Robust, Radiation Tolerant Command and Data Handling and Power System Electronics for SmallSats

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***Abstract*—In today's budgetary environment, there is significant interest within the National Aeronautics and Space Administration (NASA) to enable small robotic science missions that can be executed faster and cheaper than previous larger missions. To help achieve this, focus has shifted from using exclusively radiation-tolerant or radiation-hardened parts to using more commercial-off-the-shelf (COTS) components for NASA small satellite missions that can last at least one year in orbit. However, there are some portions of a spacecraft's avionics, such as the Command and Data Handling (C&DH) subsystem and the Power System Electronics (PSE) that need to have a higher level of reliability that goes beyond what is attainable with currently available COTS parts. While there are a number of COTS components that can withstand a total ionizing dose (TID) of tens or hundreds of kilorads, there is still a great deal of concern about tolerance to and mitigation of single-event effects (SEE).**

The Goddard Modular SmallSat Architecture (GMSA) is an initiative at NASA Goddard Space Flight Center (GSFC) to address these radiation tolerance and reliability issues, while also minimizing development cost and schedule. The goal of GMSA is to develop a highly reliable, modular, flexible, and extensible small satellite implementation approach that can incorporate spacecraft components and subsystems that either developed within NASA or procured from industry.

This paper provides details of a new technology development effort that will implement a miniaturized C&DH and PSE within a 6U (10cm x 20cm x 30cm) satellite. This effort has a goal of enabling ambitious science missions using SmallSats that can operate for longer durations in harsher environments than can be achieved with existing SmallSat technologies.

The GMSA PSE uses Direct Energy Transfer (DET) topology with the battery connected directly to the bus. The shunt control technique is a linear sequential full shunt which provides a simple solar array interface and can support both 3-axis stabilized and spinner satellites. The PSE includes all the circuits needed to perform telemetry and command functions using an I2C interface with the C&DH. In addition, the PSE has been designed, tested, and verified to meet launcher vehicle safety requirement.

The GMSA C&DH functionality is implemented as a SmallSat Common Electronics Board (SCEB) and an Adapter Board. The SCEB can be configured to implement a variety of serial communication interfaces including RS-422, I2C, SPI, and SpaceWire. There are also a number of available general purpose input/output (GPIO) signals. The SCEB includes a reprogrammable FPGA that contains a soft-core processor running flight software (FSW) based on NASA GSFC's Core Flight System (cFS). Lastly, the SCEB interfaces with an Adapter Board that contains the analog circuitry that converts temperature, voltage, and current data collected from multiple points within 6U satellite to a digital format that can be processed, stored, and downlinked using the front end communication interface.

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1. INTRODUCTION

NASA Goddard Space Flight Center (GSFC) is developing the Goddard Modular SmallSat Architecture (GMSA) to improve reliability while minimizing power, mass, volume, cost and schedule constraints. Initially GMSA is targeted for 6U small satellites, however in the future it will extend to 12U small satellites. GMSA will apply to NASA missions primarily beyond low earth orbit (LEO) with longer durations and harsher operating environments than are typical for current SmallSat missions. Our targeted mission duration lifetime is 2 years following deployment. GMSA includes two subsystems: the Power System Electronics (PSE) and the Command and Data Handling

(C&DH) subsystem. The GMSA PSE is compatible with Goddard SmallSat Battery Pack which consists of nine Lithium-Ion rechargeable type 18650 cells. The battery provides a maximum capacity of 80 Watt-hours (Wh) at nominal voltage of 11.1V.

2. BODY

Currently Goddard is developing the GMSA PSE and C&DH subsystems. This development differs from commercial products by focusing on the following: higher reliability, higher level of fault tolerance based on GSFC experience, higher power capacity for larger spacecraft and instruments, lower risk as it is designed with GSFC best practices, selecting flight qualified parts, ability to tailor design and parts for unique environments (e.g. high radiation), and ability to control efforts to balance cost and schedule. Each GMSA card has 90 mm x 90mm form factor, which includes a 5 mm keep-out zone on two sides for the edge holder.

2.1 GMSA PSE:

The GMSA PSE is a Direct Energy Transfer (DET) system with the battery connected directly to the bus. The shunt control technique is a linear sequential full shunt which provides a simple solar array interface. This topology can support both 3-axis stabilized and spinner satellites. The GMSA PSE provides electrical power to all subsystems including the instruments of the SmallSat. It includes all the circuits needed to perform telemetry and command functions using an I2C interface with the C&DH subsystem. Additionally, the PSE has been tested and verified to meet launcher vehicle safety requirements.

The GMSA PSE consists of five cards:

- Battery Charge Regulator (BCR): The BCR process solar array input power to provide fine battery charge control and supply the load demands. Excess power is dissipated in the linearly controlled shunts. The separation inhibits and battery telemetry are part of this module.

  There is an option to provide a Battery Charge Regulator Extender (BCRX) card to expand the solar array input power capability for up to six segments (75Watts total).

- Power Distribution Unit (PDU): The PDU converts the primary battery bus into three isolated outputs: +12v, +5v and +3.3V. The +12V can provide a maximum output current of 2A, the +5V and +3.3V can provide a maximum of 3A. The +3.3V is a low drop output linear regulator which is driven by the +5V and can provide maximum output current of 1.5A

- Power Switches Board (PSB): The PSB distributes primary and secondary voltages to the un-switched essential and switched non-essential loads. This board provide 10 switches, where each switch can provide a maximum output current of 1A.

- Actuator Board (AB): The AB provides current limited outputs for software controlled pulsed loads like deployable booms or solar array panels. It also distributes battery bus to high power loads (like the transmitter and/or propulsion sub-system).

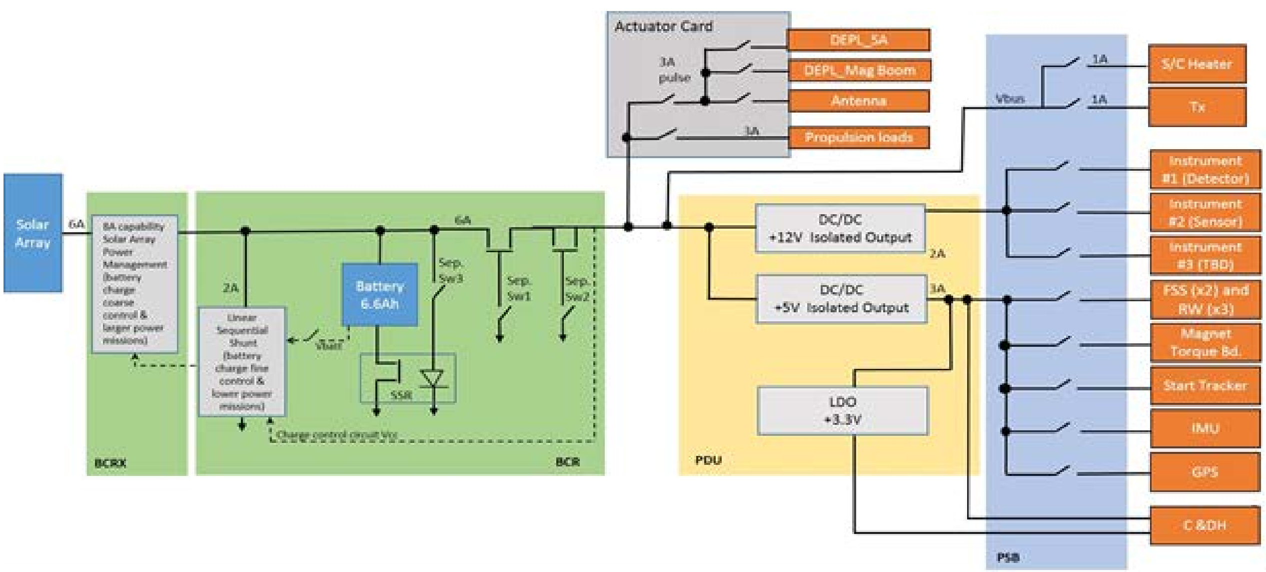

Figure 1 GMSA Electrical Power System Block Diagram

- Backplane Board (BP): The BP is used to connect all the PSE cards together to share the power Bus, secondary power, and I2C lines. Figure 1 shows the GMSA Electrical Power System (EPS) Block Diagram.

The GMSA EPS includes three subsystems: Solar Array, Power System Electronics, and Battery Pack. The Solar Array (SA) subsystem will be selected and procured separately by mission. The Battery Pack is a GSFC in-house design compatible with the GMSA PSE. It consists of nine Lithium-Ion rechargeable type 18650 cells. The battery pack is configured with 3 strings in parallel, with each string having 3 cells in series. With this configuration, the battery has a capacity of 80 Wh at nominal voltage of 11.1V. It will provide power to the satellite during eclipse period and will sustain a bus voltage from 10.8 V to 12.6 V. Figure 2 shows the GMSA Battery Pack.

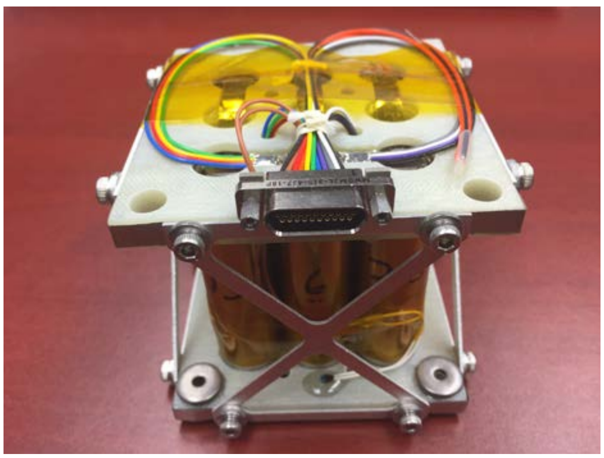

Figure 2 GMSA Battery Pack

The PSE performs functions for the full mission life cycle, including the following: launch inhibits, battery charge, load voltage regulation, load power distribution, fault detection and correction and housekeeping telemetry. Figure 3 shows the GMSA BCR card.

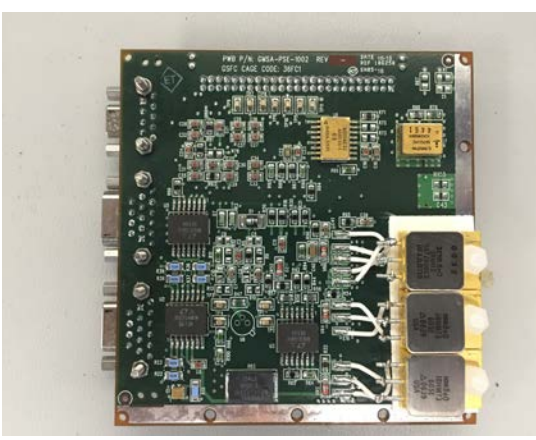

Figure 3 GMSA BCR card assembly

Although the PSE can charge the battery independently, it operates under the control of the SCEB, which performs the onboard computing within GMSA. Figure 4 shows the GMSA PSE assembly.

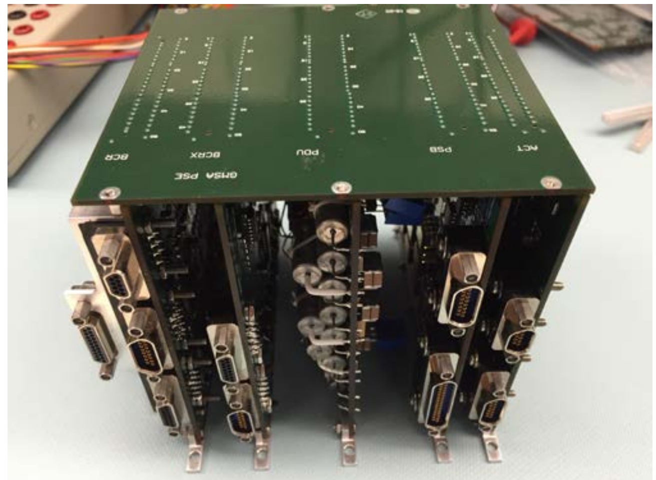

Figure 4 GMSA PSE Assembly

2.2 GMSA PSE and Battery Design Status

The GMSA Battery Pack has been assembled and tested. All GMSA PSE cards have been assembled and tested at room temperature as well as thermally cycled.

2.3 GMSA Command and Data Handling (C&DH)

The GMSA C&DH system uses the SCEB and its Adapter Board to implement C&DH functions, battery charge control, interface with the radio, and provide back-end processing for science data. This system is designed using radiation tolerant parts so that it can operate reliably beyond LEO.

The C&DH functionality is implemented using the SCEB and its Adapter Board. The C&DH uses Microsemi's RTG4 to implement a LEON3FT core running Goddard's Core Flight System (cFS) software. The GMSA C&DH has a 0.25 MB MRAM, 10 MB SRAM and 4 GB Flash. It can be configured to use up to 8 RS-422 outputs, 8 RS-422 inputs, 4 LVDS outputs, 4 LVDS inputs, 16 general purpose inputs / outputs (GPIO), 4 single-ended +5V tolerant inputs, a CAN bus interface, 2 SPI bus interfaces, and 2 I2C bus interfaces. The GMSA C&DH also has 6 coarse sun sensor (CSS) interfaces and 3 H-bridge drivers that can interface with magnet torque within the SmallSat spacecraft. An analog-to-digital converter (ADC) and 2 multiplexers can also be used to connect to multiple thermistors and monitor voltage levels within the SmallSat spacecraft. Figure 5 and 6 show photos of both C&DH boards.

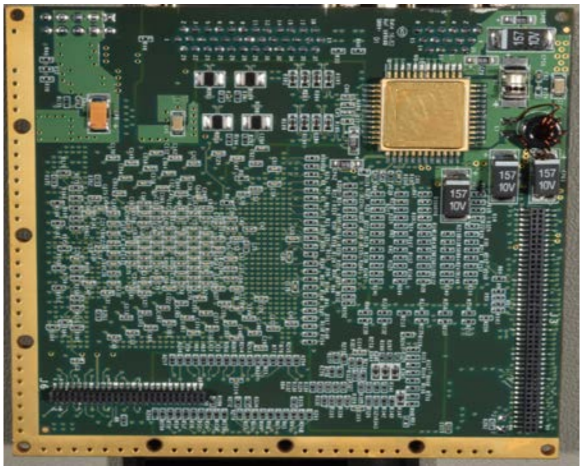

Figure 5: SCEB assembly

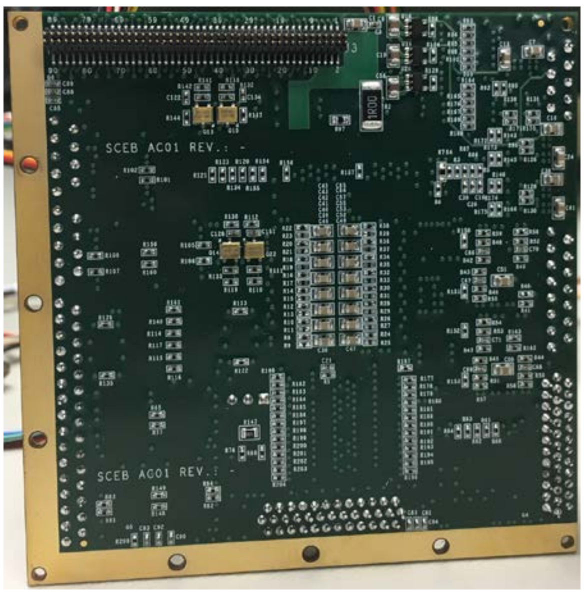

Figure 6: Adapter Board assembly

2.4 GMSA C&DH Status

GMSA C&DH boards have been designed and assembled. We have completed testing at ambient on both GMSA C&DH boards.

2.5 GMSA Hardware Environmental Test Status

The integration and test of the GMSA C&DH and PSE hardware is coming soon. The vibration and thermal vacuum testing of the integrated hardware will be next. The requirements specified in the General Environmental Verification Standard (GEVS) for GSFC Flight Programs and Projects will be followed. The vibration testing will consist of three parts (one for each of three axes) of sine burst testing and random vibration testing using qualification levels. The thermal vacuum testing will consist of a total of eight thermal cycles between -10^{o} C to +50^{o} C. One of those thermal cycles will be the survival temperature range of -20^{o} C to +65^{o} C.

3. CONCLUSION

The PSE and C&DH subsystems that are currently being tested will provide the miniaturization, flexibility, and reliability required for GMSA. This hardware will position GSFC to develop CubeSat and SmallSat science missions that can operate reliably in harsh radiation environments for durations exceeding one year.

4. ACRONYM LIST

1U = 10cm x 10cm x10 cm (H x W x L)
AB: Actuator Board
BCR: Battery Charge Regulator
BP: Backplane Board
C&DH: Command and Data Handling
cFS: Core Flight System
DET: Direct Energy Transfer
EPS: Electrical Power System
FW: Flight software
GMSA: Goddard Modular SmallSat Architecture
GPIO: General purpose input/output
GSFC: Goddard Space Flight Center
FDC: Fault Detection and Correction
I2C: "Inter IC" or I²C bus (or IIC bus)
LRO: Lunar Reconnaissance Orbiter
MMS: Magnetospheric Multiscale
NASA: National Aeronautics and Space Administration
PDU: Power Distribution Unit
PSB: Power Switches Board
PSE: Power System Electronics
SEE: Single-event effects
TID: Total ionizing dose

5. SUMMARY

GMSA technology can be applied to enable heliophysics and planetary science missions providing measurements and observations beyond LEO. These missions may be deployed in orbits where a SmallSat will experience frequent and variable eclipse periods. Hence there is a definitive need for the GMSA hardware to be adaptable to accommodate varying avionics architectures (including the EPS and C&DH), while still retaining cost effectiveness, reliability, and performance. This need drove the approach for part selection, circuit level design, and system design. We will test the GMDA hardware over the full range of expected environments to validate the GMSA for use in a wide array of missions.

6. ACKNOWLEDGEMENTS

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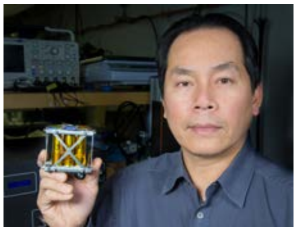
7. References

[1] IEEE Aerospace Conference Web site: www.aeroconf.org

8. Biographies



Hanson Nguyen *received a B.S. in Electrical Engineering from University of Maryland, College Park in 1998. He received a M.S. in Electrical Engineering from John Hopkins University, Maryland in 2000. He has worked with NASA Power Systems Branch for 15 years. He currently leads Ka-Band Transmitter low voltage power converter (LVPC) system of the Wide Field Infrared Survey Telescope (WFIRST) mission which is the next major observatory beyond the James Webb Space Telescope (JWST) and the highest priority large mission in Decadal Survey. He has been involving with NASA GSFC research and developing a high reliability SmallSat PSE and Battery program since 2013. Prior to this, he leaded engineering group for several LVPC systems designed and implemented at GSFC's missions such as Solar Dynamic Observatory (SDO) and Lunar Reconnaissance Orbiter (LRO) Ka-Band Transmitter, Laser Communications Relay Demonstration (LCRD), Ice-Cloud-and land Elevation Satellite-2 (ICESAT-2) Advanced Topographic Laser Altimeter System (ATLAS), and Global Precipitation Measurement (GPM). Prior to NASA, he worked at Mind/Brain Institute at John Hopkins University.*

James Fraction *received a B.S. in Mathematics at Morehouse College in 2002 and a M.S. in Electrical and Computer Engineering at the Georgia Institute of Technology in 2004. He has worked in the Flight Data Systems and Radiation Effects Branch at NASA Goddard Space Flight Center for 12 years designing and testing flight hardware associated with C&DH subsystems used on board a number of NASA missions including the Lunar Reconnaissance Orbiter (LRO) and Magnetospheric Multiscale (MMS). Since 2013 James has been involved with research and development work that focuses on developing high reliability SmallSat hardware that can be used to implement C&DH functionality.*