's technology will improve testing methodology resulting in the delivery of more reliable systems, while at the same time reducing the cost associated with such advanced testing. In the post-deployment phase, the application of DAFCA's technology will help protect the electronic systems against many failure conditions and, through re-programming (if applicable), ensure that unanticipated problems can be redressed.

Capabilities and Qualifications

DAFCA was founded in 2003 with the mission of developing embedded programmable logic for use in a variety of electronic systems applications. DAFCA's ClearBlue product was released to the market in 2005. Since that time, ClearBlue has been used in both ASIC and FPGA devices by many leading semiconductor companies and system integrators, including five of the top ten semiconductor companies in the world. DAFCA possesses skills in all aspects of electronics systems design, hardware IP development, and software design. In addition, the company has acquired specific skills in understanding embedded systems' behavioral properties and error conditions, which has allowed the company to construct unique solutions for testing, diagnosing, and debugging complex systems.

DAFCA's innovation, rooted in the distributed programmable instrumentation fabric, has allowed the company to expand its application from silicon validation and debug into embedded systems diagnostics and embedded systems security. The programmable fabric has numerous applications, many of which will be discovered and/or created by its customer base.

Products and Services

The DAFCA ClearBlue product is marketed and sold as a design automation tool. The tool can be purchased under a time-based-licensing or project-based-licensing scheme. DAFCA does not charge IP royalties for its standard product. In conjunction with the ClearBlue tool, DAFCA offers professional services and custom engineering services. Professional services include training, instrumentation planning, instrumentation implementation, design verification, and instrumentation programming. Engineering services for custom instruments, instrument modifications, or custom software interfaces are also offered.

Technology Maturity

DAFCA's technology is in use by many leading semiconductor companies and system integrators. DAFCA's customers include Intel, Boeing, Qualcomm, Broadcom, Samsung, Toshiba, Infineon, and STMicroelectronics.

The DAFCA ClearBlue design automation tool suite has been proven by customers to be compatible with all major ASIC design flows from vendors such as Synopsys, Cadence, Mentor, and Magma. The tool suite has also been proven compatible with a variety of FPGA flows from Xilinx, Altera, and Actel. The programmable instrumentation IP is silicon-proven, being used in many commercial ASIC devices constructed with 130nm, 90nm, and 65nm technology nodes.

DAFCA technology is deployed in some of the most sophisticated and complex electronics systems in the world. In fact, the complexity of such designs is the key reason for using DAFCA's sophisticated solutions.

Boeing PDV-2 and DAFCA ClearBlue

Project Summary

The primary objective of the project is to study the characteristics and consequences of Single Event Effects on a device implemented using Boeing's Radhard library based on a 90nm IBM process.

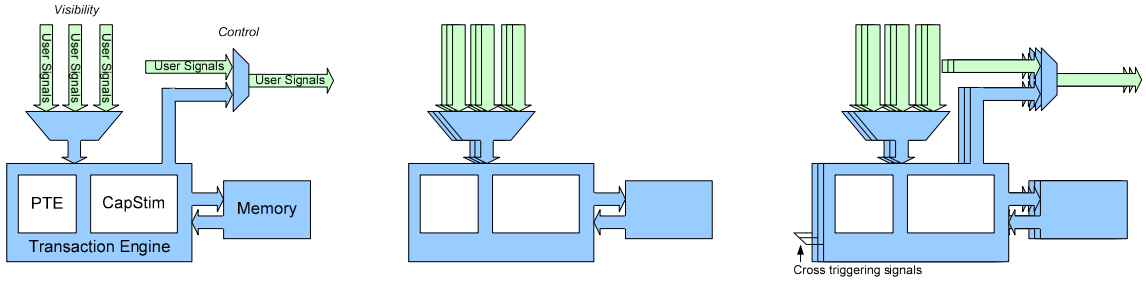
The device under consideration will be based on an ARM microprocessor core. The system will be monitored and controlled with embedded instrumentation; a combination of the ARM ETM, MBIST logic and DAFCA instruments. The on-chip *control* instrumentation will be used as functional stimulus for relevant test conditions, the creation of fault conditions and to assist with isolation of transient errors. The on-chip *visibility* instrumentation will enable the analysis of circuit state under comprehensive test conditions as well as capture the resulting behavior of the system in the presence of DAFCA defined stimulus (for fault injection and transient error isolation).

System wide visibility at multiple layers of abstraction is essential to reliable detection of errors and effect discovery. A software-centric view or hardware-centric views of the system by themselves are insufficient. Only a view that bridges software and hardware systems can provide the proper robustness and desired coverage. In particular, the ability to "cross-probe" between software instruction and hardware transaction is required, and is enabled by DAFCA on-chip instrumentation.

Instrumentation Objectives

ARM's Embedded Trace Macrocell (ETM) will be used to provide processor debug and trace capability by capturing processor state information and making such information available through a Trace Port or via the IEEE 1149.1 TAP. Standard Built in Self Test (BIST) logic will be used for memory units. DAFCA instrumentation will be used to provide visibility and control within the core, power system, and on all key interfaces. The following section describes applications of DAFCA instrumentation particularly as they pertain to monitoring Single Event Effects.

DAFCA instrumentation logic is inserted into any synthesizable RTL design. Visibility (on-chip, at-speed observability) is enabled by a configurable (optionally pipelined) multiplexer network (with FIFOs for asynchronous clock domain crossings) and a Transaction Engine. Control is provided by a wrapper multiplexer and a Transaction Engine. The Transaction Engine is a programmable state machine whose parameters such as the number of states, counters, timers, general purpose inputs and general purpose outputs are defined by the user during the RTL insertion process. Likewise the characteristics of the various multiplexers are also defined during the RTL insertion process. Most DAFCA-enabled chips have multiple Transaction Engines in order to enable concurrent visibility and control operations. The multiplexers can be connected to multiple Transaction Engines to provide concurrent triggering, assertions and performance monitoring on common signals; or each set of multiplexers can be bound to a dedicated Transaction Engine with optional cross triggering signals connected between each set.



For this application, the subsystems within the ALU will be instrumented such that error conditions can be detected, SEE rates can be measured, and faults or error conditions deliberately inserted into the design.

Similar instrument configurations will be applied in and around the MMU, Controller Units, Pre-Fetch Unit and Load/Store Unit. All key processor interfaces will also be instrumented, as will the power control system and even the ETM interface.

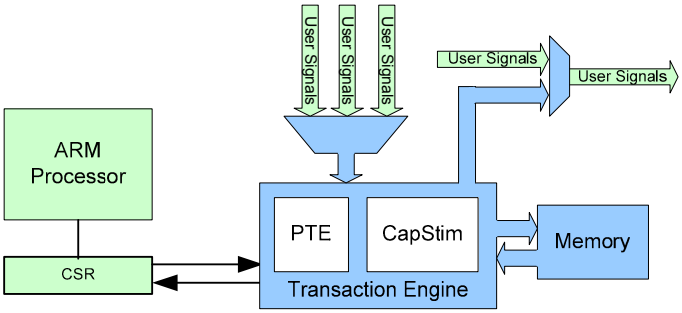
Through the instrumentation of the ETM, processor state information can be correlated to system transactions captured within DAFCA instrumentation. Note that the ETM trace messages captured within DAFCA instruments are not decoded but presented in binary/hex form.

Integration – Software and Hardware Views

There are two optional integration points DAFCA can provide in this system: one is on-chip, and the other is off-chip.

On-Chip Integration

The on-chip solution consists of a user-defined memory mapped Configuration Status Register (CSR) that provides the embedded processor direct control over instrumentation. The embedded software can enable or disable instruments, as well as retrieve general status such as trigger conditions. The most obvious application of this interface is within exception processing routines. DAFCA instruments can be programmed to "capture-always" during normal operation and stopped by a CSR instruction issued within an exception processing routine. Data captured within the trace buffer will provide visibility into the system leading up to the exception. This is useful when the effect of an error can not be easily detected in hardware, yet visibility into real-time hardware level activity is required.

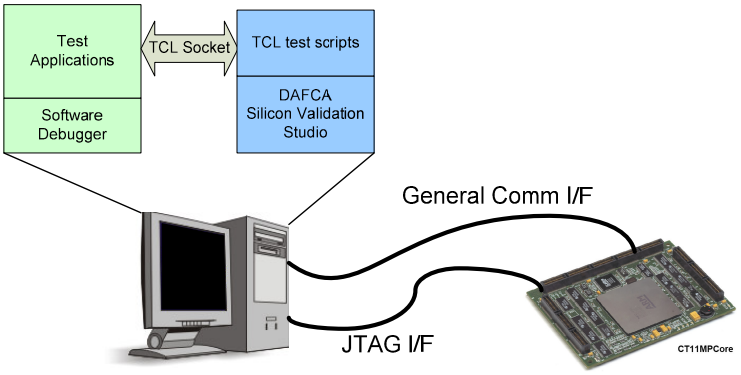


In addition to software detection scenarios, the CSR interface has other significant applications. For example, trigger conditions can be monitored by embedded software through the CSR allowing the system to react to an instrument trigger condition. The software reaction might include exception processes, evasion processes or recovery processes. In this context, consider the CSR as a means of creating a programmable interrupt (or polling) interface where the interrupt conditions are user defined and reprogrammable.

Note, that the CSR does NOT provide an instrument programming interface. DAFCA instruments must be programmed (configured) via the IEEE 1149.1 TAP interface.

Off-Chip Integration

The "off-chip" integration option provided with the DAFCA solution assumes that the device is tethered to a workstation that controls test scenarios and extracts (via JTAG) the on-chip results.



The Silicon Validation Studio (SVStudio) is used to configure and control on-chip instruments, and visualize results. Within SVStudio, a TCL interface may be used for all applications. Through a socket connection, user generated test applications can leverage SVStudio to configure and control instruments directly. Consider a test scenario where DAFCA instruments will be used for error injections. During the initialization of this particular test scenario, a SVStudio instruction is sent from the test application across the socket connection to SVStudio. This instruction informs SVStudio to load a specified error injection configuration into the DAFCA instruments. Once the configuration is loaded the error injection can be activated by another SVStudio instruction via the socket, or via embedded software and the CSR.

This is essential for constructing an automated testbench integrating software debuggers, test applications and SVStudio. The test applications, software debugger and SVStudio may or may not reside on the same physical workstation. Integration can be supported as long as a socket connection can be established.

Transaction Stimulus for Transient Error Isolation and Detection

The transaction stimulus capabilities of the DAFCA instrumentation can be used to assist with the isolation and detection of transient errors. Being as transient errors occur infrequently and for short periods of time, they are very hard to detect. However, if a transient error is suspected to occur under a certain mode and condition of operation or perhaps during a particular transaction, the DAFCA stimulus logic can be leveraged to replicate the particular mode of operation or transaction hundreds or thousands of times consecutively (by over-riding the user logic with DAFCA's on-chip instrumentation) all while continuing to monitor the system on-chip at speed with the DAFCA instruments.

This approach can be leveraged extensively to validate all modes of operation, transactions and protocols in a short time frame and ensure that transient errors are not manifesting themselves as single event effects - or isolating the cases where they do.

Single Event Effects and Transient Errors

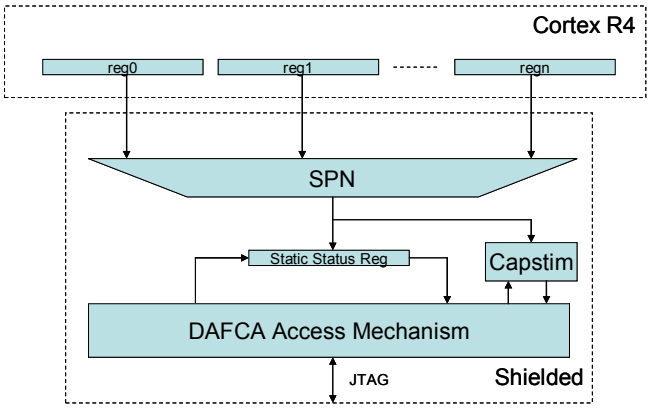
A single-event effect resulting from a transient error is a condition that we can trigger on and capture using our synchronous logic. However, transient errors small in magnitude or duration that don't cause a single event effect will not necessarily be captured or seen by the DAFCA synchronous logic e.g. transient errors that don't arrive within the setup/hold time of DAFCA flip-flops will avoid detection. In addition, transient errors may also be masked electrically through combinational logic and never even get to the output of a logic gate connected to a flop. They could also be masked logically depending on the state of the inputs to a logic gate and on which input the transient error occurs. All these "masking" effects will need to be considered when tailoring a strategy. There are custom instruments that could be leveraged, internal signal taps (vs. registers and ports) along with some

replication of the DAFCA Signal Probe Network to assist with the probability of detection of these transients that do not manifest themselves as single-event effects.

Validation Scenarios for Boeing PDV2 ASIC

Characterize register "hardness"

Run a diagnostic loop that monitors their internal configuration registers. The registers in question are ARM static configuration registers. If these experience an upset, the system functionality suffers. By tapping all of these registers, and running a diagnostic loop in the SVStudio tool, we can monitor these over time and count upsets. We can do this test with a simple static status register which will be used to read the static values periodically. If the probability of upset is low enough, this low-cost solution will enable us to detect bit-flips over time. However, if it is high enough that the probability of the same bit flipping, say, from 1 to 0 and back again during the time it takes to read all registers at JTAG speed, an at-speed capture device such as the CapStim can be used to capture and store the values at system speed. A topology that would enable both of these scenarios follows:



In both cases, a Tcl diagnostic loop will run on the SVStudio tool, gathering relevant data over time and displaying it.

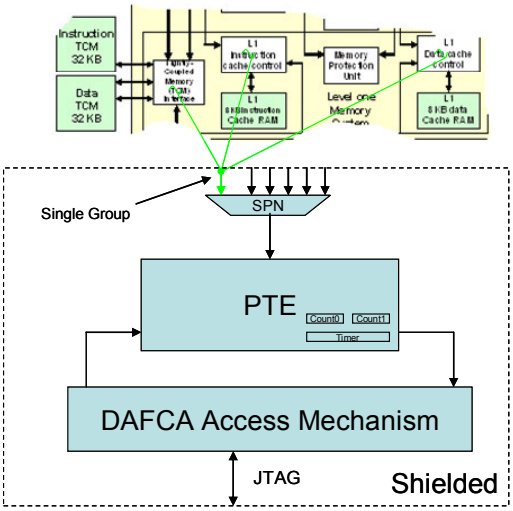
Observe error correction status for critical memories

The PDV-2 chip will utilize two single port Tightly-Coupled Memories (TCMs) attached to the Cortex R4s two TCM interfaces. In addition, the Harvard-architectured R4 has a separate Instruction and Data caches, as well as register-based tag-RAM. These memories are 72 bit with 8 bits for ECC and 64 bits for data. The goal is to observe these interfaces and record single and multi-bit errors (of course, multi-bit errors are unrecoverable in this architecture, so a long duration test should have an "ABORT" exception handler that allows code to keep executing.

There are two possible scenarios in this case:

1. Record how many of each event (single bit upset and multi-bit upset) over time.

This requires a PTE with two counters and one timer and a minimum of four states. The counters store the number of events over an absolute timescale captured by the 32 bit counter. A topology follows:

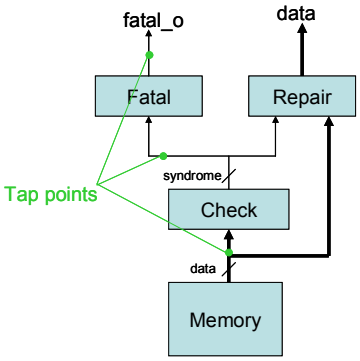


Here, we have captured the relevant ECC signals into the PTE via the SPN. The PTE watches for events and records the absolute number of single and multi-bit upsets per unit time.

2. In the second scenario, the CapStim can be added to record more information, such as syndrome bits, or simply an identifier for which memory experienced the fault. The PTE can still be used to count absolute faults. In the present arrangement, we can pack the data across a 143 bit word to capture significant numbers of events.

Specific Instrumentation

The ECC mechanism on the Cortex R4 is placed on a per-interface level. It sits between all of the memories (ITCM, DTCM, tag RAMs, D-caches and I-caches). We can count the following conditions with by tapping the signals in the picture below:

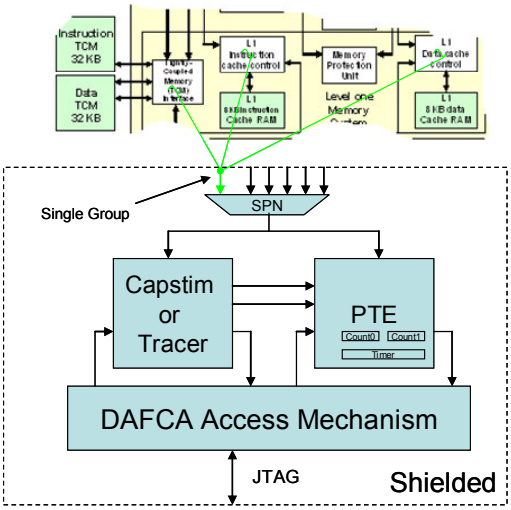


- Single bit errors
- Multi-bit fatal errors
- (Potentially) the number of bits in error

Single bit errors are identified by DAFCA instrumentation by comparing the syndrome bits to 0. If the bits are not zero, and the "fatal_o" signal is not asserted, a single bit error was corrected. If "fatal_o" is asserted, a multi-bit error has occurred, though it may not be possible to determine how many bits were in error. In such a case, it is possible to determine the number of bits if the original data is known (i.e. tapped by DAFCA), and a known pattern has been written into the memory.

Allow the ETM to trigger DAFCA (and vice versa)

The DAFCA instrumentation will be connected to the ETM interface on the Cortex R4. This exposes critical run-time information to ClearBlue, such as:



- Currently executing instruction
- Current processor context
- Load/Store Data

It also allows for ClearBlue to drive the core into debug state by wrapping the ETMDBGRQ pin.

Other Considerations

Disabling DAFCA instruments

All DAFCA instruments can be held in a reset set. In this state, instruments have no effect on functional logic. This same technique is applied during formal verification to ensure the original design and the instrumented designs are equivalent [when DAFCA instruments are reset]. The instrument reset system is user defined. In most applications the IEEE 1149.1 TAP reset signal is tied to all instrument reset inputs such that a single TAP instruction can be issue, or the global reset can be asserted, or the TMS signal can be asserted for five or more clock cycles to drive instruments into the reset state.

Note that even in the reset state, some instrument logic will consume power. For example, the multiplexer network may include pipeline registers. Even in the reset state, these registers continue to switch when a clock is present. To eliminate such switching clock gates should be added to relevant clocks feeding DAFCA instruments.

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L3 Com Jaycor in San Diego is a one stop shop, supplying complete services and support processes for radiation hardening. Collectively—under our roof, we have over 300 man years of radiation hardening experience. We can support or drive—concept development and trade space studies; derivation of requirements and flow down of radiation performance requirements from the system level to the part level; generate, track and audit, via verification and validation test and or analysis; and control radiation compliance from the foundry to the system, through all levels of integration, including rolling in radiation response back into system reliability. For the military, we handle nuclear weapon effects as well as natural radiation effects. Our personnel are long term supporters of HEART, GOMAC, RHET, and IEEE NSREC. Our staff supports the radiation effects community and has occupied essentially every volunteer position at one time or another (session chair, technical chair, conference chair, editor, publications, steering committee positions, etc). In March 2009, our staff member Dr. Dolores Walters was elected Steering Committee Chair for HEART (Hardened Electronics And Radiation Technology). One of our staff, Mr. Marion Rose, supports the Space Parts Working Group and the RHOC (Radiation Hard electronics Oversight Council), too.

L-3 Communications Jaycor does radiation testing – TID, ELDRS, SEE, EPOS, EOS, and combined environments. We've performed or are performing tests at JPL, Salk, AFRL, IRT, GA, LBL, LANL, SNL, TAMU, IU, ISU, UCD, BNL, LL, PI, Maxwell, WSMR, etc. For DoD, our sister division, Pulse Sciences (L-3 Com ATG PSD), develops and operates the nuclear radiation effects simulators. Up until last year one of our staff, Mr. Norman Hall, chaired the electronics test standards committee (ASTM), subcommittee F111. As a special note, in the 1980's and 90's we (efforts coordinated by our staff members Dr. Peter Coakley and Dr. Norbert Wild) worked with JPL, Dr. Bruce Anspaugh (retired), to develop and operate a time varying electron and gamma radiation simulator for testing materials, electronics and optical sensors. The exposure rates from the JPL Dynamitron could be varied from 100 rads (Si)/s down to submillirads (Si)/s at up to kilohertz rates (a potential useful technology for characterizing sensor performance for Europa).

With respect to analysis and radiation modeling—most importantly, we work closely with Silvaco and Simucad, commercial suppliers of Technology Computer Aided Design (TCAD) and Electronic Design Automation (EDA) tools, and use their tools for analyzing radiation response of electronics for several foundries, and have validated Silvaco radiation aware models that precisely report part level SEE and TID responses. With respect to technology innovation--to the best of our knowledge, we are the only ones with validated EDA tools for accurately forecasting/predicting dose rate and SEE sensitivity for untested components. Some of our personnel have worked closely with Silvaco during the past fifteen years to develop these modeling capabilities—Dr. Chris Nicklaw, Dr. Randall Milanowski, Dr. Manish Pagey and Mr. Jeremy Ralston-Goode.

Radiation transport – We use a number of tools for radiation transport modeling, including 3D. We have a collection of fast running 1D and 1.5D codes in our desk top tool, the Testable Hardware Toolkit (THTk). THTk is ITAR restricted but in use by more than 200 DoD contractors. Our staff member Dr. Jonathan Morrow-Jones is the brain behind THTk. Our analysts are familiar with running a number of other government and industry furnished codes as well. Collectively, these codes include—CEPXS-ONEBFP (electrons and gammas), CRÈME (space environments), SRIM (ion transport), MCNP (neutrons), etc.

Other Technology innovation—In addition to the above noted development of radiation aware EDA tools for predicting device SEE sensitivity, in 1991, we worked with LLNL to develop, verify and validate on-chip detection and fast reset for a SEL sensitive CCD controller. In 1992, we worked with a team of personnel to develop the first radiation hard High Density Interconnect memory modules. In 1993 we worked with IBM, GE, Harris and Honeywell to develop a dual locked step 1750A processor that had design margin to operate up to 1Mrad and be SEE immune. We later migrated and demonstrated similar capability for SEE mitigation on MIPS processes (NSREC circa 1993) for the LLNL AIT program. We also put the technology to use again for transient upset protection of MIPS 4600 processors by Heurikon as well as TEMIC 21020 and 21061 DSPs in the early 2000's. We generalized the transient protection scheme in the form of the System Hardening for Upset Recovery (SHUR technology) and presented the designs at the MAPLD in 2006. Over the years, we've put transient upset recovery and protection in hardware, software and firmware. In more recent time, we've pushed these designs into the silicon, developing SEL mitigation protection as well as SEL detection and latch recovery. We've worked with foundries and DoD primes to adapt JTAG IEEE 1149.4 for on chip upset detection and mitigation. In a different area of concern, going back to the 70's and 80's, we characterized and developed technologies to mitigate the effects of energetic electron induced deep dielectric charging, a.k.a. internal spacecraft charging. One of our personnel, Dr. Peter Coakley, was a co-PI supporting work at JPL on the CRRES Internal Discharge Monitor.

About SHARE: L-3 Com Jaycor is prime contractor on the AFRL SHARE program (Dr. Milanowski is the PM), a multiyear effort that was started in 2005 to dramatically improve the affordability of radhard custom ASCI design. The approach to increased affordability is to facilitate the use of commercial pureplay foundries by the military and aerospace design community. The fabless/foundry business model is one that has been overwhelmingly successful in the commercial marketplace, but prior to the SHARE program could not be used with widespread effectiveness by the radhard design community because PDK's for the desired technology were not available in an affordable EDA tool flow. L-3 is teamed with a commercial provider of advanced, affordable TCAD and EDA tools (Silvaco/Simucad) to develop radiation aware process design kits for numerous CMOS and BiCMOS processes. The full list of technologies covered is as follows:

American Semiconductor --- Flexfet 180 @ 0.18um IDG SOI CMOS
Jazz --- SBC18HX @ 0.18um BiCMOS SiGe; CA18HR @ 0.18um; CMOSCA18HA @ 0.18um CMOS; BCD25MB @ 0.25um CMOS; SBC18HA @ 0.18um BiCMOS SiGe; C05HMAK2 @ 0.50um CMOS; CA18HD @ 0.18um CMOS; CP05 @ 0.50um CMOS; CA25 @ 0.25um CMOS; SBC35QTA @ 0.35um BiCMOS SiGE; SBC35QTS @ 0.35um BiCMOS SiGE
BAE --- RH15

A key element of the SHARE program has been to provide the full suite of design tools to numerous large and small companies actively engaged in ASIC design for different government programs. L L-3 is providing tool training, applications support, test support, and in select cases also MPW runs for the mil-aero IC design community. This activity has been feeding a comprehensive Tool Flow/ PDK Verification & Validation effort. In addition to radiation hardening efforts, the SHARE program has also been applied in a DHS/DNDO-funded nuclear material sensor development effort, in which a custom ASIC is being intentionally sensitized to radiation.

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This document is submitted by TechnoSoft in response to the RFI originated by the Planetary Science Division, Science Mission Directorate, NASA, per solicitation number: NNH09ZDA008L, with release date of April 24, 2009 in relation to Radiation Capabilities for the Europa Jupiter System Mission

Space systems must operate in environments that include significant levels of ionizing radiation. The optimization of the configuration and layout of the system component is a critical step in the design process for radiation tolerance. Many space systems get deployed with hardness capabilities that are unrecognized and underutilized due to imprecise analysis techniques applied far too late in the design cycle.

Traditional Radiation Transport Analysis (RTA) is a time consuming and very expensive process. Conventional comprehensive shielding analysis can be a multi-million dollar effort for first article and subsequent updates can cost hundreds of thousands of dollars. Radiation shielding has not been an integral process of the design and analysis cycle of space systems. The radiation hardening design process is performed following the completion of detailed system design. Low-fidelity radiation analyses are conducted on mature hardware models well after the design has been competed. Hardware solutions are often missed due to long analysis cycles, complexity, or limitations on system representation. Typically, fifty percent of the system weight is neglected in traditional analysis modeling methods; this may result in the shield design being hundred percent overweight. Judicious shielding design can realize benefits in weight as well as reduced cost of electronic components due to decreased total radiation dose requirements.

Optimum shielding design can lower launch weight as well as reduce the cost of electronic components due to decreased dose requirements. Therefore it is critical to create the radiation analysis model with a fidelity that accurately represents all sub-system components, while also performing high fidelity system level analysis for both survivability and operability. Historically, the complexity involved in the development of the radiation analysis models often leads to the exclusion of details, thus impacting the fidelity of the analysis. Additionally, the long time and high cost of the radiation analysis process have driven programs to perform the shielding design as late in the engineering cycle as possible, when designs have neared finalization.

Radiation tolerance assessment of a candidate design or configuration requires the use of Radiation Transport Analysis (RTA). RTA is used to assess the effectiveness of a shielding design as well as the tolerance of the system components. The RTA process as currently used in the engineering of these systems is an iterative and time-consuming process. Radiation transport analysis and radiation shielding design optimization can be applied throughout the different stages of the system design (conceptual, preliminary, and detailed). Traditionally, the expense associated model creation for these analyses has driven programs to perform the work as late in the design cycle as possible, when designs have neared finalization. Additionally, the

complexity involved in the development with analysis model often leads to the exclusion of details, thus impacting the fidelity of the analysis. Often the radiation hardening analysis process is implemented following the completion of the detailed system design. Only low-fidelity analyses are conducted on production hardware models well after the design team has signed off. Because of the long time required for processing the design geometry for creating the analytical model for RTA, performing the analyses while the design is still taking shape is not practical.

The current design process nearly always leads to catastrophic consequences. Often problems are found that can not be fixed with minor changes. As a consequence parts are replaced with very expensive hardened versions and entire circuits have to be redesigned. Inexact shielding assessments lead to weight increases, and ultimately entire test plans have to be re-performed in order to assess and verify the redesigned system. This results in substantial schedule setbacks and cost overruns.

The Adaptive Modeling Framework (AMFrame) from TechnoSoft is a multi-functional engineering environment that facilitates rapid, integrated design, and radiation transport analysis. AMFrame developed by TechnoSoft leverages years of software development, design, and analysis domain knowledge. TechnoSoft, an engineering software company, is currently involved in several DoD engineering programs related to integrated product and process design and automation. TechnoSoft is currently under contract to support the deployment of its technology on various government programs in subsystem design and multidisciplinary analysis including radiation assessment. TechnoSoft has a strong record of technology innovation and insertion which is a testament to our thorough understanding of the needs of the Europa Jupiter System Mission (EJSM) development. TechnoSoft engineering team includes specialists with domain knowledge as well as expertise in tools, systems design and analysis knowledge, and engineering software framework and application development. Current customers include Lockheed, Raytheon, Orbital Sciences, among other companies. TechnoSoft has developed and deployed many applications on AMFrame that are currently used by NASA, MDA, the Air Force, Navy, and many government labs including Sandia and Los Alamos. AMFrame provides a knowledge-based engineering modeling environment enabling the integration and automation of analysis and design processes. AMFrame supports multiphysics modeling and geometric reasoning; overall functionalities that are critical to the automation of product and process design.

The opportunity present in this RFI is associated with the automation of the radiation analysis process to support the rapid assessment of innovative concepts for multifunctional designs. The radiation analysis process is integral to the AMFrame multidisciplinary design and analysis environment. AMFrame support the automation of modeling methods for high fidelity analysis supporting radiation, structural, and thermal assessment of design concepts. These methods support capturing the detailed design features, accurately representing component geometry and weights, and accounting for the interaction among the various components at all levels from the subsystems assemblies, such as electronic boxes, to the system level, such as a space vehicle. AMFrame integrate algorithms that support the optimization of the layout of components and the shielding design. This unique integrated design and multidisciplinary analysis environment will enable the rapid assessment of new and innovative concepts that address radiation testing and evaluation of subsystems in support of the radiation assessment and shielding challenges for the EJSM project.

The AMFrame environment introduces radiation assessment for optimum shielding design at the earliest stage of the engineering process. It will automate the high fidelity radiation analysis process and assess the radiation tolerance at each of the component, subsystem, and system levels supporting a virtual radiation testing environment. Radiation design flaws can be mitigated during the early design phase leading to integrated and increased shielding while optimizing the board level configuration and eliminating costly over-designs. When applied in the design phase, the enhanced analytical capability facilitated by AMFrame will allow reduced system shielding weight and costs, enhanced radiation tolerance, and greater design margins for space and weapon systems electronics.

AMFrame incorporates a broadly applicable engineering analysis tool and testing environment that automates total ionizing dose analysis and expedite "what if" design iterations for spacecraft electronic systems and components, which is currently a very costly and lengthy portion of the electronics design cycle. Based on current results from previous application of the technology opportunities exist for greater than ninety percent savings in engineering time while reducing shielding weights by over fifty percent.

The AMFrame comprehensive analysis and testing environment will not only reduce design cycle time and cost, but will also reduce the effort associated with compliance analysis for electronic systems. Additionally, the shielding design and optimization environment can reduce electronics costs through lowering the hardness requirements enabling the use of lower cost COTS electronics.

Additional weight savings can be achieved through the use of AMFrame for modifying the system component configuration while facilitating rapid radiation tolerance assessment of investigating the repositioning of such components. Analyses of electronics enclosures have revealed that there is often as much as a factor of four difference in exposure levels from one side of a card to another. With this information, during the layout process electronics engineers can put the softest parts in the most shielded locations. This reduces the need for unnecessary costly hardened parts, and can also result in lower shielding weight. As a result, the high precision analysis modeling capability enabled by the AMFrame RTA environment will enable spot shielding of soft components instead of high cost plating of entire enclosures. Ultimately, the radiation hardness of the system will be entirely developed in sequence. The impact of each subsystem will be factored into the radiation effects in all others. Ultimately, AMFrame will enable radiation hardness engineering to join the design process and become an integral part of the systems engineering, instead of a collection of expensive and poorly-understood band-aids added at the last minute.

AMFrame provides unprecedented benefits through increased fidelity in radiation transport analysis and its use at an early stage in the design process, therefore reducing the engineering time and costs as well as the weight of the system shielding for EJSM systems electronics. AMFrame modeling and simulation environment automates the complete process for radiation analysis and integrates engineering methods that support rapid trade study environment assessing radiation tolerance of for alternative configuration and shielding design.

AMFrame will allow highly accurate analyses that are capable of identifying radiation hardening features in the EJSM system while still in the design phase as well as identifying simple, fast, and inexpensive ways to remedy discovered design flaws well before the system design matures. The savings will be substantial in every phase of the program. The integrated analysis and

design capabilities will result in a quick turnaround for exploring and assessing design changes resulting in better product performance with lower cost.

The enhanced analytical modeling capability and the rapid engineering environment will allow for reduced system weight and costs, compressed schedules, enhanced radiation tolerance, and greater design margins. These improvements will have a positive impact on performance, affordability, and schedule.

AMFrame incorporates optimization methods for reducing the order of the analysis model. It capitalizes on facilitating rapid creation of the analysis model capturing one hundred percent of the design model geometry features and material. By enabling the thorough investigation of alternative designs and technology variables, the system will facilitate informed design decisions. The interactions between design models (geometry) and analyses are fully automated to reduce engineering time and cost while facilitating trade studies and design explorations.

AMFrame allows highly accurate assessment of hardening capabilities in very short periods of time, so that alternative layouts can be evaluated from a hardness perspective at the same time the shielding design is being optimized. The analysis results of a design can be used into account in the next design iteration, or in the next design task. When the detailed design is complete there are no hidden issues waiting to be discovered, no massive redesigns over hardening concerns, no expensive parts replacements, and no costly delay in system deployment. The detailed design is ready for a single round of verification testing because the radiation performance of the system will be a known quantity, evolved throughout the design process, and not an unknown waiting to be uncovered.

The use of AMFrame on EJSM will allow highly accurate analysis that is capable of identifying radiation hardening features in systems while in the design phase as well as simple, cheap, quick ways to remedy discovered design flaws well before the system design matures. The savings can be substantial in every phase of the program, the ultimate product will be more reliable, and the process will allow systems to be fielded significantly faster than previous generations of hardware.

Introducing the analysis process at an earlier stage of the design and providing higher fidelity models would reduce engineering cost and improve performance through weight reductions in shielding. No other RTA tools provide an environment which facilitates rapid analysis. Automating and integrating analysis modeling within the design environment is a critical step toward rapid design and radiation analysis. Increasing the fidelity of the analysis will provide the needed strategic environment for design optimization.

When applied in the design phase, the enhanced analytical capability of AMFrame will allow higher fidelity modeling, reduced system weight and costs, enhanced radiation tolerance, and greater design margins. AMFrame will allow the radiation transport analysis to accurately represent the component system masses and shapes. It will enable the design of lightweight shielding by maximizing self-shielding and is expected to result in more than thirty percent shielding weight savings as demonstrated on other candidate programs. Fully automated geometry translation will reduce deck preparation time by three orders of magnitude. High efficiency optimization can reduce analysis time by five orders of magnitude compared to manual geometry translation methods. Time and weight savings will directly impact the bottom line for EJSM radiation hardening efforts. Further, increased fidelity and confidence in analysis will reduce test requirements thus reducing the overall system development cycle costs.

Aeroflex Corporation: Radiation Hardened – Microelectronics, Processors, RF and Motion Control

There is no unrestricted information available.

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The Institute for Space and Defense Electronics (ISDE) at Vanderbilt University performs analysis, modeling, simulation and testing of radiation effects on electronics and develops radiation-hardened devices, integrated circuits, and electronic subsystems. ISDE was launched with support from the U.S. Navy SSPO and Draper Laboratory. ISDE currently supports the NASA Goddard Space Flight Center, NASA Marshall Space Flight Center, the Defense Threat Reduction Agency, the Air Force Office of Scientific Research, Arnold Engineering Development Center, ATK, Boeing/DARPA, BAE Systems, and other commercial companies and government agencies.

The Radiation Effects and Reliability (RER) Group at Vanderbilt University was established in 1987 and is the largest university-based radiation effects program in the world. The RER Group is actively involved in radiation effects and reliability research, testing, analysis, and other areas. In January 2003, Vanderbilt University established ISDE to extend the capabilities of the RER Group to serve government and commercial customers. There is close cooperation between the RER Group, ISDE, and ten professors on the electrical engineering and physics faculty who serve as ISDE Fellows.

The ISDE facility is located adjacent to the Vanderbilt University campus and provides a professional office environment conducive to engineering and project management activities. The Institute has full access to the University's laboratories and meeting facilities located on campus just a short walk away. The ISDE office is a secure, limited access facility, allowing only approved personnel to enter without an ISDE employee escort. ISDE is approved by the University to work with material controlled under ITAR and EAR regulations.

The mission of ISDE is to contribute to the design and analysis of radiation-hardened electronics, develop test methods and plans for assuring radiation hardness, radiation effects characterization and qualification testing, and the development of solutions to system-specific problems related to radiation effects. ISDE engineers help to identify radiation-related issues at the device, circuit, and subsystem/system levels, propose and implement design solutions, and devise and conduct radiation experiments.

ISDE uses an array of commercial and custom software tools for simulating radiation effects and designing integrated circuits, a high performance parallel computing cluster, several types of radiation sources, and extensive electrical characterization capability. ISDE and the RER Group have also developed many microelectronics test chips, including bulk silicon CMOS, silicon-on-insulator, and bipolar technologies.

ISDE has access to an extensive suite of test and characterization equipment for radiation-effect analysis, including an ARACOR 10-keV x-ray irradiator, two ^{137}Cs isotopic irradiators, and a 2-MeV proton source. ISDE engineers have extensive experience conducting single-event tests at facilities including Texas A&M, UC Berkeley, Brookhaven National Laboratory, Michigan State University, and Indiana University. Vanderbilt also has a Cooperative Research and Development Agreement (CRADA) with NAVSEA-Crane that provides access to a suite of radiation sources and a fully equipped parts analysis laboratory. An array of test equipment is available to facilitate the characterization of irradiated devices and ICs.

Vanderbilt's Advanced Computing Center for Research and Education (ACCRE) houses VAMPIRE, a 1200+ processor Beowulf cluster supercomputer used to execute several Technology Computer Aided Design (TCAD) suites and Vanderbilt's custom radiation transport codes.

One of ISDE's key software tools is MRED (Monte Carlo Radiative Energy Deposition), a custom radiation-transport code based on the Geant4 libraries developed by the high energy physics community. MRED is a framework for treating particle or ion energy deposition in semiconductors. The simulation software describing radiation interactions and transport in matter is a built-in Monte Carlo binary-collision code. The code is comprehensive in the treatment of all forms of radiation interacting with materials and provides interfaces for smooth operation with related programs that handle related tasks such as radiation transport, induced charge in semiconductor devices, or the analysis of circuit-level radiation effects. Space radiation environments are easily accommodated in MRED, as well as full solid-angle directionality of incident particle strikes. MRED is thoroughly calibrated to data and has a strong record of predicting both terrestrial and space experimental radiation results. Through support from NASA/MSFC and NASA/GSFC, ISDE has developed a web-based interface to MRED that allows access to the basic functionality of MRED. Through this interface, users are able to predict single event upset rates of electronic parts using MRED.

ISDE also has extensive experience in TCAD finite-element analysis of radiation effects in individual transistors and groups of transistors. These device simulations can be coupled to circuit and VHDL simulations of large electronic systems to evaluate the effects of single events on system performance. ISDE also has expertise in modeling the effects of total dose accumulation and displacement damage on individual parts and systems. ISDE has implemented radiation effects models into process design kits (PDKs) for several technologies to facilitate the efficient design of radiation hard electronics.

ISDE engineers work closely with customer technical staff throughout the radiation characterization and hardening efforts and throughout the design process. From technology identification, through design and test, and finally to documentation and qualification of rad-hard systems, ISDE and Vanderbilt provide a critical mass of aptitude, capabilities and experience for the implementation of rad-hard devices and systems

Subject: Radiation-Hardened CMOS Imaging Sensors for EJSM Mission
NASA RFI Solicitation Number: NNH09ZDA008L
Response Organization: Teledyne Imaging Sensors, LLC., Camarillo, California
Contact Information: Selmer Anglin, selmer@teledyne.com; (805) 373-4712

RADIATION-HARDENED SENSOR CAPABILITIES AT TELEDYNE IMAGING SENSORS

1. Summary of Capabilities

Teledyne Imaging Sensors (Teledyne, or TIS) develops and produces high performance visible and infrared imaging sensors, electronics and packaging for various civil and defense applications, including space-based missions that require a high radiation tolerance, high chip functionality, low power and small mass. Teledyne's imaging sensors are made with a hybrid CMOS architecture, which combines high performance detectors with high functionality CMOS readout integrated circuits (ROICs). The detector and CMOS ROIC can be independently optimized for radiation tolerance to the specific irradiating species. CMOS readout commonality for all detector materials or instrument channels simplifies payload design and system integration. Specifically, Teledyne has the following capabilities and qualifications relevant to the Europa Jupiter System Mission (EJSM):

- Teledyne received substantial research and development funds from the government to address radiation environments similar to that for the EJSM and has demonstrated critical sensor components.
- Teledyne's silicon and HgCdTe detectors cover a broad spectral range from soft X-ray, ultraviolet, visible, near infrared to long wavelength infrared (up to 16 μm), and have been designed to have a high tolerance to radiation damage.
- Teledyne has a long history of successful designs of radiation-hardened CMOS ROICs. Technologies used include Radiation-Hardened By Design (RHBD) and Radiation-Hardened By Process (RHBP). Teledyne ROICs exhibit some of highest tolerance to total ionizing dose (TID) that have been tested independently.

In the past two decades, Teledyne has successfully developed and delivered imaging sensor chip assemblies to several key NASA and U.S. Department of Defense (DoD) space missions, such as Hubble Space Telescope (HST), Mars Reconnaissance Orbiter, Tropospheric Emission Spectrometer, Deep Impact, and Moon Mineralogy Mapper, and has established a heritage of high technology readiness levels (TRL). Teledyne continues to advance the state of the art of sensor technologies to meet the stringent needs of future space missions.

2. Radiation-Hardened Detector Arrays

HgCdTe Detector. For HgCdTe detectors, the improvement in passivation using CdTe has minimized the impact of gamma-induced charge creation in bulk and surface dielectric passivation layers. The displacement damage associated with energy transfer of energetic particles to the crystal lattice is believed to be the dominant effect. Displacement damage is characterized by non-ionizing energy loss (NIEL). NIEL is rather insensitive to HgCdTe composition. Measurements of NIEL from proton irradiation of Teledyne's long wavelength infrared (LWIR) HgCdTe FPAs by Hubbs[1] showed that the displacement damage is likely operant, where decreases in detector QE and diffusion length with increasing proton dose were observed. The effects are likely associated with increases in n-type carrier concentration and concomitant decreases in Auger-1 lifetime, diffusion length and quantum efficiency. Shorter lifetime also results in higher detector dark current and reduced detector zero-bias impedance. In addition, displacement damage is likely responsible for the increases in photodiode excess current associated with the generation of Shockley-Read-Hall recombination centers in the detector bulk. These centers may also be responsible for the increases in tunneling current observed in Teledyne LWIR detectors.

Although Teledyne has a strong heritage in space-based focal plane arrays (FPAs), these detectors have not been subjected to a very high displacement damage radiation environment. Because such damage is a fundamental physical mechanism, it cannot be eliminated within the detector bulk. However, similar to approaches used in improving the radiation hardness in silicon electronics either by process or design, an understanding of underlying physics permits modification of the detector structure to minimize the electro-optical impact of displacement damage on performance. Such a detector has been designed and fabricated at Teledyne.

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[1] J. Hubbs et. al, *IEEE Trans. Nuclear Science*, p. 2435, Vol. 54, 2007

Silicon Detector. TIS' silicon detector array is a bipolar device that includes active bulk and active surfaces. In general, the detector can be designed to be immune to ionization damage such that the displacement damage becomes the ultimate limiting mechanism. The radiation-induced dark current increase is caused primarily by bulk displacement damage and the ionization damage that creates the surface traps and alters the surface charge conditions. There are several possible radiation-induced degradations in silicon detector arrays: (1) the increase in detector dark current due to the formation of deep-level traps in the bulk and at the surfaces; (2) decrease in detector quantum efficiency due to depletion voltage increases and carrier lifetime decreases, and (3) the increase of pixel electrical crosstalk due to formation of surface conduction channels.

To mitigate the above effects, several designs have been employed for Teledyne silicon detector arrays. The use of a fully depleted silicon PIN photodiode fundamentally eliminates the possible degradation in detector quantum efficiency as long as a sufficient bias is maintained across the detector. In addition, a high-resistivity, n-type silicon substrate is used, which improves the susceptibility to bulk displacement damage because the dominant hole trap in n-type silicon under irradiation is mainly due to a divacancy which contributes less to dark current[2]. Several detector designs were implemented to mitigate surface effects. One detector design has completed a detailed characterization under radiation.

3. Radiation-Hardened CMOS Readout Integrated Circuits

Teledyne has extensive expertise and experience in the area of radiation-tolerant readout integrated circuits for visible and infrared applications. Several ROICs have been designed employing both RHBP and RHBD methodologies. ROICs with verified-by-test TID tolerance within the range of the expected EJSM spacecraft have been delivered utilizing both technologies for silicon-based visible and HgCdTe-based infrared focal plane arrays. Radiation test results are available for gamma and proton total ionizing dose and gamma-induced single-event upset.

Teledyne employs modern design tools and comprehensive design flows to ensure the delivery of high performance readouts. A significant investment has been made in area of RHBD. By incorporating enclosed geometry NFET and PFET layout and field inversion considerations into Teledyne's analog and digital design tools, RHBD can be accomplished in much the same way the standard IC design is performed, and the standard commercial CMOS foundry can be used. Generation of RHBD digital libraries, with RHBD synthesis, auto place-and-route, and timing verification including parasitic effects are included in Teledyne's standard RHBD flow. These capabilities are essential for timely delivery of high performance radiation-hard designs.

The recent RHBP technologies employed at Teledyne include Honeywell 0.8 μm and 0.35 μm partially depleted silicon-on-insulator (PDSOI), 0.25 μm BAE bulk CMOS, and AMI (now ON Semiconductor) 0.6 μm bulk CMOS processes. RHBD ROICs were fabricated with standard 0.25 μm bulk CMOS from UMC and JAZZ Semiconductor and 0.35 μm CMOS from ON Semiconductor. RHBD ROICs include both analog and digital (12 bit) outputs.

4. High Dose Radiation Test Results

Available radiation test data indicates that Teledyne radiation-hardened CMOS ROICs have demonstrated TID hardness to relatively high levels. At focal plane array assembly level, the silicon FPA remains fully functional with minimal performance degradation out to a high radiation level. VLWIR infrared FPAs showed similar results. Quantitative results from these tests are described in the ITAR-restricted portions of this RFI response.

[2] J. Janesick, et al, *SPIE*, 1447, pp. 87-108, 1991.

Expertise and Capabilities on Radiation Effects in Electronic Devices and Solids at the University of Virginia for EJSM

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Response to Request for Information (NNH09ZDA008L)

This document describes the expertise and experimental facilities at the University of Virginia to be considered by NASA and instrument providers in addressing the radiation challenges for the Europa Jupiter System Mission (EJSM). Our expertise and experience relevant to this project cover the following areas: 1) Interaction of radiation and particles with matter (experimental and computational); 2) Radiation effects and damage in electronic devices; 3) Dosimetry and particle detection; 4) Space instrumentation. Facilities at the University of Virginia potentially useful for this project include: A gamma knife (dedicated to medical treatment) suitable for total ionizing dose tests, a 300 kV ion beam accelerator to simulate shallow bulk damage (e.g., for optical devices), and an ultra-high vacuum Kelvin Probe system to study charging effects, among others.

In the Laboratory for Space Research of the University of Virginia we study the interaction of energetic particles (ions, electrons) and photons with surfaces. Substantial part of our work consists in modeling surface processes in icy satellites, planetary atmospheres and magnetospheres, and interstellar grains. In the area of applied physics and engineering, we work on the development of instrumentation for space research that fly in current missions. Our work is supported by NASA and the National Science Foundation.

Expertise relevant to EJSM on radiation effects

Marcelo Famá (PhD in Physics) is a Senior Research Scientist at the Laboratory for Space Research of the University of Virginia (UVa), with extensive experimental and computational background in the interaction of radiation and particles with matter. He was responsible for the characterization and testing of the radiation tolerant program for the low earth orbit mission SAC-C (CONAE-NASA). His duties included: 1) Definition of the radiation environment and definition of the total dose for the mission (using Space Radiation software); 2) Modeling of the spacecraft shielding; 3) Development of MOSFET dosimetry; 4) Testing of parts using a cobalt therapy unit (for medical use) to characterize total ionizing dose effects in charge-coupled devices (according to standards MIL-STD-883 C and D and ESA/SCC No. 22900); 5) Total ionizing dose irradiation testing of several devices using 25 MeV electrons; 6) Radiation bulk damage testing of charge-couple devices with 10 MeV protons; 7) Estimations for single-event upsets.

He is a team member of the Cassini CAPS instrument, and also a Co-Investigator of the SERENA pack of instruments of the BepiColombo Mission to Mercury. His laboratory work at

UVa centers on the study of the interaction of radiation with planetary environments. He is actually working on ion irradiation induced charging effects in insulators.

Raúl Baragiola (PhD in Physics) is the head of the Laboratory for Space Research at the University of Virginia. He is highly experienced on surface physics and interactions of particles and photons with surfaces with applications to astronomical problems. He has 30 years experience in electron emission from ion-solid interactions. This topic is strongly related to spacecraft charging. He has been part of the Cassini plasma spectrometer (CAPS) team since its planning stage (1990) analyzing the physics and performance of the ion mass spectrometer (IMS) through laboratory and computer simulations.

Facilities at the University of Virginia

Gamma Knife Facility

The gamma knife is a device used to treat brain tumors with a high dose of gamma-radiation therapy. It operates on the principles of stereotaxy to achieve a high level of precision in localization. The facility at the University of Virginia (Gamma Knife Perfexion Model) consists of 192 Co-60 sources of approximately 30 curies each (nominal), placed in a circular array and aligned with a collimation system. Rather than being fixed, the cobalt sources are grouped into 8 sectors. Each sector can move in a linear direction back and forth over the internal collimation system, with several stopping positions. Each position corresponds to a different size collimator (4, 8 or 16 mm). The collimation system focuses the individual beams of gamma radiation to a very precise focus point located at 400 mm from the sources. The actual dose rate at the focus point is **3 rad(Si)/sec**, which is comparable to the peak dose rate of 2.3 rad(Si)/sec expected for the Jupiter Europa Orbiter (JEO) at 5 Jupiter radii behind a 2.5 mm aluminum shield. The dose rate can be modified (reduced) by using a spherical acrylic shield surrounding the sample/device.

On regular daily hours the facility is used for medical treatment. We might solicit irradiation service after regular hours. Radiotherapy medical facilities have been previously used for radiation testing of electronics intended for space applications.

UHV Kelvin Probe

We have recently acquired an ultra-high vacuum Kelvin Probe (KP) system to measure charging effects in insulators induced by charged particle (ions/electrons) irradiation. The KP is a non-contact, non-destructive vibrating capacitor used to measure the work function for metals, or the surface potential (contact potential difference) for non-metals. This instrument is appropriate to study "internal charging" in spacecrafts under ultra-high vacuum conditions, a phenomenon experienced by Pioneer and Voyager as they went by Jupiter that was addressed for the Galileo mission.

300 kV and Low Energy Ion Accelerators

The heavy ion accelerator Veeco 300 of the Laboratory for Atomic and Surface Physics and Laboratory for Space Research can provide ion beams of essentially any atomic species with energies up to 300 keV (higher for multiple charged ions). The accelerator is equipped with magnetic deflection mass analysis. Ions can be collimated and scanned onto the target surface by an orthogonal pair of electrostatic deflectors to achieve uniformity over the target. The low

energy ions accelerator can simulate the solar wind and low energy plasmas. Ions are produced by a conventional electron bombardment ion source and scanned electrostatically over the target surface. In both systems, ion currents are measured accurately using Faraday cups. Typical ion fluxes are in the range between ~10^{11} and 10^{12} ions/cm^2-s.

Other Equipment

Six ultrahigh vacuum scattering and implantation chambers
Electron guns (up to 15 keV)
Microwave discharge hydrogen lamp (Lyman-alpha)
GAM Excimer laser (10 ns pulses 193 nm)
Optical spectrometers from 100 nm (UV) to 15mm (IR)
Quadrupole mass spectrometers
Time-of-flight mass spectrometer
Target stages cooled by a closed-cycled refrigerator or liquid He
Angle-resolved electron spectrometer
Ultraviolet photoemission spectroscopy
XPS photoelectron spectrometers

REQUEST FOR INFORMATION (RFI)
Radiation Capabilities for the Europa Jupiter System Mission
Planetary Science Division, Science Mission Directorate, NASA
Solicitation Number: NNH09ZDA008L

Characterization of Electrical Materials Properties Related to Spacecraft Charging

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Capabilities and Qualifications

The Utah State University (USU) Materials Physics Group (MPG) performs state-of-the-art ground-based testing of electrical properties of both conducting and insulating spacecraft materials, particularly electron emission, conductivity and electrostatic discharge. Our efforts in this field for the last twenty years have been primarily motivated by NASA's concern for spacecraft charging caused by plasma environment electron, ion, and photon-induced currents and for radiation modification and damage of spacecraft materials and components. Our experience, facilities, and capabilities related to charging and radiation effects on spacecraft materials are directly relevant to design and survivability issue facing EJSM.

Interactions of spacecrafts with the space environment can result in charge accumulation and are known to produce >1/3 of the spacecraft system anomalies, electron upsets, damage to components, power system debilities, and even complete satellite failures that have been attributed to interactions with the natural space environment. Such problems related to power, communication and control systems are routinely encountered in NASA, military and commercial satellites in low-earth and geosynchronous orbits and on interplanetary missions. The missions related to NASA's science and exploration mission designed to develop new technologies and capabilities are even more susceptible to spacecraft charging issues as they push the limits in environmental extremes, novel electronics and instrumentation, and new materials. The scientific payloads on these missions are subject to similar effects; less severe charging can also disrupt instrumentation designed to study plasma properties and interactions. This will certainly prove true for the high radiation dose and dose rates, temperature extremes, and long durations of EJSM.

The electron emission and transport properties of materials are key parameters in determining the likelihood of deleterious spacecraft charging effects, and are essential in modeling these effects with engineering tools such as the NASA NASCAP-2K code. Surface charging results primarily from keV electron fluxes and photoemission, while deep dielectric charging is caused by high energy electron and proton fluxes from the trapped radiation. Accumulation and re-emission of electron, ion and photon fluxes in space determine charge accumulation. Dissipation or redistribution of this accumulated charge throughout a spacecraft is governed primarily by the conductivity of high resistivity components of the spacecraft.[3,12] The MPG has studied how variations in temperature, accumulated charge, exposure time, contamination, surface modification, radiation dose rate and cumulative dose can cause both recoverable changes and permanent modification in these electrical properties, or changes in related structural, mechanical, thermal and optical properties of materials and systems. Of particular relevance to EJSM are radiation induced conductivity and radiation damage and how they are affected by temperature, charge, and contamination. Such concerns are directly related to MPG studies already conducted for JWST, RBSP, SPM and Prometheus.

Possible effort for EJSM by the MPG will build on extensive existing instrumentation and expertise in this field. The MPG has been actively involved in dozens of projects studying specific effects and mitigation strategies in a wide variety of environments, each of which present their own unique sets of issues. These environments have included Low Earth Orbit (Satellites, ISS, MISSE), Polar (Radiation Belt Space Probes), Geosynchronous Earth Orbit (Communication Satellites, CRRES/IDM), L2 (James Webb Space Telescope), Lunar and Martian (Dust Mitigation), near-solar (Solar Probe Mission), Jovian (Prometheus, JUNO, Solar Probe Mission), and interplanetary (Solar Sails, Solar Probe Mission) in collaboration with NASA centers (GRC, GSFC, JPL, JSC, LaRC, MSFC,), agencies (AFOSR, ARL, CNES, DOD, ESA, ONERA, SDL) and corporations (Advanced Scientific, Aerospace, APL, ATK, Ball, Boeing, DPL Science, Northrop Grumman, SAIC) and numerous academic institutions. The MPG is a regular contributor to conferences and journals in

the field and has received sustained recognition for the NASA electron emission, resistivity, RIC and dielectric properties databases in wide use by spacecraft designers.

The MPG currently includes the PI, two research assistants, six graduate students, and five undergraduate students. USU is the state Land and Space Grant institution and a Carnegie I Research Institution. Space science and engineering is both a department and university wide emphasis. The Space Dynamics Laboratory (SDL) is an integral part of USU with an international reputation for spacecraft and sensor design, fabrication, and testing. The Physics Department has a Ph.D. program with 16 tenure-track faculty and 12 additional research faculties, the majority of which are in space-related areas.

Expertise and Facilities at USU

Extensive facilities and materials testing capabilities have been developed over two decades by the MPG for measurement of the electrical and related properties of both conducting and insulating spacecraft materials. The value of the facilities is estimated at $1-2M. Test capabilities are summarized below and details of the instrumentation and test methods are provided in the supplemental text.

Three ultrahigh vacuum (UHV) chambers are maintained with extensive space environment simulation capabilities for electron emission studies. MPG measurements include electron-induced total, secondary and backscattered yields, emission spectra, and angular resolved measurements as a function of incident energy, species and angle; ion-induced electron yields and emission spectra; photoelectron yields and emission spectra; and flux-induced surface voltage, electrostatic discharge and luminescence. The primary emission chamber is equipped with versatile surface analysis and sample characterization abilities and can simulate diverse space environments including controllable vacuum and ambient neutral gases conditions ($<10^{-10}$ to 10^{-3} Torr), temperature (<100 to >500 K), electron fluxes (5 eV to 22 keV mono-energetic, focused, pulsed sources over 10^{-2} to 10^{10} nA-cm^{-2}), ion fluxes (<0.1 to 5 keV monoenergetic sources for inert and reactive gases with pulsing capabilities), and photon irradiation (numerous continuous and pulsed monochromated and broad band IR/VIS/UV [0.5 to 7 eV] sources, with 6 to 40 eV sources pending at $20k). Custom hemispherical grid retarding field analyzer and Faraday cup detectors, custom high speed, high sensitivity electronics, and charge neutralization capabilities used with <0.1 nA, <5 μs, $<3\cdot10^{3}$ electrons/pulse pulsed-beam sources permit high-accuracy electron-emission measurements of extreme insulators with minimal charging effects. *In situ* monitoring of surface voltage, arcing, and luminescence have recently been added. A second electron emission chamber is currently under development to extend our test capacity and allow testing of lunar dust and Martian stimulant powder samples. A third existing custom UHV chamber has been dedicated primarily to angle-resolved electron emission energy spectra measurements and to contamination effects.

Four custom, fully-automated high-vacuum test chambers that operate at $<10^{6}$ Torr from <100 K to >350 K are dedicated to electron transport measurements of high resistivity materials. The Constant Voltage (CV) Resistivity Test Chamber uses enhanced ASTM 257 capacitance-geometry methods for measurements up to 10^{20} Ω-cm, using applied voltages up to 12 kV. The Charge Storage (CS) Resistivity Test Chamber (in final development) measures up to 10^{22} Ω-cm using the charge storage method. Surface voltages (~1V to 20 kV) of up to 32 samples are monitored for up to months duration using a custom charge transfer coupler and a standard Trek electrostatic field probe. Versatile, fast, sensitive, and highly stable CV and CS systems allow measurements of polarization, thermally-assisted, hopping, and diffusive transport over time scales of ms to many days. The Electrostatic Discharge (ESD) Test Chamber measures electrostatic breakdown potential up to 20 kV following enhanced ASTM 147 guidelines. Recent ESD tests focused on the effects of electric stress duration, ramp rate or temperature on breakdown. The main emission chamber has recently been used to study electron-induced discharge, by monitoring sample currents and electron and photon emission over a wide range of times (10^{-9} to 10^{4} s) and discharge energies (10^{-9} to 10^{-5} J/pulse). A fourth chamber has been used to measure radiation-induced conductivity (up to 10^{19} Ω-cm) as a function of temperature (<100 K to >400 K), dose rate and electric field when sample are subjected to 0.3 to 25 MeV electron beams over 10^{-2} to 10^{2} Rad/s at the nearby Idaho Accelerator Center (IAC). We have also studied radiation damage effects (up to 10^{8} Rad) at the IAC. Additional electron, proton, and gamma sources are readily available for use at the IAC.

The MPG also has extensive capabilities for sample preparation, conditioning and characterization. These commonly include standard coating and patterning, vacuum annealing and bakeout, outgassing tests, optical and electron microscopy, AFM and STM, AES, XPS, SIMS, UV/VIS/IR reflectivity, FTIR and photoluminescence spectroscopies, and absorbtivity/emissivity tests. .

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REQUEST FOR INFORMATION (RFI)
Radiation Capabilities for the Europa Jupiter System Mission
Planetary Science Division, Science Mission Directorate, NASA
Solicitation Number: NNH09ZDA008L

"Silicon-Germanium Integrated Electronics for Extreme Environments"

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Background and Overview

The NASA ETDP project "Silicon-Germanium (SiGe) Integrated Electronics for Extreme Environments," NNL06AA29C (John D. Cressler, Georgia Tech, Project PI; Andrew Keys, NASA-MSFC PM, andrew.keys@nasa.gov, Marvin Beatty, NASA-LARC Contracting Officer's Technical Representative (COTR), m.e.beatty@larc.nasa.gov), is a 4+ year, >$12M cross-cutting technology development project established within ESMD's Exploration Technology Development Program (ETDP) to address the needs of the Constellation Program elements for electronics possessing hardness against the lunar thermal and radiation environments. This development effort may be leveraged to provide the same capabilities to EJSM.

This project utilizes silicon-germanium (SiGe) integrated circuit technology to develop highly-integrated electronic components and systems, with extremely attractive size, weight, and power (SWAP) advantages over commercial off-the-shelf (COTS) solutions. SiGe technology has exceptional capabilities for operation over both wide temperature ranges (-180°C to +120°C) and under intense radiation exposure (multi-Mrad total ionizing dose), and thus offers substantial potential benefits to EJSM.

Capabilities and Qualifications

The overall goal of the present NASA ETDP SiGe project is to develop and demonstrate extreme environment electronics components required for lunar robotic systems with distributed architecture, using low-cost, commercial SiGe BiCMOS technology, and assemble those components into a functional Remote Electronics Unit (REU) prototype. Unlike other COTS IC technologies, SiGe offers unparalleled cryogenic temperature performance, excellent radiation immunity, wide temperature range capability, and optimal mixed-signal circuit design flexibility at the monolithic level by offering power efficient, high-speed transistors (SiGe HBTs) together on the same piece of silicon wafer with high density CMOS and passive components. This SiGe project directly addresses the following:

- Low-power, radiation tolerant, integrated SiGe BiCMOS mixed-signal (digital + analog + power) electronics for sensor/imager and actuator systems that can operate reliably across -180°C to +120°C, and under relevant radiation conditions.

- High-density packaging of these SiGe BiCMOS electronics components (with integrated passive components) which can operate reliably across -180°C to +120°C, and under relevant radiation conditions.
- Modeling and CAD tools for SiGe BiCMOS devices and packaging to accurately predict and simulate the electrical performance, reliability, and radiation tolerance of these SiGe BiCMOS mixed-signal circuits and packages across -180°C to +120°C, and under relevant radiation conditions.

Definition and implementation of a general purpose SiGe REU, capable of operation across -180°C to +120°C, and under relevant radiation conditions. It is anticipated that all of these SiGe attributes would benefit EJSM's electronics and their ability to meet environmental performance parameters.

The NASA ETDP SiGe project is demonstrating that commercially-available SiGe BiCMOS technology can be successfully used to support the extreme environment electronics needs for lunar unmanned missions, which can then be easily extended to EJSM needs by leveraging the existing infrastructure already developed with NASA funding. We have modeled, designed, fabricated, packaged, and tested SiGe BiCMOS devices and circuits, including key mixed-signal circuit blocks for use in the lunar environment, and demonstrated that such SiGe circuits can operate reliability across -180°C to +120°C, and under radiation exposure. We have implemented these mixed-signal circuits using a single, low-cost commercially-available integrated circuit solution: IBM's SiGe 5AM BiCMOS technology. We have also developed both modeling tools (device and circuit) and mixed-signal circuit libraries for NASA use, permitting seamless technology insertion into future spirals.

Expertise, Services, Technology Deliverables

Georgia Tech, a proven leader in SiGe research and development, has assembled a world class team of industry and university partners to support the NASA ETDP SiGe project, including: Boeing, BAE Systems, IBM, JPL, Auburn University, Vanderbilt University, University of Tennessee, University of Maryland, Lynguent, and University of Arkansas. Phase 1 of the effort was completed in April of 2006, successfully demonstrating the efficacy of our goals, Phase 2A was completed in April of 2007, successfully demonstrating a number of component building blocks, with optimized packaging, and multi-chip functional prototypes (Final Reports are available upon request). We launched Phase 2B on April 29, 2007. Phase 2B will run from April 2007 through September 2009. At the end of Phase 2B we will have demonstrated a functional SiGe Remote Electronics Unit (REU), a general purpose sensor interface engine, and validated it both in a radiation environment (total dose and SEE) and across wide temperature range exposure (-180°C to +120°C). Our BAE Systems team partner has already expressed interest and developed a path for productizing our SiGe components for NASA mission use.

Maturity Level of the Technology

This NASA ETDP SiGe project will raise SiGe BiCMOS extreme environment electronics technology, including packaging, to TRL 6 (demonstrated integrated circuits, packaging, models, and design libraries, and functional protoypes in relevant environments), permitting seamless technology insertion in future NASA technology spirals. We will achieve TRL-6 in the summer of 2009 in this project. In addtion, our Boeing team partner is presently inserting our devleoped SiGe components into the MISSE-7 flight experiment, potentially raising our TRL level to 7. The MISSE-7 pre-flight validation tests are continuing, on schedule for the planned launch date of November 2009.

Phase 2B Year 1 Final Report

"SiGe Integrated Electronics for Extreme Environments"

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Phase 2B Year 1 Final Report

Deliverable for
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April 21, 2008

NASA ETDP

Phase 2B Year 1 Objectives
for "SiGe Integrated Electronics for Extreme Environments"

This NASA ETDP project will demonstrate that commercially-available SiGe BiCMOS technology can be successfully used to support the extreme environment electronics needs for lunar (and Martian) missions. We will model, design, fabricate, package, and test SiGe BiCMOS devices and circuits, including key mixed-signal circuit blocks for use in the lunar environment, and demonstrate that such SiGe circuits can operate reliability at both: 1) -180°C, and 2) across -180°C to +120°C. We will implement these mixed-signal circuits using a single, low-cost commercially-available integrated circuit solution: IBM's SiGe BiCMOS technology. During technology development, we will also architect and implement optimized Ge profiles for cryogenic SiGe HBTs within the commercially available IBM SiGe BiCMOS technologies, develop both model and circuit libraries for NASA use, a robust packaging platform, and prove the component reliability, permitting seamless technology insertion into future spirals.

We have demonstrated the cryogenic capabilities of SiGe BiCMOS devices (both SiGe HBT and Si CMOS), and built device models suitable for circuit design at extreme temperatures. Our Phase 2B Year 1 circuit designs were implemented in IBM SiGe 5AM technology platform, which is a low-cost, first-generation SiGe BiCMOS technology supported by IBM and currently available through the MOSIS foundry (CRYO-2.5 + CRYO-3a + CRYO-3b experiments). A large number of diverse SiGe circuits have been designed, fabricated, and measured, and are available for NASA reuse. During Phase 2B Year 1 we have developed improved TCAD modeling capability for device operation and radiation effects across wide temperature ranges. We developed robust electronics packaging technology for extreme environments (including multi-chip module capability), and demonstrated device, circuit, and package reliability for both extreme temperature operation and radiation tolerance. A development build path and

architecture for the envisioned general purpose wide-temperature range enabled, radiation tolerant SiGe Remote Electronics Unit (REU), a general purpose sensor interface platform with NASA legacy, has been completed, and we are marching the path to building prototypes.

A Project Justification Slide and our Phase 2B Year 1 Project Major Milestones are shown below.

SiGe Integrated Electronics for Extreme Environments

SiGe ETDP / Dr. John D. Cressler, Georgia Tech, Project PI

NASA ETDP: SiGe Integrated Electronics For Extreme Environments

- **The Problem We Are Solving:**
  - we are developing low-cost electronics to operate directly exposed to the Lunar, Martian, and other extreme environments
  - e.g., Lunar missions require electronics to function from +120C to -180C (day to night), and must survive a 14 day lunar night without the need for large batteries and radioactive heating units (RHU)
  - we will create reconfigurable/modular/distributed electronics that operate in extreme environments without "warm boxes"
- **How Is It Done Today?**
  - current electronics require thermal protection ("warm boxes"), increasing system power drain, size, mass; mandates centralized architecture; negatively impacts safety and reliability
- **The Novelty of Our Approach:**
  - we will exploit the unique properties of commercially-available (IBM) silicon-germanium (SiGe) integrated circuit (IC) technology
  - SiGe devices operate down to deep cryogenic temperatures and have a built-in radiation tolerance; SiGe offers high integration capability (analog + digital + RF functions on the same SiGe chip)
- **The Risks and Payoffs of Our Project:**
  - ***payoffs***: if electronic components can be distributed and operate under extreme environment conditions without a "warm box," vehicle form factor, power needs, reliability, launch weight, safety, and mission cost can be dramatically improved
  - ***risks***: the primary risk lies in extending/validating a commercial technology (SiGe) to extreme environments
- **How Will We Measure Our Success?**
  - we will demonstrate (to TRL-5/6) reliable, functional, packaged electronic components that meet system specs down to -180C
- **Who Will Care If We Succeed?**
  - Lunar (e.g, RLEP) , Martian, and space exploration missions will benefit from modular, reusable, reliable, lower cost electronics
  - e.g., unmanned rovers, remote vehicles, landers, hoppers, sub-surface, habitats, space transportation, space orbiting stations
- **How Does This Impact CEV?**
  - our targeted is a Remote Electronics Unit (REU), which provides data acquisition and control for various applications
  - for CEV, an REU could be used as a common reprogrammable building block for Integrated Vehicle Health Management Management (IVHM), reducing size, weight, power, while improving reliability
- **A World-Class Team of University / Industry Experts in SiGe Devices/Circuits, Packaging, Maturation**
  - Georgia Tech, JPL, IBM, BAE Systems, Boeing, Auburn University, University of Maryland, University of Tennessee, Lynguent

Phase 2B Year 1 Executive Summary
For "SiGe Integrated Electronics for Extreme Environments"

This NASA ETDP project has completed Phase 2B Year 1 successfully, with all of our major goals and milestones accomplished on schedule. No significant show-stoppers to our long-term project goals have been identified. This positions us nicely for entry into Phase 2B, Year 2, which will span 4/28/08 to 4/27/09. Technical highlights of our Phase 2B Year 1 project are extensively addressed in the Review Materials and the various Deliverables Documents (on CD), and are summarized briefly here in bulleted form.

Selected Technical Highlights of Phase 2B Year 1 Include:

- Mixed-Signal Circuit Building Blocks for REU Defined for CRYO-3a / CRYO-3b Chips
- Refined SiGe HBT Compact Models Constructed, With Exhaustive New SiGe HBT Data
- Refined TCAD files of the SiGe HBT Built and Used to Understand Cryo-T Operation
- Refined TCAD Models for the SiGe HBT and Si CMOS Built for Single Event Strikes
- CRYO-2.5 / CRYO-3a / CRYO-3b Designs Completed and Sent to MOSIS For Fab
- Test Dewar for 77K SEU Experiments Defined and Under Construction
- SiGe HBT and Si CMOS Reliability Down to Cryogenic Temperatures Established
- Embedded Resistors and Capacitors Demonstrated for Cryogenic Package
- Physics of Failure Modeling of Cryogenic Package Materials Completed
- SiGe BiCMOS Device and Circuit Radiation Tolerance to cryo-T Evaluated
- RHBD Techniques for SiGe HBTs Established
- CRYO-2.5 / CRYO-3a Experiments Completed Ahead of Schedule
- Functional Circuits on CRYO-2.5 / CRYO-3a Experiments Measured (across T)
- Temperature Cycling on Circuits and Package Vehicles Completed
- 300 mK Operation of SiGe HBTs and Voltage References Demonstrated
- Refined Maturation and Application Plan Completed
- Successful Launch of MISSE-6 to ISS Included SiGe Voltage Reference
- REU Architecture and Build-Path Finalized
- 3 Channel SiGe RSI ASIC Design Competed (CRYO-3a)
- 16 Channel SiGe RSI ASIC Design Completed (CRYO-3b – in fab)
- Preparations Underway to Use CRYO-3a 3-Channel RSI ASIC for MISSE-7 Experiment
- Two Comprehensive Project Reviews Completed (+ NRC and NASA ETDP Reviews)

The documents for this Phase 2B Year 1 Final Report are detailed below, and are contained on a companion CD.

Phase 2B Year 1 Final Report Deliverable Documents

- **Phase 2B Year 1 Master Document**

- CRYO-2.5 + CRYO-3a + CRYO-3b Circuit Design Documents
- Reliability Document
- Refined Applications and Maturation Plan Document
- Device Technology Document
- Packaging Document
- Modeling Document
- Test Chip Evaluation Report

Final Report Technical Supporting Materials

Item	Document Title
1.	Quarterly Report (progress reports: June to August 2007)
2.	Quarterly Report (progress reports: September to November 2007)
3.	Quarterly Report (progress reports: December 2007 to February 2008)
4.	May 2007 Monthly Progress Report
5.	June 2007 Monthly Progress Report
6.	July 2007 Monthly Progress Report
7.	September 2007 Monthly Progress Report
8.	October 2007 Monthly Progress Report
9.	December 2007 Monthly Progress Report
10.	January 2008 Monthly Progress Report
11.	March 2008 Monthly Progress Report
12.	NRC Review Slides (November 2007)
13.	Project Review #1 Slides (November 2007)
14.	Project Review #2 Slides (March 2008)
15.	Integrated Master Schedule
16.	SiGe ETDP “List of Firsts”
17.	Phase 2B Year 1 Major Milestones and Deliverables
18.	ETDP Review (September 2007)

Note: All Final Report Documents and Supporting Materials are included on the attached CD.

TID Test Facilities at the UMLRL

A Response to RFI Solicitation Number: NNH09ZDA008L

Submitted By: Leo M. Bobek, Radiation Laboratory, University of Massachusetts Lowell, Lowell, MA 01855, Phone: 978-934-3365, Email: Leo_Bobek@uml.edu

Introduction

The University of Massachusetts-Lowell Radiation Laboratory (UMLRL) has several facilities for radiation effects research and testing. These facilities include Cobalt-60 gamma irradiation facilities for Total Ionizing Dose (TID) testing.

The dose rates and total doses anticipated for the Europa Jupiter System Mission spacecraft are readily achievable in the existing UMLRL facilities.

Since 1980, the UMLRL Cobalt-60 gamma irradiation facilities have been used extensively for evaluations of electronics and other materials such as optical components (mirrors, lenses, and windows) used for demanding aerospace applications. These facilities have been designed to provide a range of gamma dose rates up to 420 rad(Si)/sec, with integral doses to 1000 Mrad(Si) or beyond. Facilities for total ionizing dose and enhanced low dose rate susceptibility (ELDRS) testing currently provide dose rates ranging from 0.5 rad(Si)/sec to 210 rad(Si)/sec for TID tests, and 0.01 rad(Si)/sec to 0.1 rad(Si)/sec for ELDRS tests.

An alanine EPR dosimetry system, calibrated and traceable to the National Institute of Standards and Technologies, assures the accurate radiation exposure of samples and experiments. The EPR system utilizes a well know series of reactions that occur when alanine is exposed to ionizing radiation, forming free radicals. A measurement of the free radical concentration in the dosimeter is directly related to the radiation dose received. The system provides a dose range measurement from 50 Gy (5 krads) to 100 kGy (10 Mrads).

The UMLRL has provided controlled and accurate radiation test environments for a wide scope of radiation hardened components suppliers including: International Rectifier, Microsemi Corporation, Analog Devices, Assurance Technology Corporation, MS Kennedy Corporation, Barr Associates, Brookhaven National Lab and many others. As a subcontractor for several of these companies, the UMLRL has undergone DSCC audits.

In addition to the radiation environments, test development and radiation test services can be made available to provide a turnkey solution to verify and validate the performance of space level components.

The following information provides a detailed description of the various facilities available.

Gamma Cave Facility

The Cobalt-60 sources are located inside a water filled bulk-irradiation pool at the UMLRL. The sources are configured into 25 cm x 36 cm frames to produce a planar source geometry. When an irradiation is performed, the source frame is positioned onto a wall mounted rack inside the pool. For the Gamma Cave facility, the rack is located in front of a 12.7 mm thick aluminum source window through which the Cobalt-60 gamma photons enter the Gamma Cave facility (Fig. 1). The Gamma Cave is a dry ventilated irradiation room located on the experimental level of the UMLRL reactor containment building. It has a 15 m^3 volume to accommodate experimental apparatus of various sizes. Inside the Gamma Cave facility a 2.7 m^2 opening in the pool wall tapers inward to the 0.356 m^2 source window. A wide range of dose rates, from 0.5 rad(Si)/sec to 210 rad(Si)/sec, are currently achievable by varying the source activity and the centerline distance of the sample from the source window. Several small ports penetrate the one shielding wall to provide access for instrumentation cables. The Gamma Cave is typically used for TID studies on electronic components and other devices.

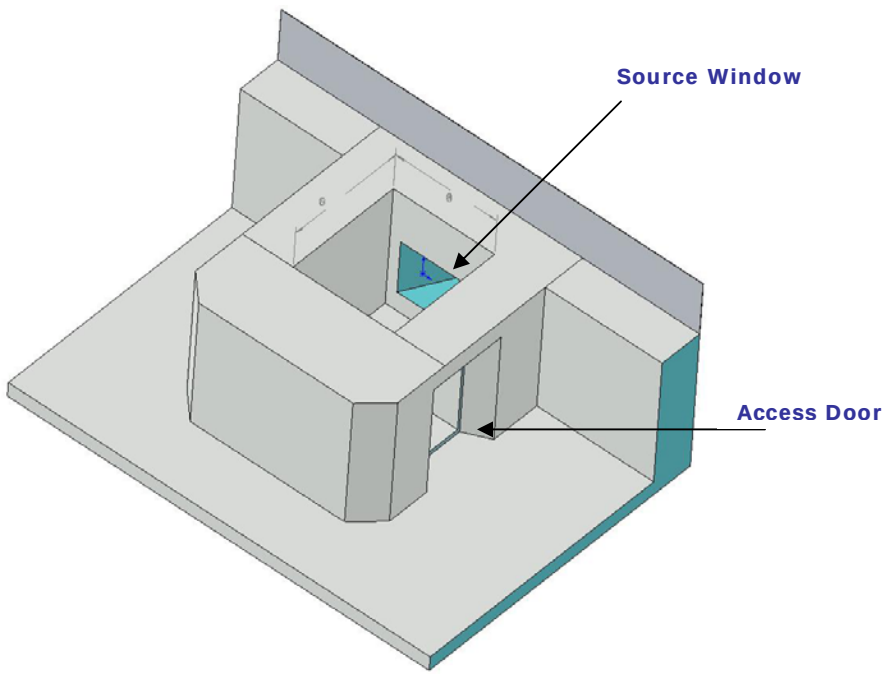

Fig. 1. Top-angled 3-D View of the Gamma Cave Facility (top removed for clarity)

Submersible Canister

A high-dose Cobalt-60 irradiator (Fig. 2) is housed at the bottom of the bulk irradiation pool. The Co-60 sources are fixed in a cylindrical geometry on top of a support unit. Irradiations are performed using a water-tight canister having internal dimensions 20.3 cm x 30.5 cm. The canister is lowered into the geometric center of the Co-60 array. An

aluminum cone bolted at the bottom of the submersible canister mates with a concentric hole on the support structure to provide a reproducible geometry. A central thimble allows for additional Cobalt-60 to produce higher dose-rates. Currently, a maximum dose rate of 420 rad(Si)/sec is achievable.

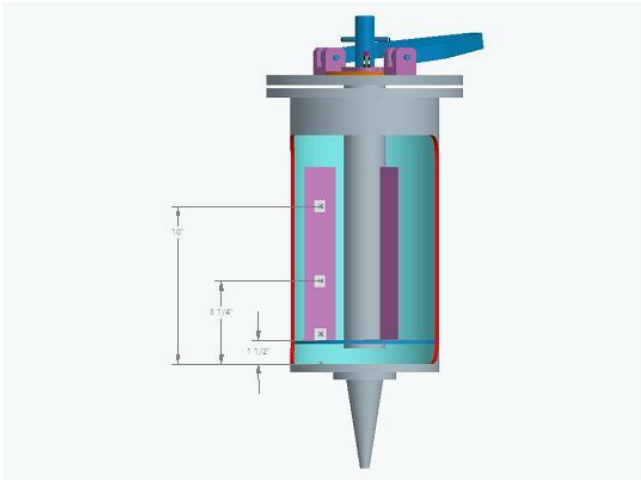

Fig. 2. Submersible Canister.

Enhanced Low Dose Response Facilities

The UMLRL has two facilities for ELDRS test requirements. The ELDRS-1 facility (Fig. 3) is located directly opposite to the Gamma Cave facility. It consists of four independent irradiation chambers. It is designed for the long-term sample irradiation at a dose rate of 0.01 rad(Si)/sec. The irradiation chambers have integrated spectral shielding to meet MIL-STD-883. Samples with a cross-sectional area as large as 34 cm x 34 cm can be uniformly irradiated in each chamber. The gamma flux in each chamber is uniform to within 10% over the cross-sectional area facing the source. Penetrations for test cables and a large area for test equipment are available. Similar to the Gamma Cave facility, irradiations are performed by placing a cobalt-60 source frame into a wall mounted rack located inside the bulk irradiation pool.

Fig. 3. ELDRS-1 Chambers (front view).

The ELDRS-2 facility is located inside a hot cell facility originally designed for radioisotope sample preparation. The hot cell houses a shielded Co-60 irradiator. The irradiator provides a panoramic gamma field permitting dose rates of 0.01 rad(Si)/sec to 0.1 rad(Si)/sec. A remotely operated overhead crane inside the hot cell is used to lift a shield (Fig. 4) to reveal the Cobalt-60 source. The hot cell also includes remote robotic manipulators, a shielded view port, and multiple conduit ports for instrumentation cables.

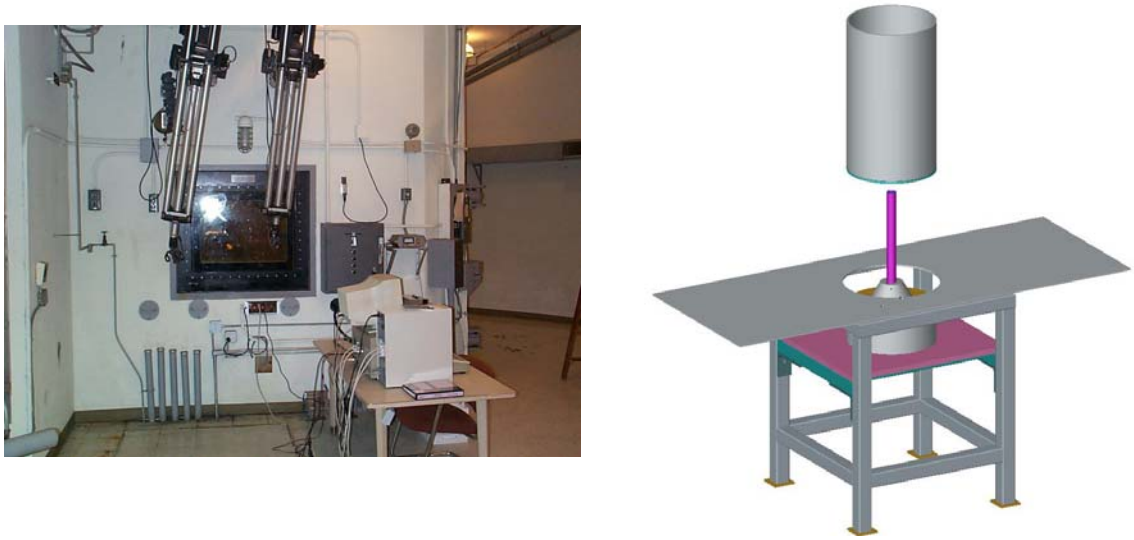

Fig. 4. Hot Cell Exterior with 3-D Rendering of Panoramic Irradiator

Additional Available Facilities

The UMLRL also includes a Van de Graaff accelerator for proton particle production and a nuclear research reactor for neutron particle production. While primarily designed for proton production, the accelerator can be configured to produce deuteron, alpha particle, or oxygen ion beams in either pulsed or DC mode. The accelerator laboratory includes a number analytical instruments and the capability for fast neutron production. The research reactor is a 1 MW, steady-state, swimming pool-type facility. The reactor provides thermal neutrons for both radioactivation experiments, including neutron activation analysis, and for digital neutron radiography. A large, fast neutron irradiator is located adjacent to one side of the reactor core for atomic displacement tests and research. The fast neutron facility is calibrated in terms of 1Mev equivalent neutrons.

End

CAVENDISH KINETICS

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Cavendish Kinetics' Reply to:
Planetary Science Division, Science Mission Directorate, NASA
Request for Information Dated April 24, 2009
Solicitation Number: NNH09ZDA008L

Cavendish Kinetics Inc., San Jose, CA, submits this document in response to the April 24, 2009 Request for Information (RFI), solicitation number NNH09ZDA008L received from NASA regarding the Europa Jupiter System Mission (EJSM).

INTRODUCTION

This document proposes the use of an inherently radiation hard, harsh environment, MEMS-based mechanical switch. The first application of this mechanical switch is for Stand Alone Non Volatile Memory (NVM) and Embedded Non Volatile Memory (eNVM).

What differentiates the Cavendish NanoMech™ technology from any other memory technology:

- Mechanical storage element that is not a charge storage device, is not thermally activated and does not use any exotic materials.
- Refractory metal as a MEMS membrane that is submicron in thickness which enables silicon based MEMS performance at a much wider temperature range, but does not have fatigue issues of ductile metals associated with radiation exposure.
- Nanometer-sized gaps in combination with the above MEMS membrane, enables native voltage (V_{dd}) or higher operation, with much lower stress or strain in the material to minimize the impact of radiation.
- Use of standard equipment and materials that already exist in an IC fabrication facility with any type of substrate including from bulk radiation hardened CMOS/SOI to SiC/GaN.
- Specialized design of the switch element that eliminates charge buildup from a radiation event and an inadvertent state change.

The technology operates over a wide temperature range while consuming ultra-low power. This technology has the attributes to withstand the harsh environmental requirements as well as expected power consumption constraints that NASA desires. NVM applications include start-up memory and storage memory systems. Cavendish eNVM technology is optimum for embedding with FPGAs, where it can significantly increase the immunity towards radiation sensitivity of existing FPGA products. Cavendish Kinetics, working with appropriate partners, would be able to supply this capability to NASA.

COMPANY BACKGROUND AND EXPERTISE

Cavendish Kinetics is an embedded MEMS company that licenses and builds devices based on its NanoMech technology. Cavendish has over 14 years of experience in the design and fabrication of MEMS

devices with the initial development occurring at Cambridge University. Development of the current memory technology began in 2006. The team has experience in DRAM, standard flash, FeRAM and MEMS devices. Cavendish's team includes two of its executives, who were responsible for bringing the Texas Instruments Digital Light Projector (DLP) from concept to production. Several of our employees have spent many years working in the defense-aerospace industry including one of the principal investigators who worked on the NASA Prometheus program in 2005. Experience also includes successful completion of multiple European projects. Cavendish Kinetics specializes in the process development, MEMS design, testing and product development of its NanoMech technology and has over 73 applied for or granted patents.

PROGRAM DEVELOPMENT

The radiation hard NVM program development is envisioned as occurring in two phases. The first phase will focus on design, fabrication and testing of a test chip that will include up to 1Mb of radiation hard NVM using Cavendish NanoMech technology. In addition, the chip will also include an FPGA using Cavendish eNVM. The test chip will carry pertinent information required to evaluate the technical requirements that will be put forth in the RFP (such as TID, latch-up immunity, operating temperature, lifetime reliability, etc.). The time for this phase is estimated to be 1.5 years, which will include design, fabrication and testing of the test chip. The test chip features and cost estimate details will be provided in the proposal in response to RFP.

The second phase of the program will focus on specific memory sub-system and eNVM-FPGA product development. The memory sub-system product design, fabrication, and qualification are estimated to take another 1.5 years. Cavendish is very confident about meeting the radiation hard requirements for its NVM technology. The eNVM-FPGA product development will occur in parallel and is expected to complete in 2.5 years. The cost estimate for the second phase will be provided in detail in the proposal in response to RFP.

CONCLUSION

Cavendish Kinetics has a novel implementation for non-volatile memory that should result in extremely high immunity to radiation. In addition, existing testing has shown an impressively wide temperature range of operation as well as very high thermal retention. The native voltage operation enables ultra low power consumption. We believe that Cavendish NanoMech NVM is one of the most attractive candidates to address radiation damage issues in microelectronic devices using standalone and embedded NVM. The confidential section further describes the features Cavendish NanoMech memory can offer. Cavendish is very interested in receiving an RFP to address radiation exposure issues with its radiation hardened MEMS switch.

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Radiation Effects Modeling for EJSM

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Capabilities and Qualifications

The capabilities and qualifications offered by PR&T, Inc (PRT) to EJSM include:

- Radiation effects modeling and analysis
- Radiation transport analysis
- Design consultation related to radiation effects mitigation
- Radiation effects test planning and execution

These are embodied in the proposed Principal Investigator, Mr. James C. Pickel. Mr. Pickel currently serves as President and Chief Scientist of PR&T, Inc (Physics Research and Technology), providing research and consulting services in the field of radiation effects on microelectronics and photonics. Mr. Pickel has been actively involved in the study of nuclear and space radiation mechanisms and effects for over 40 years and is uniquely qualified to support the radiation aspects of the EJSM design and development. PR&T, Inc. offers an independent small business solution to EJSM and their contractors for microelectronics and photonics radiation effects design, analysis, modeling, and testing. A corporate summary and Principal Investigator CV are attached.

Applicable Expertise

The principal areas of expertise applicable to the design of EJSM for survival in the radiation environments include:

- Modeling radiation effects in microelectronics and photonics
- Current state of art research in radiation transport, particularly secondary particle interactions with highly scaled microelectronics and photonics
- Expert knowledge on single event effects (SEE) and mitigation
- Expert knowledge on radiation effects in IR detectors and arrays
- Expert knowledge of state of art IR detector technology and their vendors
- Radiation test planning and execution, both microelectronics and photonics

Maturity Level of Technologies

The fundamental technology being offered by PRT is a comprehensive understanding and experience base in the field of radiation effects in both microelectronics and photonics. The maturity level of this technology is based on the 40+ years of experience and record of meaningful accomplishments, as listed in the next section.

Past Experience

- 40+ years experience in radiation effects analysis, modeling and mitigation.
- Developed original SEU rate prediction model based on convolution of RPP sensitive volume with LET distribution. This model is still the baseline approach for rate prediction as used in CREME96 and SPENVIS.
- Developed original SEU testing approach based on measurement of cross-section and effective LET using accelerator ions and angle of incidence variation. This test method is still the dominant approach and almost all SEU test data is based on this technique.
- Analysis, modeling and testing for radiation-induced transients in prototype JWST IR detector arrays.
- Developed REACT model and code used to analyze radiation-induced noise transients in JWST IR detector array designs. This model allows radiation-induced charge transport within large arrays to be analyzed and impact of radiation transients on IR sensor performance to be calculated.
- Modeling for JWST won a NASA Certificate of Recognition stating "*For the creative development of technically significant software which has been accepted and approved by NASA entitled* Modeling Charge Collection in Detectors Arrays," dated May 22, 2003.
- Formulated test requirements for initial characterization of prototype JWST focal plane array technology.
- Member of NASA/Goddard radiation test team for characterization of initial prototype JWST focal plane array technology.
- Analyzed prototype JWST focal plane array technology radiation test results and made recommendations to NASA/Goddard for technology down-selections.
- Performed early characterization and developed original models for radiation effects in cryogenic microelectronics. Developed technology for mitigating total-dose effects in cryogenic MOS devices based on MNOS gate dielectrics. Won best paper award at 1984 HEART Conference based on this hardening technology development.
- Served on Expert Advisory Board to JPL on subject of single event latchup (SEL) in COTS ICs proposed for use in Galileo mission(JPL). This work led to requirement to development of hardened parts (SEL insensitive) by Sandia National Laboratory and to successful use in the Galileo mission.
- Served on Expert Advisory Board to JPL on subject of radiation effects mitigation in use of COTS microprocessors for JPL missions. This work has led to successful use of COTS processors in NASA missions.
- Successfully completed NASA NRA on charge collection in IR detectors; "Modeling Charge Collection in Detector Arrays," period 2001 to 2002.
- Successfully completed NASA SBIR Phase I and II on Mitigating Single Event Latchup (SEL); "Single Event Latchup Mitigation in Commercial Microelectronics, " period 2002 to 2004.
- Successfully completed MDA SBIR Phase I and II on MPTB Shielding anomaly; "MPTB Total-Dose Anomaly Investigation," period 2004 to 2006.
- Successfully completed NASA Phase I SBIR on design of space experiment for shielding and dosimetry; "MISTI Shielding and Dosimetry Experiment," period 2006.

Corporate Summary: PR&T, Inc.

PR&T, Inc. (PRT) is a privately-held small business that was founded in 1995 by James Pickel as a research and technology consulting company specializing in radiation effects. PRT was incorporated in 2002. PRT provides radiation effects consulting services to the spacecraft electronics and photonics community and performs innovative research and engineering related to radiation effects in microelectronics and optical sensors. PRT has two employees. Our key mission is to enable the space community manage the risk of using COTS microelectronics in the space radiation environments.

PRT's facilities are located in Fallbrook, CA in Northern San Diego county. Equipment related to this project include 5 computers and specialized software including Microsoft Visual Studio.net, Microsoft Visual C++.net, ITS, Geant4, MCNPX, SPENVIS (and associated tools), NOVICE, CRÈME-96, Crème-MC and REACT. For radiation testing, PRT has experience with and typically uses standard accelerator facilities, including University of California Davis (UCD), Texas A&M University (TAMU), Lawrence Berkeley Laboratory (LBL), Brookhaven National Laboratory (BNL), University of Indiana (UI) and Boeing Radiation Effects Laboratory (BREL). For hardware development and laboratory instrumentation needs, PRT subcontracts to other companies with specialized capabilities, including Space Micro Inc., NextGen Inc., and The Aerospace Corporation.

CV: James C. Pickel

Mr. Pickel has been actively involved in the study of nuclear and space radiation mechanisms and effects for over 40 years. He began his technical career at Oak Ridge National Laboratory where he worked in the field of chemical processing and industrial applications of radio-isotopes from 1965 to 1968. He began his microelectronics career at Rockwell International Corporation in 1968 where he worked on radiation effects for the Minuteman Missile system and other strategic weapon systems. He was one of the original researchers in the field of single event effects and developed the first single event upset (SEU) rate prediction models. His original models and algorithms for SEU rate prediction are still the dominant approach used today as embodied in the CREME96 and SPENVIS analysis tools. He also performed pioneering work in understanding basic mechanisms and hardening of infrared (IR) detectors and cryogenic microelectronics.

In 1984 he joined IRT Corporation, which was later merged into S-Cubed and then Maxwell Technologies, Inc. For over 15 years, he was at Maxwell Technologies, Inc. where he was a Senior Research Advisor for Electronics Technology. He co-chaired a national ad-hoc committee to review and standardize single event effects (SEE) rate prediction methods. He developed procedures for evaluation of reliability of cryogenic electronics and performed technology development for IR focal plane arrays. He has advised on space radiation effects for several space system designs, including AIRS, MSTI, OMPS, TES, CrIS, New Horizons, and JWST. Related to the James Webb Space Telescope (JWST) technology development, he has recently performed detailed studies and modeling of effects of radiation induced transients from secondary particle reactions in IR focal plane array performance.

He has served the IEEE Nuclear and Space Radiation Effects annual conference (NSREC) as Technical Program Chairman, Guest Editor, Short Course Chairman, Short Course Instructor (twice), Awards Chairman, Session Chairman and Reviewer. He also has been an active participant in the Hardened Electronics and Radiation Technology (HEART) conference, the Infrared Information Symposia (IRIS) conference, the Radiation Hardened Electronic Technology (RHET) conference, and the Radiation and its Effects on Components and Systems (RADECS) conference, with numerous papers and presentations. He has approximately 40 publications in refereed journals on the subject of radiation effects in microelectronics and photonics. He twice (1984 and 1997) received the Best Paper award for the HEART conference. He is a Fellow of the IEEE and the citation for his selection reads "*For contributions to the development of methods to characterize, model, and mitigate the effects of single event mechanisms in microelectronics*."

Section 2

2.1 Introduction

LGS Innovations, a subsidiary of Alcatel Lucent, has performed an extensive level of research and development on optical systems designed for use in space applications. In particular, LGS has developed a method for reducing the radiation sensitivity of optical fibers, specifically those used for communications and sensor applications, such as Light Detection and Ranging (LIDAR) or Differential Absorption LIDAR (DIAL). LGS believes that the developed technique could prove useful to NASA for development of radiation hardened optical systems and subsystems for the Europa Jupiter System Mission.

2.2 Radiation Effects on Optical Fibers

It is well known that exposure to ionizing radiation will increase the absorptive losses of an optical fiber. The physical reason behind this effect is due to the generation of color centers within the matrix of the optical fiber, which are produced when the bonds between constituent atoms are physically broken. The formation of these color centers has been shown to be dependent on dose rate, total dose, temperature and optical fiber composition. In general, the formation of the color centers, and hence the increase in optical absorption, is proportional to dose and dose rate but inversely proportional to temperature. The relationship between fiber composition and radiation sensitivity is, however, complex and is dependent on concentration. Each dopant used to manufacture the optical fiber will result in the formation of a unique color center(s) upon exposure to ionizing radiation. In turn, each of these color centers will result in an increase in optical absorption over some portion of the optical spectrum. This increase in optical absorption will, in time, lead to a degradation in system performance.

2.3 Typical Mitigation Techniques

Given the increased applicability of fiber optic based devices for space applications, coupled with the increased demand on performance it has become necessary to employ all techniques possible to ensure reliable, long term operation in radiation environments. Of these techniques, the most basic is to spot shield critical fiber optic components to an exposure level that does not adversely affect performance. While spot shielding is the easiest to implement, it is often at odds with other system / subsystem requirements, such as size and weight. One possible alternative to spot shielding is to design an optical fiber that is not inherently sensitive to exposure to ionizing radiation, thus reducing the generation of color centers at or near the wavelength of operation. The problem with designing such an optical fiber is that the elimination of the color-center generating dopants ultimately results in an optical fiber with poor performance.

Given the obstacles associated with the above methods, LGS has developed a proprietary technique for reducing the overall radiation sensitivity of an optical fiber that does not rely on, nor require, changes in either system design or fiber design. The technique involves processing the optical fiber after the fiber is manufactured and the technique has been successfully applied to optical fibers used in fiber optic gyroscopes, fiber optic lasers, fiber optic sensors and high power optical amplifiers.

2.4 Mitigation of Radiation Effects on Optical Fibers

LGS has applied the proprietary radiation mitigation technique to pure silica core fiber, ytterbium doped fiber, erbium doped fiber and erbium-ytterbium co-doped fiber. As an example of the effect of the technique on radiation sensitivity, a plot of the induced loss as measured at 1600 nm as a function of total dose is given in Figure 4 for both a treated and untreated sample of erbium-ytterbium amplifier fiber. Both fiber samples were exposed at a dose rate of 108 kR(Si)/hour at a temperature of 22 ^{o}C.

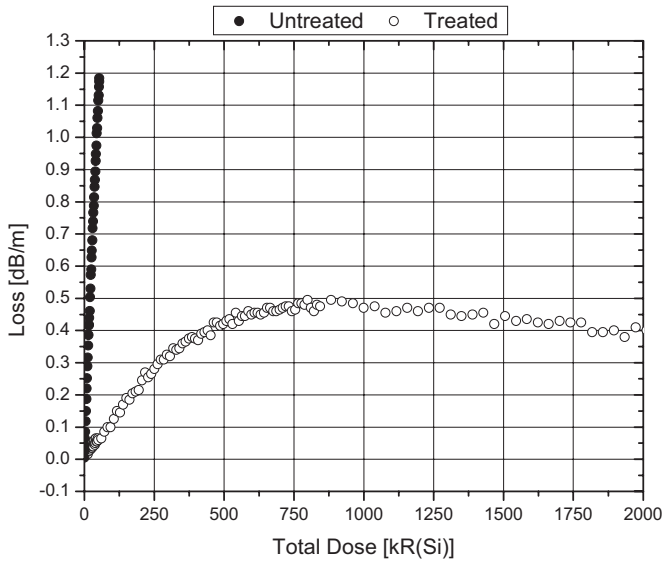

Figure 4 Increase in optical loss at 1600 nm for an untreated and treated erbium-ytterbium fiber sample exposed at 108 kR(Si)/hour.

For the untreated sample, the induced loss reaches a value of 1.2 dB/m after 54 kR(Si) of exposure, while the treated sample only exhibits an induced loss of 0.04 dB/m. As shown the treated fiber only exhibits a total induced loss of 0.4 dB/m after at total exposure of 1.97 MR(Si). Typically, fiber optic systems (amplifiers, LIDAR, etc) contain on the order to 5 to 10 meters of rare-earth doped fiber. When these lengths are considered, the utility and advantages of the mitigation technique become significant.

A sample of erbium-ytterbium fiber that had been placed through the radiation mitigation technique was used to assemble a high power fiber optic amplifier, where no changes in performance were noted as compared to baseline performance using an untreated fiber sample.

2.5 Applicability to EJSM

Based on publically available information, both the Jupiter Europa Orbiter (JEO) and the Jupiter Ganymede Orbiter (JGO) will be equipped with optical devices. Specifically, the published information indicates that both orbiters will be equipped with laser altimeters operating at 1064 nm.

A typical system for a LA (as well as a LIDAR or DIAL system) can be constructed using a ytterbium based fiber optic laser. Similar results have been demonstrated using ytterbium doped fiber as those shown for erbium-ytterbium fiber in Figure 4. Given the harsh radiation environment that both orbiters will experience, in particular the JGO, LGS believes that its proprietary radiation mitigation technique would greatly enhance the performance and reliability of any fiber optic system aboard the orbiters.

In particular, fiber optic devices are highly susceptible to radiation induced damage during storage (during interplanetary cruise) or during periods of non-operation. This is due to the lack of thermal or optical annealing of radiation induced damage. LGS believes that its mitigation technique offers a significant level of radiation protection during these periods without the complications or expense associated with additional shielding or specific design of an inherently resistant optical fiber.

COMPOSITE RADIATION SHIELDING FOR INSTRUMENTS AND ELECTRONICS

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Abstract

ATK Space Structures has extensive experience with design, analysis, and processing of laminated composites and conductive bonds in structural composites. Radiation Shielding concepts have been modeled for predictive radiation transport and structurally for weight optimization of point designs. Current radiation hardened designs target low-distortion support structures. Laminated panel shielding/low transmission design methods are in development. Initial survivability testing is complete and preparations are underway for additional panel fabrication and radiation transport testing starting in 2009. Testing will include shielding/transmissibility, key mechanical properties characterization, Coefficient of Thermal Expansion (CTE)/thermal stability, and high exposure survivability.

Technology Readiness Levels

-- 2009: TRL 1-2, (MRL 3-4)

-- 2010-2011: TRL 3-4, (MRL 5-6)

ATK anticipates the ability to design and build shield panels that will meet the EJSM environment shielding requirements in the 2010 time frame. This product will be significantly lighter than Aluminum for same shielding and stiffness.

Enabling technologies for radiation shielding technology related to this mission have been demonstrated:

-- Design, Analysis, and Processing of laminated composites bonded into precision assemblies

-- Shielding design by predictive Transport Analysis of natural radiation environment and contracted test verification

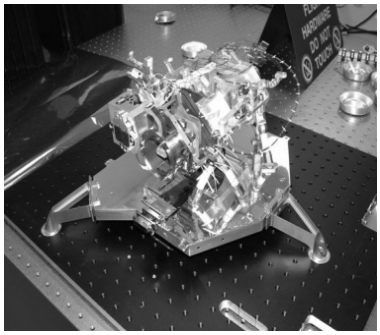
-- Military Missile shielding program

-- Over 300 Stable Structures for RF, Optical, and Sensor Bench projects

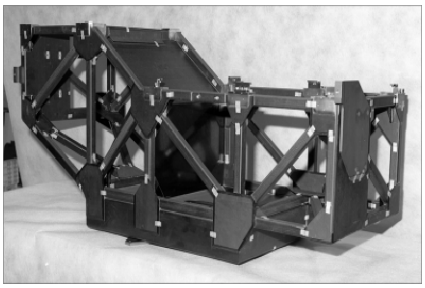
-- Several electronic shielding enclosures

-- Spectrometer Instrument projects

ATK Spacecraft Systems and Services has a long history of providing instrument packaging for space applications, including the Moon Mineralogy Mapper flown on Chandrayaan-1, of which a variant is being considered for the EJSM mission.



Moon Mineralogy Mapper



STSS ~3' Tracker Bench

Mars and Stardust Enclosure

ITI Response to RFI for the Europa Jupiter System Mission

Name and Contact Information:

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Statement of Capabilities, Qualifications, Experience, and Maturity:

Implementation Technology, Inc. (ITI) is a small, woman owned business incorporated in the state of California. The ITI team consists of a small core of Company capabilities augmented by access to numerous nationally know Subject Matter Experts (SMEs) that are pulled together, as a team, to focus on a particular problem or task. This team has extensive experience to provide expert capabilities across all areas of radiation hardening design and qualification disciplines required to support the design and development of the EJSM spacecraft in order to operate within the ionizing radiation, single event, and displacement damage environments expected for the EJSM mission. This includes the radiation hardening system engineering disciplines to develop radiation hardening design, qualification and hardness assurance requirements flowdown; component/circuit hardening analysis and design support; radiation shielding analysis and design; spacecraft charging assessment and mitigation; and special hardening assessment and mitigation capabilities unique to sensor/instrument payloads, including degradation and noise mitigation techniques.

This capability has been applied to numerous space systems and missions over the years, including previous Jupiter missions, i.e., Pioneer, Voyager, and Galileo missions, as well as numerous military and three letter agency satellites such as DSP, DSCS II, DSCS III, FleetSatCom, UHF FollowOn, - - -, GPS.

In the area of project management and oversight, ITI has recently developed unique project management tools (MATRIX) that has been applied to assist in the management and implementation of the Project Radiation Hardening Program. The tool provides the context sensitive information necessary to conduct each activity in a single location. It also is applicable to additional disciplines (such as Reliability, Safety, QA, - -) that have definable requirements and activities that must be addressed or conducted at one or more assembly levels of the system. This tool has been utilized recently on the Mission Assurance effort of the Juno Project.

ITI assisted in the organization and is currently participating in the Radiation Advisory Board support to the Juno Mission Assurance Manager. Previously, ITI participated in, and chaired, an earlier technical peer review committee for the assessment of systems engineering and radiation hardening issues and mitigation approaches for the earlier Europa Explorer Mission Concepts study.

As cited in the RFI, the estimated Total Ionizing Dose, TID, range for the JEO mission (i.e., 2900 kRad(Si) behind 100 mils Al shielding to 817 kRad(Si) behind 320 mils Al shielding) will pose an extremely difficult hardening challenge. Also, as noted in the RFI, the minimum die-level part TID capability is expected to be 100 kRad(Si) behind 100 mils shielding for the JEO mission. This anticipated die-level TID capability is probably achievable for many piece parts, however, it is likely to pose a significant challenge for many other parts; i.e., power devices, analog devices, etc. This may be particularly daunting when considering the likely additional requirement for a design margin (usually a factor of 2). The anticipated peak dose rate of about 2.3 Rads(Si)/sec., behind 100 mils Al shielding, as noted in the RFI, will also pose a significant challenge to deal with the radiation-induced transient and noise effects which can alter various spacecraft and instrument functions critical to mission performance and success. It should be noted that some sensors, by their nature, cannot be placed behind 100 mils of aluminum

and will see higher total dose and dose rates. Additional mechanisms, such as, Single Event Effects (SEE) and Enhanced Low Dose Rate (ELDRS) effects will likely be of significant concern.

To meet these challenges, judicious trades between radiation shielding, hardened piece parts/components, circuit design, software driven mitigation techniques, and operational/functional flexibility will be required. Spacecraft charging, both external and internal, will also be a significant concern. This will require detailed modeling and analyses to define the environmental and design requirements and mitigation techniques. A stringent hardness assurance program will be required in order to ensure the hardened designs are implemented in the flight hardware and software.

The ITI team can address all of these major challenges, as well as, support the overall EJSM radiation hardening program. Specifically, the ITI team has been involved in the development and/or utilization of numerous applicable radiation hardening design analysis tools and procedures that have been used in various spacecraft and rad-hard technology development programs. For example, the ITI team supported the development of the Defense Threat Reduction Agency (DTRA) Hardened Sensor Design and Test Protocol (ITI was also the overall editor), as well as, the companion Testable Hardware Design Protocols for Space Systems. In the area of analysis and design tools to support rad hard designs, the ITI team has experience in utilizing various circuit analysis and design tools, i.e., SPICE, VHDL, SEE, Silvaco, etc.; spacecraft charging modeling and analysis tools, i.e., GEANT 4, ECEMP Charging Analysis & Hardening Tool; integrated radiation shielding codes which couple CAD models directly into radiation transport and response codes. All of these tools are mature, operational tools suitable for use on the ESJM Radiation Hardening Program. The team has experience in supporting "hardened-by-design" techniques, particularly in relation to electro-optic sensor devices, such as, CCD FPAs, Hybrid FPAs and Active Pixel Sensors , as well as, working closely with specialized device design organizations and foundries to fabricate, evaluate and radiation test hardened devices. The ITI team has extensive experience in the area of radiation testing, including testing for permanent damage (TID, DD) and in the particularly difficult area of the measurement of performance (transient/noise) of analog circuits/components, such as focal plane arrays, utilizing advanced fiber optic test instrumentation.

The management tool MATRIX, (Mission Assurance Tracking Requirements In eXcel) is tailored for each program to provide a systematic decomposition of the system and arrays system elements with the associated activities and requirements of the element. A separate sequence is provided to reflect the specific requirements and activities of each discipline using the tool. MATRIX answers questions such as:

- *From a discipline management point of view*

  What is the status of this discipline? How many actions must be performed? How many of each status category (identified, ongoing, complete, problems, - -, not applicable)? At what assembly level do these status evaluations appear? What design elements is associated with each status evaluation? What is the background information supporting these status evaluations? More.

- *From a discipline technical point of view*

  As above but data for a specific test, analysis, or evaluation.

MATRIX is maintained current through interaction with the discipline lead or designee. It **Does Not** independently make judgments of status, acceptability, applicability, etc. MATRIX can automatically generate reports and presentation material with this information.

ITI's experience in implementing radiation hardening programs and providing radiation hardening oversight to system hardening programs, including the prior Europa Explorer Mission Concepts study and the on-going Juno Project, would be directly applicable to the ESJM Project. The ITI team has over 100 years experience in the radiation effects arena and knows the players, facilities, and tool well. ITI can add additional capability as needed or desired by an ITI customer.

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- Contact Info:
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      21000 Brookpark Road, Cleveland, Ohio 44135
      Tel: (216) 433-3462, Fax: (216) 433-8705,
      Email: Rainee.N.Simons@nasa.gov
- Capabilities and Qualifications: Radiation Tolerant Wide Band Gap Semiconductor Device Technology
- Description of the Respondent's Applicable Expertise: Please see attached paper entitled "Total Ionizing Dose Test Results on X-Band GaN HEMT RF Power Amplifier."
- Maturity Level: TRL 2 to 3
- Past Experience Delivering Similar Technologies for Space Missions: Example would include the traveling-wave tube amplifiers for the Lunar Reconnaissance Orbiter (LRO) and CoNNeCT missions.

Total Ionizing Dose Test Results on X-Band AlGaN/GaN HEMT RF Power Amplifier

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I. INTRODUCTION

Recent advances in the area of wide bandgap semiconductor materials such as gallium nitride (GaN) have led to superior microwave and millimeter-wave amplifiers performance as compared to conventional III-V semiconductor based components. The reason for this is because GaN has higher critical breakdown field, saturated (peak) electron velocity, 2DEG sheet electron density, and thermal conductivity as compared to other III-V semiconductors. A summary of key material parameters are presented in Table I. Transistors fabricated from heterostructure wide band-gap semiconductor materials such as, aluminum gallium nitride/gallium nitride (AlGaN/GaN) have demonstrated high power density, with high efficiency and high linearity, at microwave and millimeter-wave frequencies [1]. High power, high efficiency and linearity are of prime importance for high data rate digital satellite communications [2]. In addition, the high power density implies that the outputs from fewer numbers of devices need to be combined (see Fig. 1) to achieve a target power level. Furthermore, the ability to operate reliably in high radiation space environment [3] is also equally important. When semiconductor GaN was exposed to electron fluence, the measurements showed that the energy required to displace an atom from its lattice position is about 20 eV, which is 2X higher than for GaAs [4]. Hence, GaN is more resistant than other III-V semiconductors to displacement damage. Furthermore, total dose gamma radiation effect on the static, high frequency, and pulsed current-voltage characteristics of silicon nitride passivated discrete AlGaN/GaN high electron mobility transistor (HEMTs) were reported in [5].

Table I: Comparision of key III-V and wide bandgap semiconductor material parameters

Parameter	GaAs	GaN
Bandgap (eV)	1.42	3.49
Saturated (peak) electron velocity ($x10^7$ cm/s)	1.0	1.5
2DEG sheet electron density (cm^{-2})	$<4x10^{12}$	$1\text{-}2x10^{13}$
Critical breakdown field (MV/cm)	0.4	3.3
Thermal conductivity (W/cm-K)	0.5	>1.7
Relative dielectric constant (ε_r)	12.8	9.0

The only significant change observed in the device characteristics was -0.1 V shift in the threshold voltage (V_{TH}) after total dose of 600 Mrad. In addition, proton radiation experiments, with both total dose (to 300 Mrad) and displacement effects, have been reported [6,7] for discrete transistors, but not for RF circuits. Hence, these transistors have excellent radiation hardness characteristics. In this paper, the performance of an X-Band (10 GHz) AlGaN/GaN HEMT based hybrid RF power amplifier when exposed to total dose gamma radiation of about 2.1 Mrad is presented.

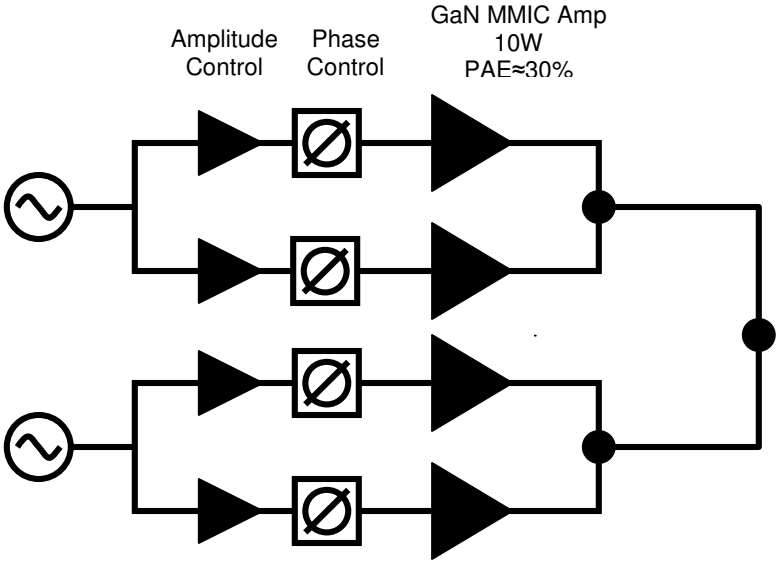

Fig. 1 A 1:4 Power Combiner Architecture for GaN MMIC Amplifiers

II. Basic AlGaN/GaN HEMT Structure

A schematic cross section of a basic millimeter-wave AlGaN/GaN HEMT transistor is shown in Fig.2. The heterostructure is grown by plasma assisted MBE on a semi-insulating silicon carbide (SiC) substrate. Typically thickness and composition of the layers are: 100 nm AlN nucleation layer, 1.5 µm GaN buffer layer and a 25 nm $Al_{0.20}Ga_{0.8}N$ barrier layer. The Pt/Au Schottky T-gate is 0.2 µm long. The Ti/Al/Ni/Au source and drain ohmic contacts are 2 µm apart with the gate centered. The passivation layer is silicon nitride (SiN). The spontaneous and piezoelectric polarization effects provide the 2 Deg channel charge. These effects enable device structures without extrinsic doping to exhibit sheet electron densities, N_s on the order of $1\text{-}2\times10^{13}/cm^2$.

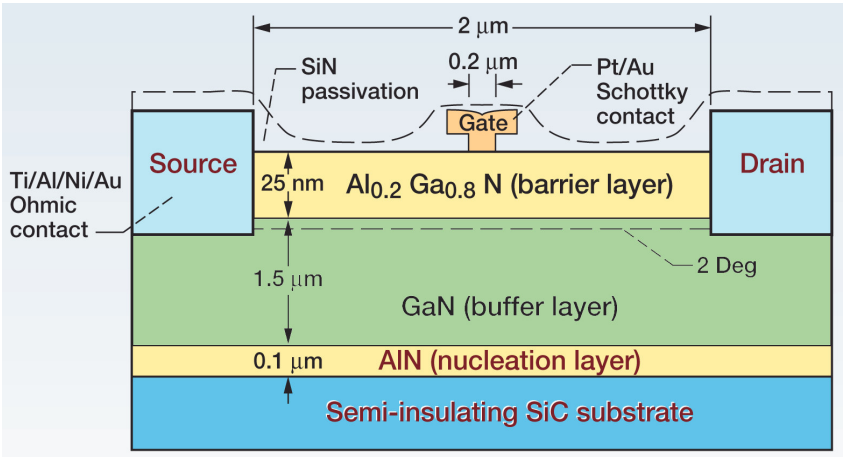

Fig. 2 A Typical AlGaN/GaN Millimeter-wave HEMT Structure

III. AlGaN/GaN HEMT-Based Hybrid Test Amplifiers

The AlGaN/GaN HEMT-based hybrid test amplifiers were designed and developed at the Wright Site of Air Force Research Laboratory. The AFRL/SND-fabricated transistors were processed on commercial gallium nitride epitaxy grown on SiC substrates. The Metal Organic Chemical Vapor Deposition (MOCVD)-grown structure consisted of an AlGaN barrier layer on an unintentionally doped GaN buffer layer. The amplifier utilized a 0.3 micron gate-length, 150 micron gate-width, two-finger, T-gate, silicon nitride-passivated AlGaN/GaN HEMT, with total gate periphery of 300 microns. The device structure of the AFRL-fabricated 2 X 150 micron AlGaN/GaN HEMT was similar to that reported in [8]. Input and output impedance matching for the amplifiers was accomplished on alumina substrates. The transistors were die-attached onto copper tungsten carriers with a high thermal conductivity epoxy, and the alumina matching networks mounted with indium lead solder. For dc and microwave characterization purposes, the amplifier assembly was considered to be the Wiltron Universal Test Fixtured-hybrid amplifier assembly. The AFRL/SND-designed hybrid GaN power amplifiers were representative GaN technology test vehicles, with 3-4 W/mm 10 GHz power densities, simultaneously with >35% power-added efficiency and ~6.5 dB power gain, at a 20-volt drain bias.

IV. Pre- and Post-Radiation Exposure Microwave Performance

Microwave power characterization at 10 GHz was performed at AFRL/SND on the GaN hybrid amplifiers prior to dc-biased total dose gamma radiation exposures at NASA-Goddard Space Flight Center (GSFC), as well as after the radiation exposures. The Co^{60} source at GSFC is a room air source, where the pencils are raised up out of the floor, during exposures. Active dosimetry is performed, using air ionization probes. Testing is done in a step/stress manner, using a standard Pb/Al filter box. Dose rate typically varies slightly from one exposure to the next, but is roughly 25 rads/s. Parts were under DC bias during exposures, but not actively exercised. As shown below in Fig. 3, minimal changes in microwave power performance were observed before and after gamma radiation exposures.

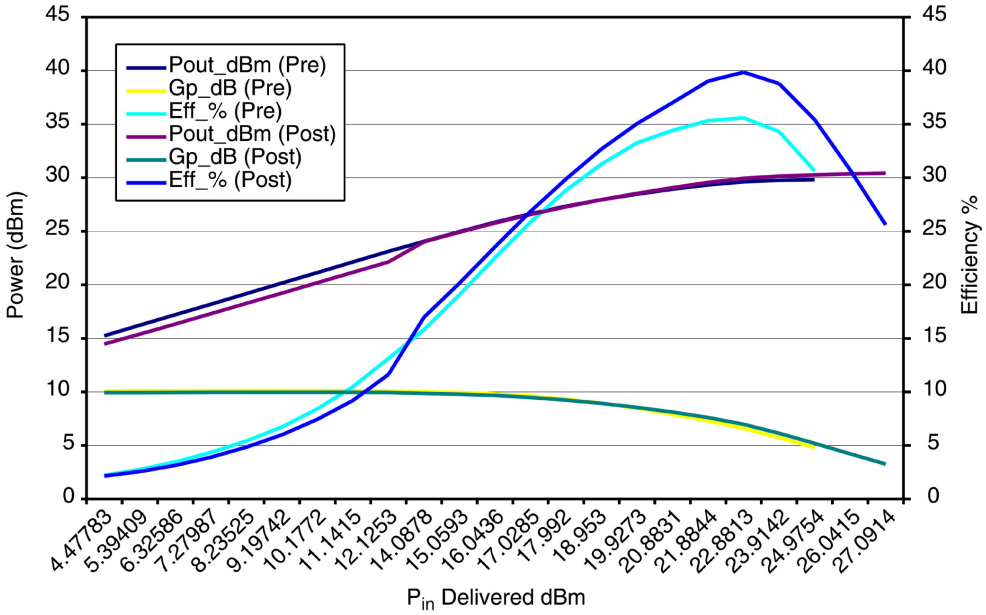

Fig. 3. Pre- and Post-Radiation Exposure 10 GHz Output Power, Gain, and Power-Added Efficiency Performance for the AlGaN/GaN HEMT-Based Hybrid Power Amplifier.

The gallium nitride amplifier's 10 GHz output power and power gain are approximately unchanged. The slight increase in peak power-added efficiency (PAE) may be attributed, in part, to a slight decrease in operating Ids. The small decrease in operational Ids, for Vgs = -2.5 volts, may have resulted from a slight dc-burn of the AlGaN/GaN HEMT during the dc-biased total dose gamma radiation test procedure. In addition, conditioning effect may occur when circuits are first operated under bias. These amplifiers had not been conditioned before irradiation. Further there is no indication that radiation damage reduces the PAE.

V. Conclusion

These promising results are the first published data on biased GaN HEMT power amplifiers under gamma radiation. Although the radiation levels in this work were lower than in [5-7], they were still higher than required by many systems. Further, these first post radiation exposure power results indicate that gamma radiation did not have detrimental effect on the microwave performance. For a given output power level, RF systems which would be exposed to radiation can be built by combining the output of fewer devices, if GaN-based HEMTs are used, rather than other III-V alloy semiconductors. This is an important system advantage.

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[7] A.P. Karmarkar, B. Jun, D.M. Fleetwood, R.D. Schrimpf, R.A. Weller, B.D. White, L.J. Brillson, and U.K. Mishra, "Proton Irradiation Effects on GaN-Based High Electron Mobility Transistors with Si-doped $Al_xGa_{1-x}N$ and Thick GaN Cap Layers," IEEE Trans. Nucl. Sci., Vol. 51, No. 6, pp. 3801-3806, 2004.

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The Open University

e2v

NASA REQUEST FOR INFORMATION

RADIATION CAPABILITIES FOR THE EUROPA-JUPITER SYSTEM MISSION

Radiation Tolerant Detectors and Focal Plane Arrays for EJSM Imaging Instruments

Proposer Details

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Statement of Capabilities and Qualifications

We intend to make available to EJSM instrument proposers optical detectors which are tolerant to the severe EJSM radiation requirements.

Our aim is to provide, if required, Focal Plane Arrays for imaging instruments and associated radiation characterisation/modelling expertise, which will be critical for the operation and understanding of imaging instruments throughout the EJSM mission.

Applicable Expertise and Components

The Open University and e2v technologies in the UK recently formed a collaboration moving the e2v Centre for Electronic Imaging (CEI) to the OU campus at Milton Keynes. The CEI is involved in a number of past and present space missions including among others XMM-Newton, Chandra, JET-X, GAIA, and Chandrayaan-1. The head of the group (Andrew Holland) is an expert in detector physics, working on a range of detector developments over the past two decades. e2v has extensive experience in providing world-class high performance radiation tolerant arrays for space instrumentation. With over 60 years experience, e2v is an established organisation providing high quality CCD and CMOS imaging detectors for specialist scientific applications. The Open University provides a wealth of expertise in the analysis and characterisation of radiation-induced damage to CCD and CMOS detectors, and a long history of space heritage.

Applied imaging detector expertise covers areas such as characterisation of high resistivity CCDs, characterising responsivity, noise, depletion depth modelling/measurements and work on ASICs for low noise readout of CCD arrays. Direct radiation expertise for example has included work on the proton radiation damage study of the swept charge device (CCD54) used in the Chandrayaan-1 X-ray spectrometer. Studies directly relevant to this RFI include characterisation work to one of the proposed JUNO star trackers, investigating the radiation damage effects from gamma-ray, electron and proton exposure.

This expertise has direct application to EJSM, as many of these skills will be required for any instrument involving CCD or CMOS detector arrays, and the group has working relationships with many facilities which can be used to simulate space radiation; protons, electrons, gammas and neutrons

Of particular relevance to a mission to Jupiter, e2v has previously demonstrated TV imaging in devices irradiated up to 1MRad. Currently a study is being carried out on radiation hardened devices to characterise the device performance between 0 and 1MRad. The work has been acknowledged with an invited paper at SPIE's Optical Engineering and Applications Focal Planes for Space Telescopes IV Conference in San Diego, August 2009.

It is worth noting that some of the early work performed by our collaborators, on the effects of ionising radiation, was performed using ^{90}SR β. Subsequent characterisation demonstrated good correlation with the effects of γ irradiation, which has been used for most ionising radiation testing.

e2v also have a capability to design, package, test and qualify radiation hardened CMOS sensors for Space missions, working with several foundries to establish this capability. e2v are also developing back-thinned CMOS processes and initial results are encouraging.

Through this RFI we aim to provide the capability to supply sensors in an integrated focal plane array (FPA), complete with associated proximity electronics. This facilitates the distribution of electronic components within the FPA to better optimise overall performance, and also simplifies the procurement of the system. Electronics heritage is based on that of the Space Science & Technology Department of the Rutherford Appleton Laboratory (RAL) with whom e2v have formed a collaboration in which space electronics systems built and qualified at e2v use RAL designs and technical support. RAL has supplied such electronics into a number of missions, notably Stereo-SECCHI and Solar Dynamics Observatory.

Technology Maturity Level

The technology which is proposed to be provided has a high maturity level, although further work is required to fit the requirements of EJSM.

e2v have been designing and manufacturing CCDs since the early developments in the late 70s. Since 1981, e2v has supplied sensors for almost 100 satellite imaging systems, the majority of which have flown, or are still flying. In the last 10 years the trend has been dominated by full custom sensor and package designs in recognition of the high TRL.
e2v have space qualified and supplied CMOS APS to a major European prime, but such sensors currently have significantly less space heritage than CCDs.

We expect the agencies to take a view on current TRL of radiation hard CCD and CMOS APS, and what may be necessary to raise TRL to a suitable level for this application. The OU/e2v collaboration is well placed to carry out any work deemed necessary to raise TRL of either (or both) technologies as required.

Past Experience/Heritage

The OU has a rich heritage in space instrument design and delivery, with a particular interest in optical instrumentation. Past mission involvements include providing scientific instrumentation for Rosetta, Cassini-Huygens, Beagle 2 and ExoMars among others. As development work for the UVIS instrument, extensive work has taken place designing and building a high precision optical system, including focal plane array design using e2v detectors as proposed here.

e2v has completed over 80 different CCD designs, and has a CMOS portfolio of four devices with further designs under way. Designs and processes have been developed to enable direct imaging with CCDs over the wavelength range 1µm to 0.1nm (1eV to 10keV). (This has been extended to higher energies using scintillators, either directly applied or by use of an intermediate fibre optic plate). We are developing a similar capability with CMOS APS.

Custom devices have been developed for several space programmes and for ground based astronomy, but also for medical (primarily dental X-ray) instruments and a range of other ground based scientific instruments. Specific radiation hard development was performed for the nuclear fuel business, for fuel rod inspection. Two vertex detectors (3×10^8 pixels) have been supplied to the Stanford Linear Accelerator, where they performed for several years with very little degradation from radiation.

Highlights of space applications:

- EPIC & RGS on XMM
- SPOT
- Hinode : EIS, XRT & SOT
- Hubble WFC3
- Kepler
- Stereo-SECCHI
- New Horizons : RALPH & LORRI
- MRO HiRise
- Pleiades
- Solar Dynamics Observatory: HMI & AIA
- Gaia

Request for Information Response

Radiation Capabilities for the Europa Jupiter System Mission (EJSM)

Prepared for

National Aeronautics and Space Administration (NASA)
Planetary Science Division
Science Mission Directorate
City, State, ZIP

In response to

Solicitation Number:
RFI NNH09ZDA008L

Prepared by

Ball Aerospace & Technologies Corp.
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Technical POC: **Paul Atcheson, 303-939-6189**
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May 22, 2009

Ball Aerospace
& Technologies Corp.

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Ball Aerospace is pleased to provide this RFI response detailing our radiation capabilities relevant to the Europa Jupiter System Mission. For 50 years, Ball Aerospace has played a major role in the development of advanced spacecraft and instrumentation for scientific pursuits. We offer all the services and expertise necessary to take challenging mission requirements and develop them into robust precision flight hardware. *Our RFI response contains no proprietary or ITAR restricted information and may be given the widest possible distribution.*

1. Europa Star Tracker (NASA/JPL Contract 1219580)

Ball Aerospace conducted a detailed Europa radiation-hardened star tracker study for Jet Propulsion Laboratory (JPL) during 2000 and 2001, completing a preliminary design review (PDR) in early 2001. Subsequently, the Europa program was terminated. As a result of this and other work, Ball Aerospace is highly qualified to support future missions to the outer planets, including the most challenging radiation locations. The study provided important results in two areas; 1) design concepts that can provide reliable star tracking in the Jovian environment and 2) investigation of the available mechanical, optical and electronics materials suitable for fabrication of a tracker and methods that can be used to provide shielding and other mitigation for an electro-optics instrument that will be used in a demanding environment. The latter information is of general interest to instrument designers. In subsequent work for NASA, JPL and the Department of Defense (DOD), Ball Aerospace has continued the process of providing solutions for the outer planets environment by presenting solutions for low mass shielding, introduction of new electronics architectures (including rad hard ASIC processors and CMOS APS focal planes) and continued testing of commercial electronics products.

During the Europa study, Ball Aerospace made substantial progress in the following areas:

- Completed Initial System Design
  - Top-level design with initial electrical, electronic, and electromechanical (EEE) parts list and initial mechanical and optical design
  - Operational concept
  - Performance predictions
  - In-process manufacturing and test approach
  - Performance test plan (approved by JPL) for detector qualification, in-process test flow and environmental test processes
- Designed radiation test program for CIDs (focal plane technology of choice at the time of the study)
  - High energy electron environment closest to Europa environment
  - Total dose
  - Transient response
- Completed radiation test program

Since completion of the Europa tracker study, Ball Aerospace has continued its development of concepts for outer planets applications by:

- Writing proposals related to this demanding requirement
- Radiation testing of CMOS APS focal planes consistent with the likely performance and environments of the EJSM
- Continuing to support DOD high radiation environment tracker designs
- Development of analysis tools and algorithms
- Creation and commissioning of a state-of-the-art stray light facility; characterized radiation effects on optical elements; performed measurements of darkening of optical elements, lens elements, window material, and coatings

Assessment of Compliance	Mass, power, performance, alignment accuracy and coverage were found to meet the specifications.
Thermal Design is Simple	Occasional sun exposure is handled without problems
	Radiatively cool case and focal plane
Radiation Design	Qualified to 300 Krads
	Radiation sector analysis including Monte Carlo particle transport calculation. Models of exterior structure, lens assembly, part packaging
	Radiation control plan was approved by JPL Nov 30, 2000
Optical Design	Outer window to protect inner elements
	Fluorescence and phosphorescence considerations
	Radiation hard glasses to prevent darkening
	Conductive outer coat to bleed space charge

Maturity Level

Ball Aerospace's assessment is that its design for the Europa tracker reached technology readiness level (TRL) 5-6 (depending on the element of technology being considered) during the study. Nonetheless, Ball Aerospace is starting from a leadership position and stands ready to assist NASA with this challenging assignment.

2. Ball Aerospace Capabilities for Jupiter Missions

2.1 Radiation Analysis Group

The radiation engineers at Ball Aerospace have been modeling the effects of the Jupiter system for the past decade. Ball Aerospace worked closely with JPL as the team grappled with the unique issues faced during the early Europa Orbiter work. Ball Aerospace has remained at the forefront of work on Jupiter's radiation effects by participating in nearly all of the proposals for Jovian missions (e.g., Europa Orbiter, Inside Jupiter, Jupiter Icy Moons Orbiter [JIMO], and Juno). The Ball Aerospace radiation group is comprised of 11 full-time employees with over 150 years of combined experience, including three PhDs.

Ball Aerospace pioneered the radiation testing of low-intensity, low-light solar arrays for Jupiter with high-energy (100 MeV) electrons to properly simulate the untested aspects of the environment. Displacement damage effects are commonly associated with protons, but the high flux at Europa makes electron-induced displacement damage an important consideration, especially in sensitive imagers. Ball Aerospace continues to follow the developing understanding of electron Non-Ionizing Energy Loss (NIEL) and the exceptions where it does not linearly correlate to parameter degradation.

Ball Aerospace remains committed to state-of-the-art radiation modeling. On internal R&D funds, we developed an analysis code that combines forward Monte Carlo radiation transport (Geant4) with software for specific imager functionality in order to generate realistic scenes of radiation hit noise which uniquely addresses the high-energy Jovian background. The use of a forward Monte Carlo routine is unique in allowing for the modeling of the stochastic nature of Jupiter's high-energy electron background in imagers. Ball Aerospace has developed the RadSAT© utility which allows boxes or entire space vehicles to trade the impacts of mass, cost, and schedule against a variety of mitigation strategies (e.g., part replacement, box-level versus spot shielding, lot testing, circuit hardening, etc) in any radiation environment.

Ball Aerospace also collaborates with industry partners to pursue radiation hardening opportunities. We have recently funded research by Radiation Assured Devices (RAD), in collaboration with Texas Instruments (TI), into a process for inserting radiation hardening techniques into commercial processing lines without rad-hard-by-design rework.

2.2 Detector Technology Center

The Ball Aerospace Detector Technology Center (DTC) has expertise in radiation-hardened detectors and provides expertise and services for radiation-hard detectors and focal plane arrays for defense, commercial and civil programs. The DTC offers customers a photons-to-bits detector solution with detector experts in each of five subareas: 1) detector design and development, 2) focal plane array packaging design and development, 3) focal plane electronics, 4) focal plane integration and test, and 5) focal plane array systems engineering. The 14,600 ft2 center in Boulder, CO, was constructed in 2006, including 1,804 ft^2 of Class 5 clean rooms and 1,832 ft^2 of Class 7 clean rooms. The DTC staff varies depending on the requirements of on-going programs. Typically the DTC is staffed with 75 people, 12 of whom hold doctorates. This staff has experts in all areas of detector engineering. The DTC is led by a dedicated leadership team averaging 22 years of aerospace and detector experience.

The DTC employs state-of-the art methods to produce detectors and focal plane electronics designs for the anticipated radiation environment. Custom modeling software including the TRAPPER model of charge transfer efficiency and the Monte Carlo simulation tool, STAM allows the simulation of detector performance during operation in transient environment and hot pixel population growth.

The DTC routinely qualifies detectors for total ionizing dose, displacement damager dose, transient response, single event upset, single event latch-up, flash-x-ray response and neutron re-

sponse at University of California Davis Crocker Laboratory (CA), Radiation Assured Devices (CO), Texas A&M and various other laboratories that house sources of radiation. Radiation shielding based on Ball Aerospace radiation effects modeling is incorporated into the package design.

2.3 Ball Aerospace IRREL Team

In 1987, the InfraRed Radiation Effects Laboratory (IRREL) was established at what is now the Air Force Research Laboratory (AFRL) and tasked it with (1) the independent characterization of the radiometric and radiation hardness performance of visible and infrared focal plane arrays (FPA) developed under various government programs, and (2) the development of innovative techniques to advance the state-of-the-art in FPA characterization to allow program requirements to be met.

Ball Aerospace has operated the IRREL since its inception. The Ball Aerospace IRREL team brings an in-depth knowledge of the IRREL and has established a track record of responsiveness to the IRREL's requirements, delivery of high quality data products and continued commitment to customer satisfaction.

Over the past 20 years, the current IRREL staff has written over 30 technical reports documenting both clear and radiation characterizations of FPAs, presented over 40 papers at radiation conferences IRIS/MSS, HEART, SPIE), and have had six publications in refereed journals. Two IRREL papers have won best paper awards at the MSS Conference. They have characterized FPAs in gamma, neutron, and proton environments, and under high dose rate conditions (Flash X-Ray). The techniques and procedures developed by the Ball IRREL team during these experiments have established the state-of-the-art in FPA characterization techniques and have become the industry standards for characterizing FPAs in both clear and radiation environments.

The IRREL test system, used to provide performance testing on readout integrated circuits (ROIC) as well as visible and infrared FPAs in a variety of nuclear environments, is portable and was specifically designed to interface to nuclear radiation facilities around the country. The test system, designed and built by the Ball Aerospace IRREL team, continuously undergoes hardware and software upgrades to insure that it can properly operate and acquire data from today's state of the art focal plane arrays. The test system has been used to perform radiation characterization testing on both analog and digital FPAs, ranging in size from 64x20 to 8Kx8K, and data rates up to 80 MHz.

The Ball Aerospace IRREL team have used this system for total ionizing dose (TID) and debris gamma tests at the AFRL ^{60}Co radiation facility at Kirtland Air Force Base (AFB), NM, Flash X-Ray tests using the Febetron at Kirtland AFB, the Pulserad 1150 at L-3 Communications Pulse Sciences (formerly Physics International) in San Leandro, CA, as well as the former Blackjack 3 facility at Maxwell Laboratories in San Diego, CA. Electron beam testing has been performed at Hill AFB's Survivability and Vulnerability Integration Center outside Ogden, UT. Neutron fluence testing has been performed at the Fast Burst Reactor on White Sands Missile Range, NM, and proton fluence tests are performed three to four times a year at Crocker Nuclear Laboratory on the campus of the University of California at Davis.

Notice of Intent
Response to RFI for Radiation Capabilities for Europa Jupiter System Mission
Solicitation Number: NNH09ZDA008L

Submitted by:
Broad Reach Engineering Company
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Summary
Broad Reach Engineering is a recognized leader in the development of space flight hardware and software for use in LEO, MEO, GEO and planetary applications. For the Europa Jupiter System Mission we propose to provide key enabling technology, specifically a recently completed 1MRad PowerPC440 based CPU, as well as system and hardware design capabilities to be used for spacecraft and payload electronics implementation.

Company Background
Broad Reach Engineering was founded in 1997 by a group of experienced aerospace engineers with the intent to provide innovative and cost effective high-end products and services to the aerospace industry. Broad Reach believes in a no-nonsense engineering approach to providing the solution that best fits the mission requirements. Broad Reach Engineering is a privately/employee/family owned business. Broad Reach Engineering maintains offices in Boulder, Colorado, Golden, Colorado, and Tempe, Arizona. The Tempe site serves as a design center for Broad Reach avionics and software. This facility, located in the heart of the Phoenix Metro Area, has over 1500 square meters of office and laboratory space. The facility includes a laminar flow clean room, electronics assembly lab, two dedicated avionics labs, and numerous assembly and test tools, including a NASA certified thermal vacuum chamber, BGA installation machine, and component X-Ray facility.

Quality Engineering
Broad Reach Engineering adheres to the highest standards in the design and implementation of space flight hardware and software. The Broad Reach AS9100 aligned Quality Assurance System backs this commitment with a comprehensive and efficient set of processes and protocols that address all critical epochs in the production life cycle. Our approach has been scrutinized and approved by numerous customers including Lockheed Martin, NASA/JPL, MIT-LL, Ball Aerospace Corporation, Boeing, JAXA, and Orbital.

General Products and Services
Broad Reach Engineering develops hardware and software for spaceflight missions and ground systems. Products include spacecraft avionics, science payload electronics, spacecraft flight software, ground and spaceborne GPS receivers for precision orbit determination (POD) and occultation science, ground support hardware and software, and mission design and analysis services. Broad Reach has developed a variety of products in the past – ranging from LEO to GEO and beyond. Recent and ongoing mission participation includes Lunar Reconnaissance Orbiter, COSMIC, AFRL XSS-11, AFRL Angels, Mitex, Tacsat-2, SUMO/FREND, LADEE, and TerraSAR-X. Broad Reach Engineering customers include both domestic and international organizations. We have experience exporting our products in compliance with

United States export regulations through the use of DSP-5 licenses, Technical Assistance Agreements (TAA), and Technology Transfer Control Plans (TTCP).

EJSM Applicable Technology, Capabilities, and Services

BRE PowerPC440 CPU

The Broad Reach Engineering BRE440 CPU is designed to meet the requirements of a wide variety of current and future space and high reliability application, including the most demanding applications such as the EJS Mission. The BRE440 CPU is a fully radiation hardened implementation of the IBM PowerPC 440 processor core in a true System-On-a-Chip design, including floating point unit. Broad Reach Engineering has licensed the PPC440 core from IBM and has integrated it into the in-house developed chip design. Broad Reach Engineering has fabricated the device on Honeywell's HX5000 150nm ASIC process. The first BRE440 devices have been delivered to BRE in March 2009. The device runs at 133Mhz over a full space mission temperature, voltage and radiation range. Device testing shows a TID of >1MRad at the chip level, latch-up immunity, and worst case SEU rate of one upset every 20 years. The first BRE440 devices are slated for launch on a variety of missions starting in 2010. We expect this device to have multiple years of in-space heritage by the time the EJS Mission development begins. The investment to date in this device from BRE alone is greater than $7M, not counting investments by Honeywell in the HX5000 line.

Radiation Hard Avionics for Space

BRE has extensive experience delivering radiation hard avionics for space missions ranging from LEO to the Moon. Avionics include C&DH systems, EPS systems, motor controllers, and payload electronics. The Broad Reach Engineering approach focuses on providing the highest quality of available parts together with tried and proven design methods for space flight hardware development. Solutions are custom designed for the specific environment and functional requirements, while incorporating the extensive experience of our employees and our company on-orbit performance and past design history.

Selection of Past & Ongoing Avionics Experience

Tacsat-2/AFRL	Core spacecraft avionics (C&DH & EPS), GPS Receiver, Payloads
Worldview-1/Ball	Data processing & Encryption Board
LRO/NASA	Redundant Antenna & Array Gimbal Motor Controller
SUMO/DARPA	Robotic Arm Controllers
XSS-11/AFRL	Core spacecraft avionics (C&DH & EPS)
Angels/Orbital/AFLR	Core spacecraft avionics (C&DH & EPS) & Payload Controller
TerraSAR-X/Astrium	GPS Receiver for Space
LADEE/NASA	Core spacecraft avionics, Laser Communications Controller
STP-SIV/Ball	Core spacecraft avionics (C&DH & EPS)
Advanced EHF	Science Payload
Kompsat-5	GPS Receiver
COSMIC	GPS Receivers (6)
ST-7 LISA Pathfinder	Payload controller
EQUARS/Brazil	GPS Receiver
AMS/LMA	Core spacecraft avionics (C&DH & EPS)
Aquila/Air Force	Core spacecraft avionics (C&DH & EPS)

Additional Information

Additional public information may be found at www.broadreachengineering.com. Additional non-public information is available. For inquiries, references, and to obtain further information please contact BRE at the POC information above.

A Draper Laboratory White Paper

Radiation Capabilities for the Europa Jupiter System Mission

Technical POC
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In Response to:
NNH09ZDA008L

May 21, 2009

INTRODUCTION

The Charles Stark Draper Laboratory (Draper) provides systems solutions to some of our nation's most challenging problems. The Laboratory draws upon unparalleled expertise in guidance, navigation, and control, and is among the leaders in fields of fault-tolerant computing, highly reliable embedded software, autonomous and human-collaborative systems design, and miniature, low-power electronics. Design and development activities are augmented by highly integrated modeling and simulation, hardware-in-the-loop, and environmental test capabilities. Draper applies its expertise to a broad range of domains, including autonomous air, land, sea, and space systems; information integration; distributed sensors and networks; precision-guided munitions; air traffic flow management; military logistics; and biomedical engineering and chemical/biological defense. To this end, Draper maintains a highly skilled and motivated workforce supported by exceptional design, fabrication, and test facilities. This combination of highly trained technical talent and state-of-the-art facilities enables the Laboratory to not only deliver first-of-a-kind systems incorporating innovative technology, but in selected instances, to deploy the solutions in limited quantities, supporting them throughout the life cycle.

OVERVIEW OF RELEVANT CORPORATE KNOWLEDGE/EXPERIENCE

Draper has extensive experience in designing rad-hard systems for both space vehicles and strategic weaponry. We possess unique capabilities in designing rad-hard systems for the strategic Navy, Air Force, Missile Defense Agency, manned and unmanned space missions. We have full system development and prototyping experience, including part selection, subsystem and circuit design hardening, sensor and readout hardening, and system architecture design for fault tolerance.

Draper has designed robust systems able to withstand the harsh environment of extreme dose rate, total dose, high neutron flux, single event effects and EMP environments. At the system level, we have experience in performing trade studies that balance hardness with functionality and performance. We have the ability to define external environments and perform three-dimensional radiation analyses for shielding trade studies of external and internal shields.

At the subsystem level, Draper has experience in hardening sensors, readout electronics, and processors through hard part selection and/or COTS, hardened by design approaches. We have design synthesis, circuit analysis, and advanced circuit simulation capabilities utilizing state-of-the-art device radiation models developed by Institute for Space and Defense Electronics at Vanderbilt University. We have experience in performing challenging/iterative trade studies that balance performance with cost.

In addition to the capability to design, build and test new systems for a sponsor's unique specifications, we also specialize in COTS evaluation and hardening. By applying proven system and circuit design techniques, existing COTS designs can be evaluated for survivability in total dose and single event radiation environments. Guidance can be provided to cost-effectively improve designs for hardening depending on the target environment.

At all levels of system integration, Draper has extensive experience in requirements definition, verification, and validation. Designs can be fully simulated to verify hardness and performance. We also

have experience to design, execute, and evaluate fidelity of radiation tests. We have experience and access to total dose, proton, and heavy ion radiation test facilities across the country.

HIGH PERFORMANCE COMPUTING

Draper is supporting the National Reconnaissance Office (NRO) On-board Programmable Expandable Reconfigurable Architecture (OPERA) program in the role of spaceflight electronics subject matter expert. OPERA is developing a 49 core high performance, radiation hardened by design processor for space applications. As part of OPERA, Draper is surveying advanced memory and storage technologies.

SPACE ELECTRONICS MINIATURIZATION

Draper has pioneered the development of ultra-dense electronic modules for over 15 years, employing a fabrication process called Multi Chip Module - Deposited interconnect (MCM-D). Draper has developed highly specialized design methods, fabrication processes, and low volume production facilities, and is uniquely positioned to develop and deliver exceptionally compact custom systems. The MCM-D process has a proven track record as a versatile platform for custom, high performance circuits and systems. It has been qualified to MIL-STD 883C, Method 1011, -40°C/125°C liquid-to-liquid shock, and over 1000 systems have been delivered for 0-70°C fielded operational use. When suitably packaged at the system level, MCM-D modules have been successfully qualified for mechanical shock, 36-inch drop onto concrete, vibration according to MIL-STD-810E, Method 514.4, and operational thermal cycling -32°C/71°C. None of Draper's fielded systems have experienced a failure to date. Draper's MCM-D based systems represent the highest packaging density achieved, and provides unique deployment opportunities due to the small size and configurability of the MCM-D platform.

Draper has three facilities dedicated to the development and production of MCM Packages. In its Cambridge, MA location, The MCM-D lab consists of a class 10,000 cleanroom complex, which houses the MCM-D assembly equipment, and multiple satellite labs. These satellite labs are a combination of cleanroom and standard lab space, and house specialized equipment for unique elements of the process such as die harvesting and thinning, thin film sputter deposition, and advanced photolithography.

The second MCM package fabrication facility is embedded in Draper's MEMS fabrication lab. This dual-use 4000-ft^2 class 1000 cleanroom complex supports the development of advanced MEMS and BioMEMS systems. By leveraging an existing base of expertise in MEMS processing, particularly deep reactive ion etching, thin film processing, and wafer bonding, Draper has been able to develop this novel packaging technology and position it for transfer to production.

Draper is currently in the process of qualifying its third MCM-D location; a production facility in St. Petersburg, FL. This facility includes a combination of class 1000 and class 100 cleanroom space totaling over 7000-ft^2, as well as additional high quality manufacturing space. It will have more than three times the capacity of Cambridge and will enable the two facilities to focus on distinct development and production missions. It will be ready for pilot production in October 2009.

Capabilities and Qualifications:

AMS Test Services is a provider of reliable solutions for Total Ionizing Dose, Enhanced Low Dose Rate Sensitivity, and Neutron Fluence testing. AMS has a working relationship with the Radiation Laboratory at the University of Massachusetts in Lowell, which allows us to provide these test solutions in a timely manner at very competitive costs.

AMS is currently providing TID services on weekly basis for a manufacturer of JANSR radiation hardened mosfets in compliance with their DSCC approved test methods. The staff at AMS has experience performing tests per test methods 1019 and 1017 of MIL-STD-883 and MIL-STD-750. Our product focus has been power mosfets, transistors, diodes, optocouplers, and linear devices.

Description of Services: AMS can perform tests per a predefined set of procedures and guidelines provided by our customer as is the case with the mosfet testing listed above. Or AMS can develop test plans, procedures, and methods to be compliant with MIL-STD-883 and MIL-STD-750 based on inputs from a customer on the particular component that requires characterization or qualification.

AMS can work directly with component manufacturers, system integrators, and end users to perform radiation characterization and or qualification of components used on the Europa Jupiter System Mission. AMS works closely with the Reactor Engineers at the Radiation Laboratory at UMass to insure the radiation exposures fully meet the requirements outline in the approved test plan.

AMS provides detailed reports for all characterization and qualification test performed for a customer. The reports would include a copy of the test plan, device types tested (including date codes, wafer numbers, etc.), bias conditions, facilities used for the test, pre and post electrical data, graphs, and a summary of results.

Past experience: The staff at AMS has over 7 years experience characterizing components for ionizing dose and neutron fluence response. In particular the JANSR and linear voltage regulator products our staff has tested over the years have all ended up on space flight or military programs.

Our staff has participated in several DSCC lab suitability audits over the years and is familiar with requirements to achieve this for methods 1019 and 1017.

Best Regards,
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Radiation Hard UV LED and Photodetectors

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Requested information in response to
NASA RFI Solicitation Number: NNH09ZDA008L
"Radiation Capabilities for the Europa Jupiter System Mission"

May 22, 2009

Abstract

We report measurements of ultraviolet light emitting diode (UV LED) performance under conditions simulating operation in an orbiting satellite. UV LED light output maintained within less than 3% observational uncertainty, over more than 21,000 hours of operation in a nitrogen atmosphere, and over 10,000 hours operation at a pressure of less than 10^{-7} torr vacuum. In addition, irradiation with 63 MeV protons to a total fluence of 2×10^{12} protons/cm2 does not degrade the UV light output. Spectrally, the emissive center-wavelength and spectral shape are unchanged after proton irradiation within the precision of our measurement. These results qualify the UV LED operation lifetime and radiation hardness for space flights. Similar development is underway for photodetectors.

1. Introduction

Radiation-hard, high-reliability ultraviolet (UV) light emitting diode (LED) and UV photo detectors will be of great value to Europa Jupiter System Mission and other future satellite missions UV light source and photodetectors. UV LED and detectors can be used for charge management during the flight, and for spectroscopic analysis for gas component around Jupiter system. We have selected and characterized GaN UV LED products and discovered their radiation hardness, and operation hardness under vacuum condition. Soon we will conduct shake and bake tests to complete full space qualification for UV LEDs.

2. UV LED Radiation Hardness

We have experimentally demonstrated the extreme radiation hardness of GaN based UV LEDs. The proton irradiation test was conducted at the facility in UC Davis. Figure 1 demonstrates the light output of the UV LEDs of 63.8 MeV proton irradiation. The UV LEDs maintained light output for total fluence of 63.8 MeV $2\text{x}10^{12}$ proton/cm^2. This result is favorably compared with Jovian Tour radiation energy spectra. In addition, the spectral shapes were unchanged after proton irradiation, as shown in Figure 2.

3. UV LED Operation Lifetime Test

Since 2004 we have been developing UV LED charge management system. We have continued UV LED power and spectral lifetime tests starting in early 2005. The UV LED in nitrogen rich environment has now been operated more than 21,000 hours without significant power drop. The spectral shift is measured to be ~1-2 nm towards shorter wavelengths, which actually enhances photoelectric effects. Another power stability test has been initiated in a vacuum chamber and now has been running close to 10,000 hours without seeing appreciable power change. These results are shown in Fig. 3.

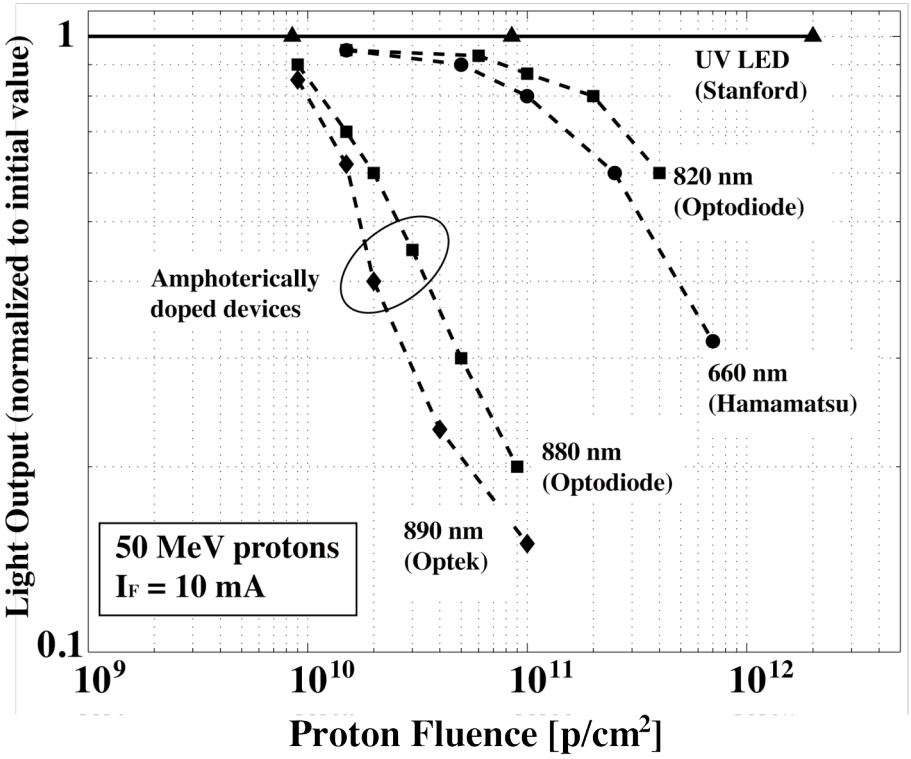

Figure 1. Results from proton irradiation test on UV LED (Other measurement from A. H. Johnston and T. F. Miyahira, "Characterization of Proton Damage in Light-Emitting Diodes", IEEE Trans. Nuclear Science, 47 (6), 1999)

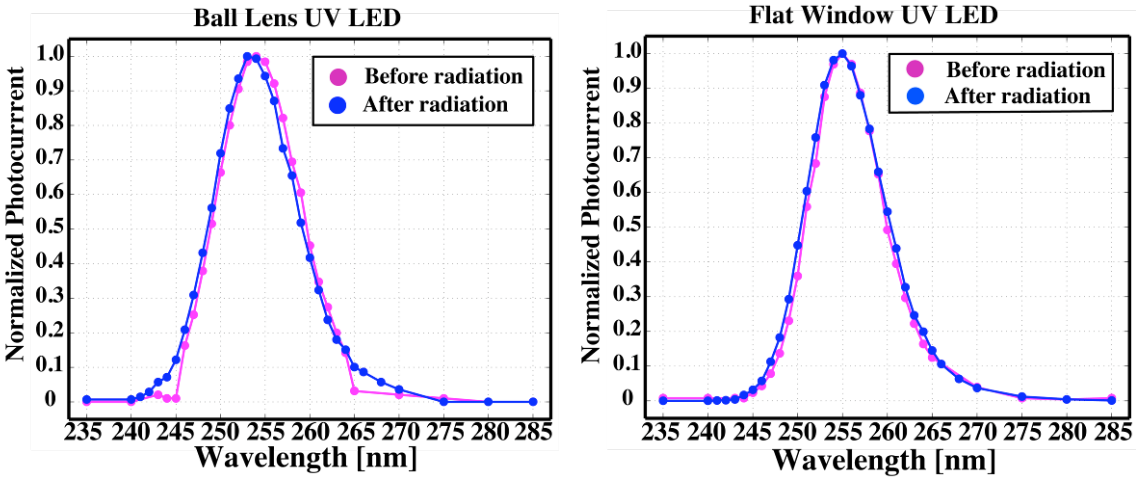

Figure 2. Proton irradiation results: No spectral shift was observed after irradiating protons on the ball lens /flat window UV LEDs

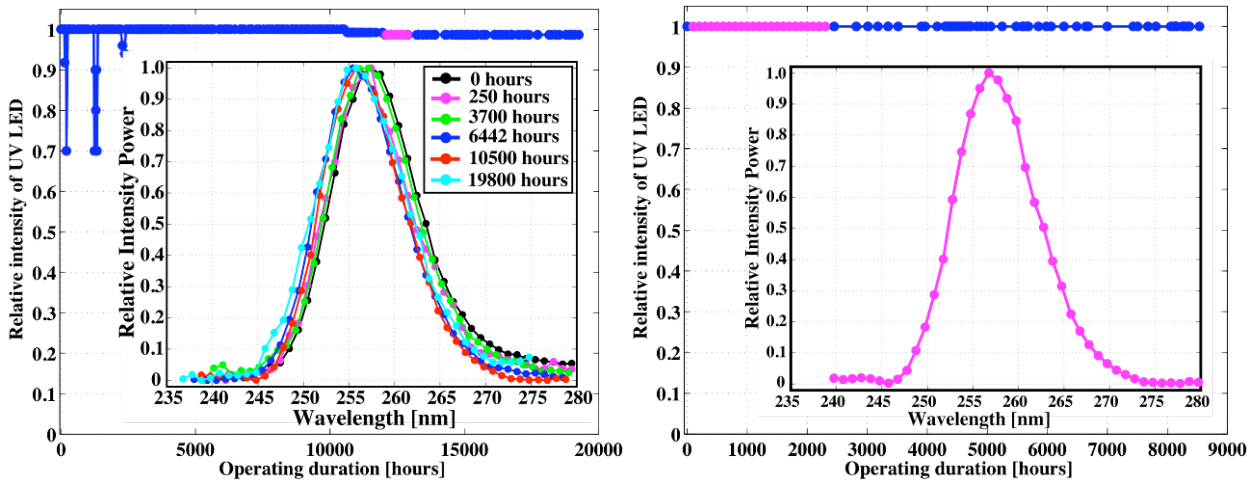

Figure 3. Lifetime tests of UV LEDs: (Left) nitrogen environment test. (Right) vacuum environment test.

4. Capabilities and qualifications statement

In collaboration with a vendor, the respondents provide GaN UV LEDs, photodiodes, special packaging for space flights in radiation harsh envrionment. We have worked on both component and system technologies for space flights, and we produced many publications.

5. Applicable expertise, services, components, facilities or technologies

We have extensive experiences in optics, electronics, UV LED devices, GaN physics, radiation testing, and charging management in space flights. We have extensive research and development facilities in component fabrication and system integration at our home institutions, and have access to a variety of radiation sources.

6. Maturity level of the respondent's technologies in terms of heritage

We have been conducting UV LED operation lifetime testing since 2005 and on going as of now. The accumulated lifetime is now longer than 21,000 hours. This is the first and longest test of any GaN devices. We have demonstrated the extreme radiation hardness of UV LED up to the fluence of $2x10^{12}$ protons/cm^2 with energy of 63.8 MeV. These results are unique and leading the world.

We will take the UV LEDs to shake and bake tests at NASA Ames Center soon, thereby completing the full space qualification of this exciting new device.

We also have extensive experiences in system technology development. We are designing a UV LED science instrument for space flight.

7. Past Experience and capability in designing, developing, and delivering similar technologies for space missions

One of us has multiple flight experiences at NASA Ames Research Center. Our charge management heritage traces back to GP-B. The UV LED charge management system will become the baseline of LISA mission. We are currently developing the Modular Gravitational Reference Sensor (MGRS), a future core instrument for precision space flights.

Electronics for Extreme Cryogenic Space Environments

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Abstract
NASA's deep space missions require electronics and components that must endure extreme cryogenic temperatures and radiation environments. The University of Arkansas together with partnering universities and industry have designed various cryogenic radiation hardened silicon germanium (SiGe)-based electronics circuits and systems that can be used to build spacecraft instruments, robotic components, life support electronics components, and other ASICs for space. Designing for a limited weight/mass to meet the temperature and radiation constraints are some of the challenges facing space instrument providers. Our poster will present SiGe-based electronic components and technological advances that would yield reduction in weight and cost, and improve efficiency for the Europa Jupiter System Mission or any deep space mission.

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NOTICE OF INTENT

Solicitation Number: NNH09ZDA008L

Title:

Rugged, Radiation Hardened & Wide Temperature Range Low Power Crystal Clock Oscillators for Europa Jupiter System Mission

Company: Frequency Management International Inc. (FMI)

PI: Kouros Sariri

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FREQUENCY MANAGEMENT | INTERNATIONAL

1.1 Overview

Frequency Management International (FMI) Intends to deliver reliable crystal and clock oscillator solutions that meet and exceed the operating temperature range and radiation tolerance as well as other operating environmental requirements expected for the Jupiter Europa Orbiter (JEO) and the Jupiter Ganymede Orbiter (JGO).

FMI has been involved in the development and fabrication of very focused and unique timing and frequency control devices such as piezoelectric crystals and crystal clock oscillators, which are required to operate under extreme environment operating conditions. The significant and compelling attributes of the FMI's high reliability solutions include high radiation tolerance, stable operation (output waveform & frequency stability) as a function of temperature, wide voltage range, low power consumption, shock, vibration and high ambient pressure. Our optimum solutions are typically aimed at prospective system applications in the aerospace (scientific and commercial) as well as the energy exploration industries.

We have been able to bring about the necessary disciplines in the design and fabrication of customized frequency control products based on the broad experience of our key technical personnel in electronic frequency and timing control and specific expertise in commercializing the critical elements of the solution technology. We have successfully implemented and commercialized the optimum solutions thru an effective and proven product realization discipline. The tightly controlled manufacturing processes and very experienced operators and disciplined managers follow the established fabrication roadmaps according to the ISO certified quality documentation. The manufacturing operation at FMI has been planned and implemented to cater to customized product manufacturing practices. As a result, the FMI manufacturing operation offers significant advantages over larger manufacturing facilities that are broadly focused on grand scale manufacturing priorities. These large scale operations lack the attention needed for lower volume and more customized product fabrication needs.

1.2 Heritage

Our technical staff has accumulated a combined 120 years of experience directly related to crystals resonators and crystal oscillators. Our relevant experience in the design and fabrication of radiation hardened crystals and oscillators for space applications goes back more than 23 years. A few examples of the space programs that have benefited from our design and manufacturing expertise in the past include Mil-Star, Intelsat7, Cassini, Mars Pathfinder (Lander & Rover), and the subsequent Rover missions including the MSL. There have been numerous commercial space programs with companies such as Loral and Boeing (formerly Hughes Space) that can be added to this list including those presently in process such as the Galileo (GPS). The combination of our design and fabrication expertise and the recent successful NASA SBIR effort for extreme temperature and radiation hardened crystal oscillators (NNG04CA26C) have already

resulted in new configurations and performance benchmarks. One such direct result is the smallest form factor for radiation tolerant crystal oscillators in miniature hermetic microelectronics packages for space applications with the operating temperatures that could extend down to -180°C and extended to upward of +200°C.

1.3 Our Technology

In optimizing our solutions for JEO and JGO (abbreviated as JE/GXO), FMI will take into account the various preferences and restrictions as imposed by the system requirements and the procurement authority. The solution proposed by FMI shall utilize all the extensive experience and expertise in the design and fabrication of high reliability crystals and clock oscillators in order to successfully produce the clock oscillator solution for each of the two missions. The piezoelectric resonators design rules developed for extreme temperature applications and its follow-on derivatives will be readily available to be utilized for this program regardless of the actual operating temperature ranges considered for JEO/JGO.

Figure 1 depicts a simplified crystal oscillator block diagram. The frequency control network typically includes piezoelectric crystal resonator and a number of passive elements such as resistors and capacitors for proper loading and matching of the active circuit elements. Although, the circuit designers may decide to use a separately packaged FMI crystal resonator with the on-board amplifiers and buffer stages, our complete crystal oscillator solution would be an integrated device that contains the electronics and the piezoelectric crystal resonator in the same small microelectronics package.

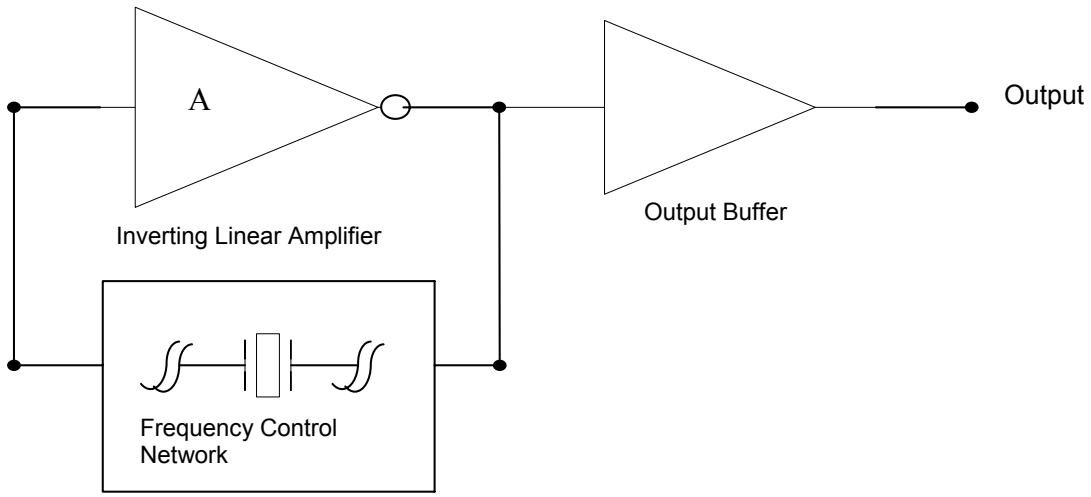

Figure 1- Crystal oscillator Simplified Block Diagram

As shown in Figure 1, a rugged, stable and robust crystal resonator with its matched impedance and performance to the driver circuit would be a significant element in the total solution. FMI is fully qualified and prepared to design and fabricate wide range of piezoelectric resonators and the associated mechanical support structure at the

frequencies intended for the JEO/JGO missions. In general, optimization of resonator geometry, frequency stability and mechanical ruggedness are at the heart of crystal design for Hi-Rel applications. As for crystal resonators used in the design of JE/GXO, the provisions for radiation tolerance considerations are well understood and the roadmap is quite clear.

The most robust way of improving the frequency stability of the quartz crystals vs. total ionizing radiation is to use swept quartz. Sweeping is a high-temperature electric-filed-driven solid-state purification process that improves the radiation induced frequency shift slope from 1E-12/rad (synthetic quartz) to 1E-13/rad (synthetic swept quartz) for 1Mrad TID[1]. With swept quartz, the frequency shift due to TID of 1Mrad is estimated be about -0.1ppm while for the synthetic (none swept) quartz a frequency shift of -1ppm would be expected. It should be noted that the described frequency shift as a function of TID may be much smaller than the temperature induced frequency shift or the long term drift of the crystal frequency.

With the correct crystal orientation, the high quality factor swept crystal will deliver the desired stability as a function of temperature. Figure 2 describes crystal frequency stability vs. the temperature range that is optimized for wide temperature range applications such as the surface of Mars and provides optimum frequency shift over a temperature range that spans more than 300°C while maintaining stability of better than 250ppm with a single rotation piezoelectric crystal cut.

[1] IEEE-UFFC Dr. John Vig

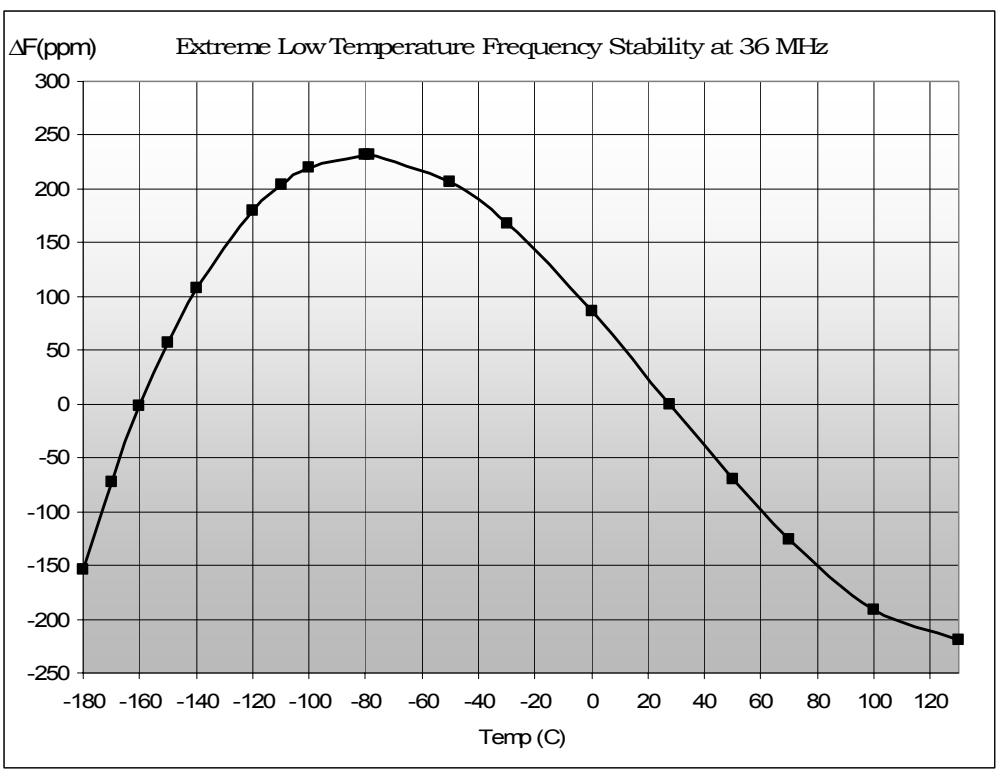

Figure 2- An example of frequency stability vs. temperature range at 36 MHz

Standard approach for mechanical ruggedness emanates from FMI's remarkable history of designing extremely rugged crystal resonator support structure via proven design verification and evaluation methods including finite element analysis as well as real life testing. FMI has completed numerous design examples of miniature crystal resonator design and integration that is required to reliably perform under extreme shock and vibration.

The JE/GXO design specifically addresses both objectives of radiation tolerance and hardness as well as low power consumption simultaneously. The state of the technology provides for power efficient designs that are also radiation hardened. In addressing the total dose implications as covered in the NOI document, it should be emphasized that FMI solutions meet and exceed the 100Krad (Si) TID. Furthermore, we are prepared to offer the optimum solution that specifically addresses the other constraints of the electronic modules in each of the two missions. JE/GXO could be provided in the appropriate enclosures depending on the system design strategy as more details of the project become available. Our solution would be essentially adaptable (in either case) to the other pressing restrictions and limitations of the system (i.e. thickness of the enclosure) so that at no time it could become the design bottleneck.

The features and options of the available CMOS-SOI or radiation tolerant baulk CMOS device technologies can be configured for the low power consumption. Configurations based on monolithic ASICS (instead of more traditional hybrid configurations) combine radiation hardness, low power consumption and smaller size package footprint. It should be noted that power consumption for crystal clock oscillators highly depend on the actual crystal and output frequencies. FMI has the unique advantage of being the only company in the filed that has intimately worked on traditional hybrid configurations as well as the newer ASIC based designs (SOI and baulk CMOS). The technical staff of FMI have been involved in the development and validation of the two CMOS-SOI clock generators ASICS over the last 12 years.

With the availability of the miniature surface mount footprint, we have already addressed size, power and weight considerations while keeping the radiation tolerance in check. A remarkable 85% saving in the footprint area compared to the conventional space level flat-pack crystal clock oscillator form-factor is just an example of our superior approach. In general, all components require the relevant quality evaluation, certification and documentation according to the program objectives. FMI routinely works with reputable component vendors who are fully familiar with the stringent component level requirements of the high reliability semiconductor devices.

Facility Information

FMI has consistently invested in its facilities over the last 6 years and offers manufacturing processes that address extreme operating temperature applications ranging

from -180°C to + 490°C. This is the widest range available to any U.S. based company in our industry. FMI retains 20 employees and consultants that are involved in the design, development, manufacturing, quality and facility operations. Sales, marketing and administrative management make up the rest of the organization. Highlights of the manufacturing, R&D and QA facilities are described as follows:

1- Hybrid manufacturing and resonator fabrication clean room facility includes

- Nitrogen filled material storage
- Material kitting and inspection stations
- Component attach stations for die level attachment
- Epoxy curing & thermal profiling stations
- Wire-bonding stations for ball bonding and wedge bonding (Au & Al)
- Wire bond integrity inspection
- Crystal attach and the related curing processes
- Functional (Electrical) test
- Pre-seal vacuum (stabilization) bake station
- Vacuum deposition for precision frequency adjusting
- Resistance welding station (in Nitrogen and Helium atmosphere)
- Seam welding station (in Nitrogen and Helium atmosphere)
- Raw material kitting, inspection and sorting
- Crystal resonator lap, polish and beveling processes and inspection
- Chemical etching stations
- Crystal resonator cleaning including the ultrasonic cleaning stations
- Crystal mask preparation and loading station
- Plasma based vacuum deposition station
- Post deposition inspection station

2- Quality inspection and testing facility offers devices testing & evaluation according to various aspects of Mil-std-883 and Mil-std-202 and Mil-PRF-38534

- Burn-in ovens (includes dedicated power supplies and current meters for burn-in tests)
- Aging ovens
- Room temperature electrical test station for crystals and oscillators
- Computer controlled (Lab view) test stations for over temperature performance evaluation of crystals and oscillators
- Temperature cycling test setup
- Constant acceleration station
- Fine leak and gross leak test stations
- Workstation for visual and pre-cap inspections
- Provisions for remote visual inspection

3- Engineering Design & Development (R&D)

- CAD workstation
- ISO controlled & documented design documentation system
- Prototype assembly, testing and evaluation