The Advent of the PnP Cube Satellite

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Abstract— **In terms of time and budget, integration is a significant time-consuming component of spacecraft development. While many useful COTS spacecraft components are available, interfacing and controlling these components in an integrated satellite system remains a complex engineering task. The Stanford/Cal Poly CubeSat and Poly-Picosatellite Orbital Dispenser (PPOD) standards have begun to standardize small satellite mechanical systems and revolutionize the way small satellites are deployed. NASA has recognized this as evident by their Educational Launch of Nanosatellites (ELaNa) program which recently selected 17 CubeSats for the ELaNa-4 launch in 2012 (including one high school). To capitalize on this momentum, the Air Force Research Lab (AFRL) has organized and supported a team of commercial and academic laboratories to develop and test an over-arching Space Plug-and-play Architecture (SPA) set of standards to support the rapid integration of independently developed satellite modular systems. SPA represents not only an electrical inter-connection and communication scheme, but a complete model for a self-organizing and self-configuring system to support the rapid assembly of mission-specific small satellites. Rather than forcing existing modules to be re-developed to a common messaging standard, SPA utilizes an XTEDS (eXtended Transducer Electronic Data Sheet) model. Each satellite module contains an electronic document describing its interface, capabilities, messages, data formats, etc. By reading a components XTEDS, other systems can quickly integrate and utilize a new module. While designed to initially take advantage of nanosatellites, everything developed can easily scale to larger spacecraft, UAVs or other aerospace and defense systems. This paper discusses our experience in developing the CubeSat Trailblazer, a 1U SPA-only spacecraft – launching in 2012 as a testbed for SPA technology. The mechanisms of self-organization for independent modules as a cooperating communications system are discussed. The simplifications associated with software development of a Command and Data Handler (CDH) is also presented.**

1. Background: CubeSats, ELaNa and Revolutionary Change

Several programs are now creating revolutionary changes in the space industry. The first is the CubeSat model [1]. The CubeSat is a nanosatellite class structure defined in Units. A 1U stands for a satellite that is one unit in size (4" x 4" x 4"). A 2U doubles the length. The 3U spacecraft is the largest satellite that will fit in the Poly Picosatellite Orbital Deployer (PPoD) launcher. Currently, the PPoD is the accepted standard for CubeSat development. It was announced at the CubeSat Workshop in Logan, Utah in August, 2011 that there are currently 26 countries building CubeSats. CubeSats have allowed countries like Columbia and Spain that could never afford a space program to begin to design, build and launch a space mission. Although CubeSats are the tools, the real catalyst has been the NASA Educational Launch of Nanosatellites (ELaNa) program [2]. ELaNa has made it affordable for academic institutions to have their spacecraft placed into orbit. Before this program, few opportunities existed for CubeSat launch with average launch cost of approximately 10,000 dollars a pound. ELaNa has changed everything. It is now possible for academia to easily get to space while at the same time building an entirely new generation of students excited about space activities. The Trailblazer spacecraft [3] described in this document is being launched as part of the ELaNa program. There has always been a struggle to determine if the CubeSat model is capable more complex missions than have previously been demonstrated. The ELaNa Program is opening the door again and changing the potential missions for CubeSats thus increasing the missions these spacecraft are capable of performing. The new ELaNa solicitation is allowing for submissions of 6U satellites [2]. These spacecraft will be 4" x 8" x 12". The larger spacecraft are beginning to create opportunities for real missions such as imaging, communications and space weather. A 6U spacecraft has sufficient room for large enough optics to begin to do high resolution imaging of Earth from space. There are several serious issues that need to be addressed as this paradigm moves forward. The first is the level of complexity. A 1U CubeSat generally has a very limited mission and as such, the level of complexity of design was greatly reduced. This meant that the average developer could write all the required code to support the hardware in a few weeks. Most of the hardware has standard interface, connectors and software. As the size of the spacecraft grows, this paradigm begins to break down. There is not a linear curve when comparing time of completion of a software project to the number of lines of code written. As the complexity of the Command and Data Handling system increases, the time required to design, code, integrate, and test the system exponentially increases. The amount of time required to write the control system for a 3U spacecraft is not three times the amount of time required for a 1U. There are more modules and interface issues to be addressed. This significantly increases development time and costs for a larger Nanosatellite spacecraft. Secondly, to be truly responsive, there must be a way to easily reuse hardware from one system to another. Traditional spacecraft development has often failed here. Without a standard bus interface, there is often no easy way to move parts from one CubeSat (or larger spacecraft) to another.

The way to truly advance small satellite development is to find a method to break the one-of-a-kind mentality in our current satellite build paradigm. One of the competing standards in this area is AFRLs open source SPA bus and the Satellite Data Model software architecture. [4]. Several spacecraft are currently being built to this standard including the Quadsat [5] and the Trailblazer [6] missions. The power of this methodology is that components from one satellite can easily be integrated into a different satellite in a truly PnP fashion. Parts and software can be developed without a specific mission in mind and then be automatically configured and used in a variety of satellite missions in a rapid fashion. This strategy significantly reduces the size and complexity of the Interface Control Document (ICD). The ICD for many spacecraft is where failure occurs. Often, this has been the reason for CubeSat success. The ability to utilize kits to assemble systems reduces the possibility of

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[1] IEEEAC Paper #1, Version 1, Updated 3/11/2011.

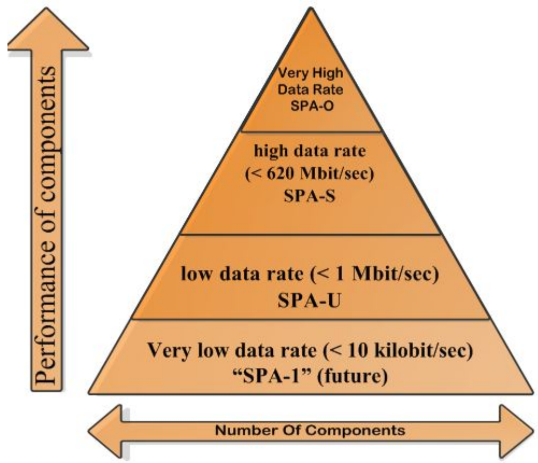

Figure 1. The hierarchical view of SPA identifies the lower data rate at the bottom of the pyramid and the higher optical version at the top.

errors. Being able to integrate spacecraft in a modular fashion is a powerful tool to serve the needs of the global space community. Although the Space Plug-and-play Architecture (SPA) [4] is currently used in small spacecraft, there is nothing prohibiting its integration into larger spacecraft or other systems. Newer additions to the SPA standard were intended to be utilized on larger spacecraft. Configurable Space Microsystems Innovations and Applications Center (COSMIAC) at the University of New Mexico in conjunction with the Air Force Research Laboratory (AFRL) and the Space Dynamics Laboratory (SDL) have been responsible for training more than 700 individuals on SPA in the past 24 months. Modules and nanosatellites are now being developed by commercial vendors and academic institutions that are SPA compatible and thus, interchangeable.

As shown in FIG 1, there are a wide variety of different types of SPA protocols. Each has their own data rate limits. Just as an organization would not use an optical interface for a thermometer, they also would not use an I2C interface for a high-speed imager. There are different flavors of SPA for different hardware components or larger spacecraft. All SPA communications standards employ a self-discovery mechanism to allow the detection and address identification of connected devices. There are three basic components that make up each SPA system: XTEDS, ASIM and SSM.

The SPA paradigm provides an open source design medium for utilizing a well-established bus architecture. A timeline showing the history and projected path ahead for SPA is presented in FIG 2 and details some of the major milestones of the program.

To validate whether a module is communicating properly via the SPA-protocol, we need a reference implementation of SPA standards. SDL has developed just this, which is called the SPA Services Manager (SSM). The SSM (formerly known as the SDM) is responsible for component discovery, component registration, data centric queries, time distribution, and internal systems health monitoring and status reporting. These functions are accomplished by multiple SPA Subnet Managers, a Central Addressing Service (CAS) and a Lookup Service. The SSM provides an interface for the modules on the bus and the applications that control the modules. The SSM communicates with all the ASIMs and the software applications. It will be responsible for maintaining an active data registry of the modules and providing a central look up service for applications. The SSM is responsible for performing discovery of a subnet.Every sensor, control, or communications device that might be utilized for a CubeSat spacecraft has a data sheet that describes control inputs as well as data input and output messages. As such, control software in a satellite is traditionally programmed specific in a very custom and specific way. The SPA approach is to embed the data sheet information concerning utilization of a device into an electronic document called an xTEDS (Extended Transducer Electronic Data Sheet). The xTEDS is an XML document conforming to a specific schema wherein controls, data values, and messages associated with the device are documented. The xTEDS conforms to a published schema. To facilitate correct xTEDS development, the SPA system provides an xTEDS Wizard allowing a developer to construct a device xTEDS through a graphical user interface and menus with standardized terminology and have that xTEDS checked for syntactical correctness. The satellite developer need not by an XML programmer. The xTEDS Wizard then synthesizes a device emulator (based upon the xTEDS content) that can be used to test and validate interactions and operations with a spacecraft processor.

To support a device and conform to the xTEDS specified operation, the SPA model utilizes a small ASIM (Applique Sensor Interface Module), a nano low-power processor that both stores the xTEDS for the device and implements the SPA model communications implied by the xTEDS. In effect, the ASIM controls and operates the device according to the devices published data sheet. The ASIM also provides a standardized communications protocol to implement the xTEDS interface, providing a standardized interface for the rest of the SPA model and spacecraft processor(s).

The third component of a SPA model is the control and data handler software, called the SSM (SPA Services Manager) – formerly known as the SDM or Satellite Data Model. When powered on, the SSM (through use of the standardized SPA communications protocols) detects and identifies the address of each connected device ASIM. It then registers the device by interrogating each device to retrieve and store the device xTEDS. As such, the SSM understand the device xTEDS. The SSM can now allow custom modules provided by the satellite developer to communicate with the device in a standardized way using a powerful and syntax-rich library of SPA routines within the SSM. For example, applications software could be written to utilize a sun sensor without knowing which specific sun sensor has been connected to this satellite. In fact, any sun sensor (and associated ASIM) could be used in a satellite design without modifications to the application software. Sun sensor modules and applications software become plug-and-play; able to configure and cooperate through the SSM model. On the Trailblazer spacecraft, the SPA subnet that is being used is SPA-1 based on the I2C standard.

2. The Trailblazer Satellites A New Idea

The Trailblazer series of spacecraft [8] evidences both the flexibility and reduced complexity of the SPA standards. In the first stage, Trailblazer I [6] will consist of commercial-off-the-shelf components converted to be SPA compliant. The flexibility is evident by the fact that these components can

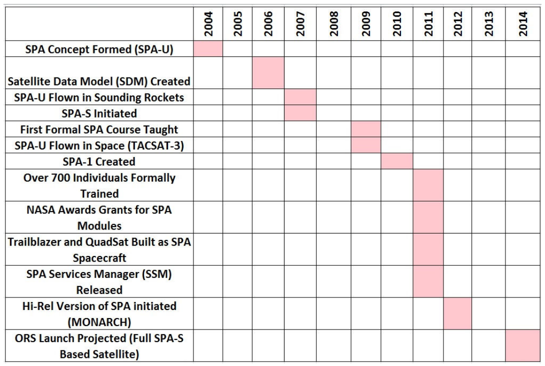

Figure 2. Presented here is a timeline for the SPA development

now be easily integrated onto future SPA platforms. Complexity is reduced by removing the need for the component developers to address the issues of interfacing the ASIM to the bus, they need only interface their device to the ASIM and develop an XTEDs [7] to describe the functionality of their module. Trailblazer I will be based entirely on a SPA bus implementation and will conform to the dimensions of a 1U CubeSat discussed above. In addition to demonstrating the capability of converting existing components to be SPA compliant, it will also demonstrate the reliability of the bus in a space environment. Time to completion and level of design complexity can be further reduced with a SPA tool suite which allows for quick and accurate generation of the ASIM programming code, XTEDs, and SSM applications. The use of these tools allows for easy design of new SPA components, or conversion of existing components into SPA compliance. This allows for a demonstration of the bus reliability in a space environment, as well as the capability of converting existing components to be SPA compliant. With the dimensional constraints and power budget of Trailblazer, the development team elected to use the SPA-1 standard. SPA-1 is the most recent addition to the AFRL SPA family (see FIG 1). The SPA-1 data transfer protocol is based on 400 kbit/s I2C making it not only the lowest bandwidth, but also the lowest power option for SPA.

As discussed above, Trailblazer I will demonstrate both SPA bus reliability, and the capability of converting existing components to be SPA compliant. In addition, there is a dosimetry payload, and an experimental circuit board prototyping payload aboard Trailblazer. These two modules serve as further demonstration of the capability for CubeSats to perform impactful scientific missions. Details of these payloads will follow. Both payloads as well as the supporting components that make up the bus architecture are all interfaced through a total of five low power SPA-1 ASIMs. The Bus architecture consists of an electrical power system (EPS) from Clyde Space [9], a pluggable processor module designed at AFRL based on an ATMEL AT-Mega, an UHF radio from Astrodev [10], and a passive magnetic attitude stabilization system from ISIS [11]. Together these modules are networked to form the entirety of the satellite architecture based completely on the SPA-1 protocol.

As outlined in a previous publication [6], the Plug-n-Play dosimeter is one of the two primary payloads aboard Trailblazer I. This module monitors the accumulation of ionizing radiation in orbit with a depletion mode, p-channel RadFet from REM which is fabricated with a thick oxide to maximize its sensitivity to radiation. An ASIC from NuTREK called the NuDose is configured to force a specified current through the RadFet. As radiation penetrates the oxide in the RadFet, electron-hole pairs are created and then separated via the electric field in the dielectric. The positive charge drifts toward the conduction channel and becomes trapped in the oxide. This modifies the threshold voltage of the device, and consequently changes the resistance between the source and drain electrodes. The NuDose must maintain the selected current through the Fet and thus the voltage across the source and drain must increase to compensate for the increased channel resistance. This voltage is sent out to an external analog to digital converter on the SPA-1 ASIM. The ASIM can be configured to periodically, or by request, transmit the 10bit binary number corresponding to this voltage via the SPA-1 bus.

The second payload will be a rapid prototyped Inertial Measurement Unit (IMU) [3]. This payload will test a new 3-D PCB design methodology. 3-D PCB design can improve the limited volume that is available and found on each CubeSat mission by filling in the open space with critical electronics. In addition, the IMU may provide a low power, low cost solution to position acquisition. As with the rest of the satellite, these payloads have been fitted with an ASIM to make them SPA-1 compliant and to facilitate their use in future satellites.

3. Results

AFRL has organized and supported a team of commercial and academic laboratories to develop and test an over-arching Space Plug-and-play Architecture (SPA) set of standards to support the rapid integration of independently developed satellite modular systems. Nanosatellite missions are currently being developed around these SPA standards and while the first set of formal standards have already been developed in collaboration with AIAA, they have been complicated by the fact that the results are constantly changing even as they are being written. The growth of the size of the nanosat from 1U to 6U is creating a critical need for a method to more quickly design and integrate traditionally unrelated modules and SPA has been shown to be a possible solution. Additionally, 1U (or smaller) spacecraft are also driving the day when personal spacecraft may become a reality. However, there is nothing forcing the SPA standard to remain in the Nanosat arena. This standard is easily extensible to larger aerospace and defense systems. Government organizations such as NASA are awarding companies such as Maryland Aerospace Institute [12] with contracts to make their Attitude Determination and Control systems to be SPA compliant - more components will become available that can quickly be implemented. The timeline presented in FIG. 2 provides a roadmap of where SPA has come from as well as a path ahead.

4. Future Work

Trailblazer-II: Space Environmental Test System (SETS) will be the next satellite developed by COSMIAC based on the SPA standard. It is being designed around a 6U satellite structure. SETS will extend the work accomplished on the first Trailblazer satellite by utilizing not only the SPA-1 bus protocol, but also the SPA-U bus protocol. SETS will be controlling the SPA busses with Space Dynamics Labs SPA System Manager (SSM) running on the AFRL NanoCDH

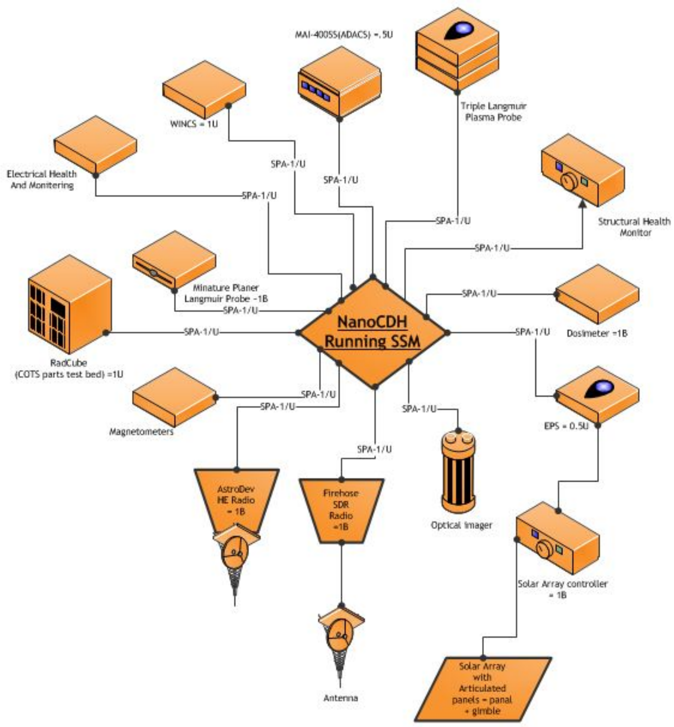

Figure 3. This is the block diagram view of the SETS spacecraft being proposed utilizing the SPA protocol.

Command and Data Handling platform.

SETS will provide flight heritage to new technologies in the area of communications, space weather, and commercially-off-the shelf parts (COTS). The communication payloads include SPA compliant software defined radio (SDR) [13], a dosimeter and a variety of different Langmuir probes for environmental monitoring. SETS will also include other hardware that has already been made SPA compatible and that can be easily integrated into this new spacecraft.

The real path ahead for SPA will be its utilization in a high reliability environment. To adapt to this challenge, a high reliability version of SPA has been created called MONARCH.

5. Conclusions

The conception of NASAs ELaNa program is evidence of increased interest in small satellites and their capability to perform valuable space missions for a fraction of the cost and time of larger satellite programs. There are radical changes coming to the small spacecraft arena in the next five years. Many of these changes are being brought about due to the infusion of higher reliability minature electronics. Several large governmental organizations are already investigating the possible capabilities that ”swarms” of nanosatellites can achieve. One recent series of research found that with less than 100 CubeSats, it would be possible to achieve 24 hour a day ”eyes on” surveilance over the tropics.

The time in the future for the personal satellite may not be far off. Also, with the advent of 6U satellites, the lines between small satellites and big satellites will continue to become more blurred. With the miniaturization of components, more and more missions will begin to be performed by smaller spacecraft that can be rapidly designed, built, tested and deployed. Only through an open source method of rapid satellite bus development can we truly gain the ability to rapidly develop and deploy these critical systems while at the same time reducing design complexity.

Acknowledgments

This material is based on research sponsored by the Air Force Research Laboratory (AFRL) under agreement number FA9453-08-2-0259. The U.S. Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copyright notation thereon. The Trailblazer team would also like to acknowledge the guidance and mentorship of Dr. Jim White without whom this project might not have been possible.

References

[1] California Polytechnic State University. Cubesat design specification. http://www.cubesat.org.

[2] N. S. F. Center. (2011) Elana: Educational launch of nanosatellites. Internet. NASA. NASA/Goddard Space Flight Center, NASA Headquarters Acquisition Branch, Code 210.H, Greenbelt, MD 20771. [Online]. Available: http://prod.nais.nasa.gov/eps/eps_data/147535-OTHER-001-001.pdf

[3] C. K. Brian Zufelt. (2011, April) Trailblazer: Proof of concept cubesat mission for spa-1. Internet. Cal Poly CubeSat Workshop. San Luis Obispo, CA. [Online]. Available: http://www.cosmiacpubs.org/pubs/COSMIAC%20CubeSat%20WS.pdf

[4] J. Lyke, J. Mee, F. Bruhn, G. Chosson, R. Lindegren, H. Lofgren, J. Schulte, S. Cannon, J. Christensen, B. Hansen, R. Vick, A. Vera, and J. Calixte-Rosengren, “A plug-and-play approach based on the i2c standard,” in *Proceedings of the 24th Annual Conference on Small Satellites*, Logan, UT, 8-10 August 2010.

[5] I. K. J. C. L. J. R.-C. R. N. Fredrik C. Bruhn, Per Selin, “Quadsat/pnp: A space-plug-and-play architecture (spa) compliant nanosatellite,” in *Infotech@Aerospace Conference, Unleashing Unmanned Systems*, AIAA. AIAA, March 2011.

[6] J. H. C. J. K. M. Craig J. Kief, Brian K. Zufelt. (2011) Trailblazer: Proof of concept cubesat mission for spa-1. AIAA Infotec Conf. COSMIAC. [Online]. Available: http://www.cosmiacpubs.org/pubs/AIAA_Trailblazer.pdf

[7] S. S. Pasko, “Using rdf schema and taxonomies to describe a flexible, standards based spa ontology,” in *Infotech@Aerospace Conference, Unleashing Unmanned Systems*, AIAA. AIAA, March 2011.

[8] B. K. Z. Craig J. Kief. (2011, August) Trailblazer, spa and radiation testing overview. Summer CubeSat Developers Workshop. COSMIAC. Logan, UT. [Online]. Available: http://www.cosmiacpubs.org/pubs/Trailblazer_CSworkshop.pdf

[9] Clyde Space. (2011, February) 3u cubesat eps. http://www.clyde-space.com/cubesat_shop/eps/12_3u-cubesat-eps.

[10] (2009, 26 July) Astrodev helium radios. http://www.astrodev.com/public_html/downloads/datasheet/Helium-Specification.pdf.

[11] ISIS. (2011) Passive magnetic attitude stabilization system. Internet. ISIS. [Online]. Available: http://www.cubesatshop.com/index.php?page=shop.product_details&flypage=flypage.tpl&product_id=29&category_id=7&option=com_virtuemart&Itemid=69&vmcchk=1&Itemid=69

[12] (2011, December) Maryland aerospace institute is awarded sbir. http://sbir.gsfc.nasa.gov/SBIR/abstracts/11/sbir/phase1/SBIR-11-1-O1.03-9552.html?solicitationId=SBIR_11_P1.

[13] J. H. Reed, *Software Radio: A Modern Approach to Radio Engineering*. Prentice-Hall, 2002.

BIOGRAPHY

Craig Kief received his MS degree in Computer Engineering from the University of New Mexico and serves as Deputy Director of COSMIAC. He also serves as the lead Program Manager for the Air Force Research Laboratory's Cubeflow training program and is a Research Scholar on the faculty at the University of New Mexico. In this capacity, he is responsible for overseeing curriculum and training development, teaching short courses, and coordinating the scheduling and registration of COSMIAC courses.

Brian Zufelt is an electrical engineer and graduated from the University of New Mexico. He has written many tutorials over FPGA design utilizing VHDL. He has also assisted many community colleges in the creation of FPGA based curriculum. Over the last 3 years, Brian has been working with the Air Force Research Lab (AFRL) and the Configurable Space Microsystems Innovations and Applications Center (COSMIAC) to create Space Plug-and- Play Avionics (SPA) components, and provided training on Space Plug and Play Avionic tools and architecture.

Scott Cannon is a professor at Utah State University in the Deptartment of Computer Science and member of the Small Satellite software group at the Space Dynamics Laboratory at Logan Utah. Dr. Scott Cannon has been a leader in the areas of Space Plug-and-play Architecture technology for the past ten years most recently leading the overhaul of the Satellite Sensor System

James Lyke is technical advisor to the Air Force Research Laboratory's Space Electronics Branch (Space Vehicles Directorate) and an AFRL Fellow. Jim has lead over one hundred in-house and contract research efforts involving advanced packaging, radiation-hardened circuits, and scalable, reconfigurable architectures, with recent emphasis on rapid formation of complex systems ("plug-and-play"). He has authored over 80 publications, four receiving best paper awards and has been awarded eleven US patents. He is a senior member of IEEE and associate fellow of AIAA. His BSEE is from the University of Tennesse, MSEE from the Air Force Institute of Technology, and PhD from the University of New Mexico.

Jesse Mee received his B.S. in Electrical Engineering from UNM in 2009 concentrating on microelectronics. In 2010 he completed his M.S. degree with the honor of distinction in Electrical Engineering at UNM. His research was related to reliability physics of microelectronics for space application. In particular he concentrated on the reliability degradation phenomenon known as Negative Bias Temperature Instability. Jesse has been working the Air Force Research Laboratories since 2008 and presently focuses on optical backplane design for satellite bus architecture.