Argus: Radiation Effects Modeling on a University Nanosat

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ABSTRACT

The Air Force Research Laboratory's University Nanosat Program (UNP) was established in 1999 to train students at dozens of universities in the space systems engineering process and provide space flight opportunities for a few. The NASA Educational Launch of Nanosatellites (ELaNa) program was established in 2010 to provide flight opportunities for dozens of university missions, but does not directly support student training. Then a curious thing happened: several UNP schools were selected for ELaNa launches. Then, a more curious thing happened: everyone thought that this was a great idea! This **is** a great idea, because: 1) it provides opportunities for more universities to fly relevant, reliable missions, and 2) it expands the pool of flight-capable universities to small schools. Argus, a space mission in development at Saint Louis University and Vanderbilt University is one such mission. Argus will improve the predictive modeling of the effects of space radiation on modern electronics by calibrating these models with experimental data produced by on-orbit devices. This paper describes the UNP and ELaNa programs, the opportunities for synergy, the Argus mission and spacecraft, and the ways in which the Argus program has benefited from these opportunities.

INTRODUCTION

The year 1999 was a consequential one for Bob Twiggs (then at Stanford University) and for university-built satellites. This was the year that he and Dr. Jordi Puig-Suari introduced the CubeSat/P-POD concept;[1] it is also the year that AFRL, NASA, DARPA and AIAA collectively started the University Nanosat Program (UNP) in response to a very public challenge Twiggs made at a previous Conference on Small Satellites.[2] Now, in 2012, those two streams are merging in the NASA-sponsored launches of several UNP-sponsored CubeSats.

UNP and ELaNa

The goal of UNP is to improve the recruiting, training and retention of spacecraft engineers by sponsoring 2-year design/build competitions, with the winning school earning AFRL support to make their spacecraft flight-ready and find a ride into space. Since 1999, thousands of students at several dozen universities have benefitted from the program; two missions were launched and three more are manifested for launch this year. Two more UNP competition winners are in the integration & test phase, awaiting a future manifest.

UNP efforts have centered on 50-kg "ESPA-class" secondary launch opportunities. As we will discuss, below, one consequence of this approach is that only large universities (engineering enrollments greater than 3,000) have won the competition. The time from the start of a competition cycle until launch of that cycle's winner has ranged from 5 to 7 years, which means that no student is able to participate in the entire design lifecycle.

Meanwhile, over the past three years, NASA has reversed its policy of not being "a launch broker for universities" by has selecting 49 university CubeSat missions for launch under the Educational Launch of Nanosatellites (ELaNa) program.[3] Early results of ELaNa launches are troubling, however, as 40% of the first wave of CubeSats to reach orbit have been unable to meet their mission objectives. NASA's sponsorship provides essential support and direction for the pre-launch verification and the launch itself; the program does not have the resources to provide systems engineering support to the schools.

Yet, there is very good news, for NASA and AFRL are allowing schools to participate in both programs. Two entries in the Nanosat-6 competition have been manifested on NASA ELaNa flights, and four missions proposed for the Nanosat-7 competition have been selected in NASA's latest round. We believe that UNP and ELaNa provide a unique synergistic opportunity to provide better training and better in-space outcomes than either program can do on their own – especially for small schools that cannot hope to field the larger spacecraft.

Argus

As an example, we present Argus, Saint Louis University's entry in the Nanosat-7 competition. The purpose of Argus is to improve the modeling of the effects of space radiation on electronics by monitoring the behavior of known electronic parts in space and comparing in-orbit performance with predictive models on the ground. Argus is a 2U CubeSat selected for launch by NASA in the third cohort.

Argus is a collaboration between the Space Systems Research Laboratory (SSRL) at Saint Louis University and the Institute for Space and Defense Electronics (ISDE) based on overlapping interests: SSRL in space systems engineering research and education, ISDE in radiation-effects modeling and in space-qualifying modern electronics. The payload-bus interface as well as the spacecraft-ground interface have been designed intentionally to maximize the ability of each institution to meet its objectives. Therefore, while the Argus campaign will be described as a purely SSRL-ISDE activity, it is possible (and even expected) that ISDE will fly its payloads on other spacecraft, and that SSRL will fly other payloads on its spacecraft.

Paper Overview

In this paper, we will present Argus as one potential approach to leverage the benefits of UNP and ELaNa to do real science and real engineering education on a student-built CubeSat. We will begin by introducing the UNP and ELaNa programs. We will establish the need for space-based testing of the effects of radiation on modern electronics, and justify Argus as a means of meeting those needs. We will describe the types of electronics to be tested; the concept of operations for each flight experiment; and the design of the specific spacecraft. Special attention will be paid to the means by which nominally radiation-vulnerable spacecraft (CubeSats) can be used as radiation-modeling experiments. We will discuss SSRL's two UNP/ELaNa missions: COPPER, an Argus pathfinder carrying a demonstration version of the flight systems (manifested for an August 2013 launch) and Argus. We will also discuss the organizational and systems engineering processes necessary to simultaneously develop several missions at two small engineering schools.

A TALE OF TWO SPONSORS

The University Nanosat Program

The University Nanosat Program began in 1999 in response to Bob Twiggs' public call for greater NASA/DoD support of student-built spacecraft. Originally a joint effort of AFRL, DARPA, NASA and AIAA, ten schools were selected to build spacecraft, with the intent that all ten would build and fly spacecraft on secondary opportunities (nominally the Space Shuttle).[2,4] Arizona State University, New Mexico State University and the University of Colorado teamed up to field a multi-spacecraft mission, 3CornerSat (3CS). 3CS was the only mission to complete the integration & test process and launch. It was manifested on the maiden flight of the Delta 4 Heavy in 2004; since two of the three 3CS vehicles were manifested, this was called the Nanosat-1/2 mission. Unfortunately, performance problems with the launch vehicle resulted in a suborbital flight for 3CS.

As a result of the lessons learned from this first round, UNP was reorganized into a 2-year cycle, where about a dozen schools would compete for a single launch sponsorship. The student teams would receive AFOSR funding and regular reviews by the AFRL sponsors as well as recruited industry professionals. The winning school would be selected based on the DoD relevance of its mission and the ability of the school to complete a flight-ready spacecraft to meet the mission. The designs have centered around 50-kg spacecraft with a secondary (ESPA-class) launch. At the end of the 2-year cycle, one school would be selected to complete their spacecraft and enter the DoD Space Experiments Review Board (SERB) process for a sponsored launch. The Nanosat-3 competition began in January 2003, and a new cycle has started every two years since then. According to AFRL, more than 5,000 students at thirty-one schools have participated.

In the author's opinion, the benefits of participation in UNP are significant. [Full disclosure: the author was a student participant in NS-1/2 and a PI for NS-3 through NS-7.] Students receive tremendous technical advice and program management assistance; they must pass a stringent design review every 6 months, and the flight competition review has very high standards. AFOSR provides enough support to keep a program operating. Dozens of undergraduates that participated in the author's UNP activities are now in key systems engineering positions at AFRL, NASA, Orbital, SpaceX, APL and many other places. We believe that the UNP experience helped bring them into aerospace and trained them to attain these positions.

As a spaceflight activity, however, the results are mixed. As shown in Table 1, there is a three- to five-year delay from the selection of a winner to launch. Since the winner is chosen at the end of a two-year competition, that means it is at least five years from the inception of a student-satellite program to its UNP-sponsored launch. Informally, it appears that at least 18 months of the post-selection delay is due to the additional time it takes for the UNP winner to complete and deliver a flight-ready spacecraft. Moreover, 29 schools have participated in at least one of the first 5 UNP cycles, but only four schools have had their missions fly, with two more schools due to fly this year.

In addition, smaller schools appear to be at a competitive disadvantage. As also shown in Table 1, every UNP winner has been a large engineering school (more than 3500 undergraduates in engineering). Obviously, enrollments are not an exact measurement of the resources available to a UNP entry, but they do provide an order-of-magnitude indication. For example, the number of graduate students working on Cornell's NS-4 winner was almost double the total number of students working on the NS-4 runner-up.

Table 1: University Nanosat Program Flight Results. Missions in blue were separately selected by NASA for launch. Engineering enrollment for 3CS is the combined enrollment for all three schools.

Year Selected	Mission	Mission	Year Launched	Schools	Engineering Enrollment
2001	Nanosat-1/2	3CS	2004	ASU, Colorado, NMSU	11000*
2005	Nanosat-3	FASTRAC	2010	Texas	7700
2007	Nanosat-4	CUSat	2012/Q4	Cornell	4500
2009	Nanosat-5	DANDE	2012/Q4	Colorado	4700
2011	Nanosat-6	OCULUS	-	Michigan Tech	3500
2011	Nanosat-6b	VIOLET	-	Cornell	4500
-	Nanosat-6c	**Ho'oponopono**	2012/Q3	Hawaii	**900**
-	Nanosat-6d	**COPPER**	2013	SLU	**600**
2013	Nanosat-7 (winner not yet selected)	**Argus**	-	SLU	**600**
		PrintSat	-	Montana State	**1000**
		Ho'oponopono-3	-	Hawaii	**900**
		ARMADILLO	-	Texas	7700

The author must pause for a moment to emphasize that this is **not** a criticism of the University Nanosat Program. If we take away the four UNP manifests in this century (2001-2012) we are left with exactly **zero** ESPA-class launches of satellites built by American universities not named the U.S. Air Force Academy or U.S. Naval Academy. (Those academies have their own path to the SERB list.) UNP is the only agency supporting non-academy ESPA-class university missions. Just as importantly, UNP support came at a crucial time; the JAWSAT launch of 2000 resulted in the on-orbit failure of six of seven university spacecraft, and government/industry support for university-class missions was understandably low. Without UNP, it is arguable that student-built missions in the U.S. would have stopped (or ate least paused) with the Sapphire launch of 2001.

Still, in the author's opinion, the launch interface which rescued UNP-class missions (the ESPA ring) has inadvertently prevented more schools from completing and flying their missions. There are two related reasons. First, ESPA launches are still expensive, and therefore rare. University-built spacecraft are competing against professional programs for these limited launch slots. Second, and most significantly, 50 kg is just enough mass for students to create spacecraft that are too complex and/or expensive for those same students to build and test. This is especially true for the smaller schools.

CUBESATS and ELANA

Enter CubeSats. At the risk of repeating an oft-told story: in 2000, Professors Bob Twiggs of Stanford and Jordi Puig-Suari of Cal Poly defined a new set of standards to integrate & fly very small student-built spacecraft. The CubeSat standard was to enable three 10x10x10 cm cubes to fit into a single spring-actuated ejector system; the intent was to define a spacecraft size and mission scope such that students could build and fly a spacecraft within their academic lifetimes. Standard sizes and performance specifications were also intended to encourage collaboration among schools. The first CubeSats were launched in 2003, and eight years later (a blink of the eye in aerospace time), more than seventy have flown. The CubeSat/P-POD system had an early competitor (the DoD SSPL ejector) and several imitators (Canada's X-POD, Japan's T-POD and J-PODs, etc). The P-POD has been has been flight-qualified for every operational U.S. launch vehicle. While the majority of CubeSat-class spacecraft have been university-built, CubeSats have been built and/or sponsored by a range of government organizations, beginning with The Aerospace Corporation and spanning the Army, Naval Research Laboratory and the Air Force, NASA Ames, Goddard and Johnson Space Centers, and the Jet Propulsion Laboratory. Both Boeing & Northrup Grumman have flown CubeSats, and Lockheed Martin is sponsoring a university-developed CubeSat.

The standard CubeSat is 10x10x11 cm, called a 1U; a single P-POD can carry 3 1U CubeSats (Figure 1 and Figure 2), though often a single 3U CubeSat fills an entire P-POD. Depending on the customer and contract, the standard price for a US CubeSat launch is between $250k-$500k. University-built CubeSats are developed for far less than the launch costs, while the industry-built CubeSats might cost between 3 and 5 times the launch cost.

CubeSats were not always so popular. In 2006, then-Administrator Mike Griffin stood up at the Smallsat conference and told the students in the audience that it was not NASA's job to broker launches for their spacecraft; instead of pursuing these university-class missions, they should be pursuing internships in industry (which was the only place to get real experience).[5] In a stunning reversal, NASA announced in 2010 that it would sponsor the flight of a dozen university and government CubeSats under the

ELaNa program. It followed up that announcement with the selection of twenty more CubeSat missions in 2011 and thirty-three more in 2012. Of those 65 missions, 49 are led by universities.

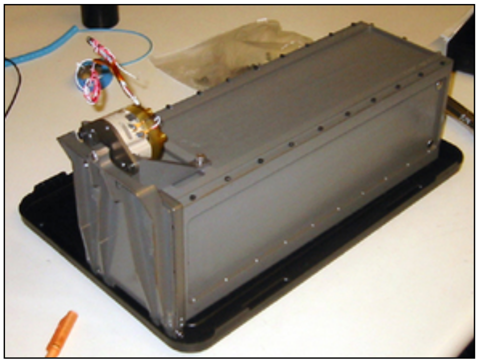

Figure 1: P-POD Ejector (Mk II) [courtesy www.cubesat.org]

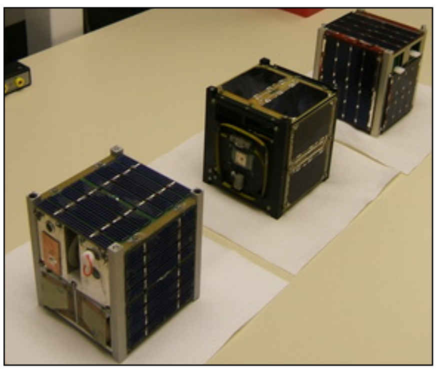

Figure 2: Typical CubeSats awaiting flight integration [courtesy www.cubesat.org]

Of course, the stunning changes that have created a favorable environment for university CubeSats could just as easily be reversed, especially if the current batch of University CubeSats fail to achieve their missions. Early results are a cause for concern: of the first eight ELaNa CubeSats, three did not reach orbit (through no fault of their own), and two more did not achieve their mission objectives (COVE/MCubed and AubieSat). Of the three that worked, one was a reflight of an earlier mission (RAX), and all three were the products of PIs with significant UNP experience (Michigan, Utah State and Montana State).

By design, ELaNa provides launch support, not mission assurance. (They certainly do not have the budget or personnel available to do that.) But the history of CubeSats does not instill confidence: worldwide, at least half of the 48 student built CubeSats that reached orbit have failed to meet their mission objectives. In the author's opinion, universities need help defining and completing more reliable missions. This is to be expected, of course; if it were easy to develop capable, reliable space missions, then there would be no reason for students to need training!

Coincidence?

Returning to Table 1, we note that six UNP entries have been selected by NASA for launch, including the 3rd-place NS-6 finisher (Hawaii) and four entries that haven't yet finished the NS-7 competition. In addition, three of the four represented schools are among the smallest in UNP (engineering enrollments below 1000). The time to launch is also shrinking: 3-4 years for the Nanosat-6 CubeSats, and potentially 2-3 years for the Nanosat-7 CubeSats.

More than a coincidence, we believe that this approach is a blueprint for flying more capable, reliable student-built spacecraft.

- With improvements in standardized components, it is now possible to create credible science and engineering missions on a CubeSat form factor. The standard parts and constrained CubeSat envelope make it possible for students to build & integrate a spacecraft in 12-18 months.
- Students who participate in the UNP cycle receive crucial systems engineering oversight and a template for managing the requirements and verification process.
- By sponsoring so many CubeSat flights, NASA has made it possible for a student mission to fly in 18-24 months (or potentially less).

SSRL has two of those CubeSat flights. In the rest of the paper, we will focus on the second mission (Argus), because it better captures the UNP-NASA synergy on a real-world-relevant science mission. We begin with the science justification.

MISSION: RADIATION-EFFECTS MODELING

Qualification of advanced integrated circuits (ICs) for spaceflight applications is one of the most significant challenges faced by spacecraft designers. Historically, radiation effects on ICs are determined using ground-based radiation sources;[6,7] response models are developed from those data and are used to predict the effects of space radiation exposure.[8] This analysis is becoming more and more difficult to implement for several reasons, including:

1. The details of the ground test and modeling techniques used by most engineers were developed in the 1980s based on assumptions appropriate for technologies of the time. Recently these techniques have failed to provide accurate reliability and survivability estimates for modern technologies, e.g., Figure 3, yielding predictions that could overestimate or underestimate on-orbit error rates by orders of magnitude.[6,11-18] This problem is not restricted to a single radiation environment or device, as shown in Figures 4-6.

2. Because of increases in IC complexity, ground-based radiation tests of modern ICs are very costly and often result in very limited information about the reliability and survivability of a component.[9,10] For example, in Ref. 9, the NASA author stated that a complete heavy

ion single event effects (SEEs) test on a modern memory would take more than 40 days per mode; this device had more than 68 different modes. This type of test requires an unrealistic 7.6 years to perform, and incurs a cost of >$46M just for the radiation source. The conclusion from Ref 9. is that exhaustive ground-based radiation-effects testing of modern complex ICs is simply not possible. Engineers are forced to design mission-specific radiation tests, in order to reduce the test matrix and costs dramatically. Radiation effects tests using the smaller test matrix still take months to execute and cost on the order of $400,000,[9] and importantly they are less rigorous. Thus, the mission assumes risk that can't be completely quantified.

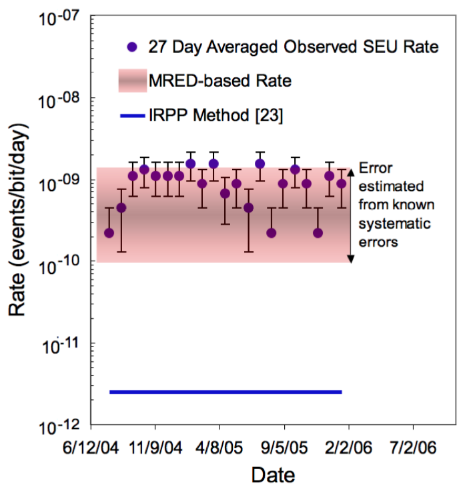

Figure 3: Comparison of predicted, observed and adjusted SEU rates for the MESSENGER mission[12]

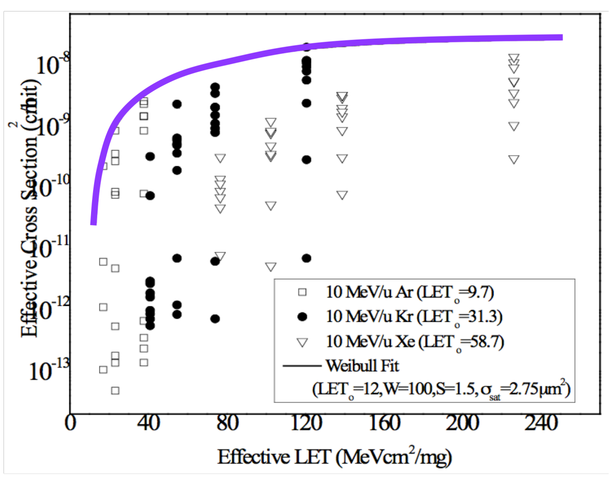

Figure 4: Comparison of Predicted and Observed Heavy Ion Effects for a 90 nm DICE latch[13]

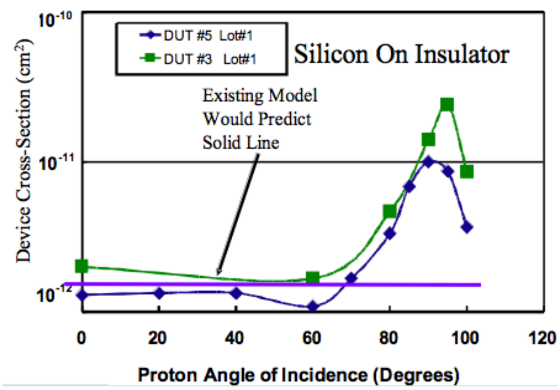

Figure 5: Proton Effects in SOI-Based Memories[14]

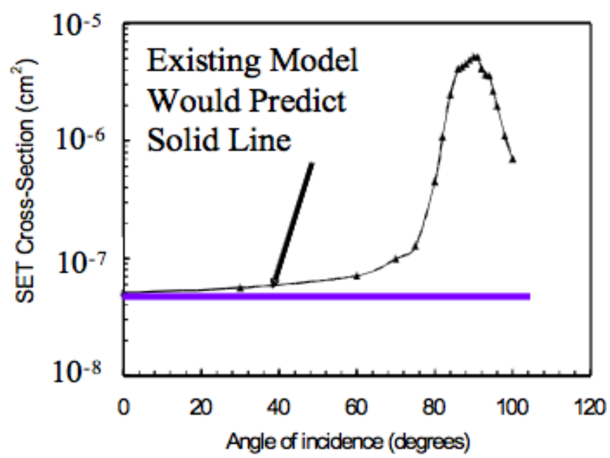

Figure 6. Comparison of Predicted and Observed Results for Optocouplers and Optical Links[19]

Available Modeling: MRED

Vanderbilt's Monte Carlo Radiative Energy Deposition (MRED) software is a custom radiation-transport code developed at ISDE based on the Geant4 libraries.[20,21] The code is comprehensive in its treatment of all forms of radiation interacting with materials and is designed to be a flexible and linguistically consistent initial-condition generator that interfaces to programs that handle related tasks such as charge transport, charge collection, and the analysis of circuit-level radiation effects. MRED is calibrated to data and has a proven record of predicting both terrestrial and space experimental radiation results.

MRED simulations will be used to predict energy deposition rates for the CubeSat orbits, which can be used to determine the soft error rate of the devices under test. MRED supplies the underlying computational engine for CRÈME-MC, a web-based tool in development for general use by the radiation effects community. CRÈME-MC provides additional capability over simpler tools like CREME86 and CREME96 (circa 1986 and 1996, respectively).

CREME96 is built upon analytical expressions to predict the failure rate of circuits, and our research has uncovered a number of classes where these analytical expressions do not apply but the Monte Carlo approach of MRED produces excellent results.[11-14,16,17] Validation of MRED computations is a key objective of the proposed flight campaign.

Argus Spaceflight Objectives

The cost of a university-built CubeSat mission is on the order of the cost of modern, limited ground-based radiation testing. Therefore, space-based experimentation could be an effective complement to ground testing. SSRL and ISDE propose to validate this hypothesis through the Argus flight campaign.

In the long run, ISDE will perform space qualification of certain modern ICs using CubeSat-scale flight experiments. However, the objective of the first set of space flights is to validate the new radiation-effects models developed at ISDE. An assortment of modern devices will be operated in space, these devices will be monitored for single-event effects (SEEs). When SEEs occur, the event information will be stored on-board for later relay to the ground.

Again, the purpose of the Argus campaign is to improve the ***modeling*** of the effects of radiation on space electronics, not to perform ***space-qualification*** for any specific modern device. Therefore, in many instances, "radiation-soft" devices will be flown in order to increase the anticipated event rates and thus the amount of data available for analysis. (Space-qualification is a long-term objective of ISDE, and may be incorporated into later missions.)

ISDE has two payloads in development, corresponding to the first two flights in the Argus campaign. These payloads are representative of the types of systems ISDE will fly.

Commodore– The Commodore payload has been rapidly developed in response to a near-term flight opportunity (COPPER, below). The main purpose of Commodore is to flight-test the bus interface, storage and monitoring electronics that will form the template for ISDE Argus payloads. Commodore is a very small printed circuit board (roughly 40 mm by 80 mm useful area) with two main features: the experiment-management electronics and the experiments themselves. The experiment manager is the interface between the spacecraft bus and the experiments; it performs all payload operations and responds to bus commands. The manager monitors all experiments and captures event data locally.

The Commodore experiment is a set of SRAM memory devices, nominally below 20 nm scale; the memory will be written in a known matter, and then the state of memory will be periodically polled to look for events. As events occur, they will be time-tagged and stored locally.

The Commodore manager interacts with the COPPER CPU via the standard I^2C protocol. The COPPER bus has the ability to activate or deactivate Commodore for power management purposes; similarly, it can adjust the duty cycle of memory monitoring and other operations. When over a ground station, the CPU will retrieve science data from Commodore and downlink.

The COPPER mission orbit is 500 km, circular; events (i.e., single-event upsets) are predicted to occur on the order of a few per day. Over the 180 day mission, this is not expected to generate statistically-significant data.

Independence– As noted above, Independence is the template for the Argus campaign. The first Independence experiment is the primary payload for Argus-High (below), with a nominal summer 2013 delivery date. The electrical, mechanical and data interfaces developed for Commodore will be used for Independence, updated as flight results for Commodore are received. The experiment manager will also be the same, but expanded to manage multiple experiments. The most significant upgrade from Commodore to Independence is volume; the Independence module fills the interior of a 1U volume using the standard CubeSat Kit mechanical attachments and electrical sockets.

The Independence experiments are open-ended; by specifying the experiment manager and routing all interfaces through it, the ISDE team has maximum flexibility to design its science experiments as well as maximizing the ability to fly Independence-class payloads on other spacecraft. For Argus-High, ISDE will fly a repeat of the Commodore SRAM experiment and an experiment to study the effects of tungsten on the radiation event rates for diodes. (Tungsten may be responsible for the increased failure rates seen on the MESSENGER spacecraft.[12]) Additional payloads will be developed in the coming year.

ARGUS OVERVIEW

As noted above, Argus is envisioned as more than one or two flights; rather, it is to be a ***sustained campaign*** of space experiments spanning many years and many launches. This campaign will involve ISDE instruments flying on multiple platforms, including SSRL spacecraft. The approach to the architecture and design of the Argus campaign is discussed in detail in Ref 22; this paper will highlight the specific design of the first Argus spacecraft.

Concept of Operations

Argus starts with a very simple operations concept. The radiation-effects modeling experiments operate continuously and require neither active pointing nor real-time monitoring from the ground. Science data is generated only when an event occurs; depending on the devices being tested, there may be minutes to hours to days between events. Therefore, the data collection requirements are very modest, and there are no time-critical events; it is sufficient that on-board science data "eventually" be relayed to the ground.

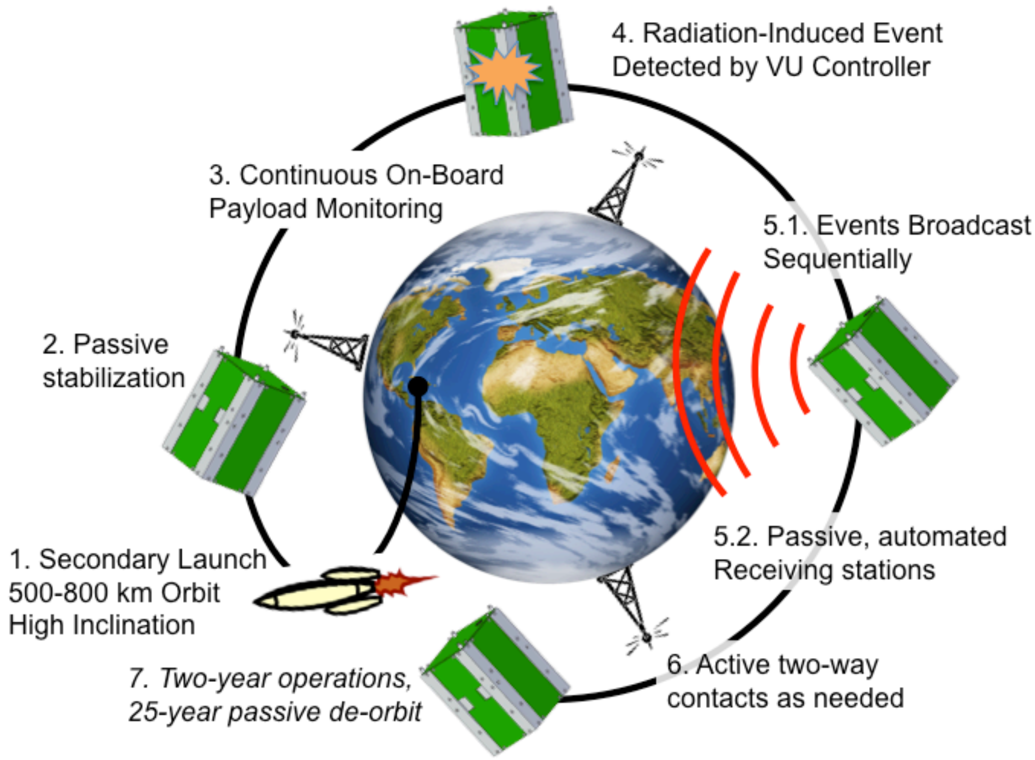

Figure 7. Argus Concept of Operations

As shown in Figure 7, Argus will be operated as an automated remote-monitoring station. It will be launched as a secondary on any available launch meeting the science orbit profile (typically, above 550km with inclinations consistent with the ground station network). The spacecraft will be ejected from the P-POD canister and immediately enter safe mode. Once mission control makes contact with the spacecraft and verifies nominal operations, the mission will immediately enter science mode; the payloads will be activated and monitored for radiation events. Argus is not stabilized and is powered via body-mounted solar arrays.

Science mission data consists of the time-tagged radiation event logs: the details of the event plus a state-of-health snapshot (e.g., attitude, thermal state, power consumption); the total data capture for an event is on the order of one kilobit, with an expectation of only a handful of events per day. Additional engineering housekeeping data will be on the same order of magnitude.

Argus is designed to be as automated as possible. On-board telemetry monitoring will respond to threatening conditions such as low battery voltage by entering safe mode and notifying ground operations via the beacon network. In reality, there are so few components on Argus that “safe mode” consists of deactivating the payload, changing the beacon message to indicate an on-board problem, and awaiting instructions from the ground. In addition, hardware will be designed with latch-up protection and software will include error detection and correction capabilities.

A distributed network of near-omnidirectional receive-only ground stations will be utilized to capture mission data. The stations automatically tune to the appropriate frequency to monitor Argus as it flies overhead. All received data is logged and automatically relayed over the internet to mission control.

The timing of beacon broadcasts, the size of the buffer and other communication parameters will be adjustable on-orbit, and thus the architecture can be adjusted based on actual event rates and ground station distribution. It is anticipated that the first Argus will be actively contacted by mission control on a regular basis, helping to establish the baseline performance for future missions.

Argus will continue in science mode until it de-orbits or components fail. The mission will generate relevant science data as long as Argus is capable of collecting radiation-induced event data. As for de-orbiting, current NASA policy for CubeSat debris management is to release the spacecraft into low-perigee elliptical orbits (e.g., 300 x 1000 km) to limit orbit life to a few years without the need for drag mechanisms. This is the expected approach with Argus.

Design Drivers

Other than the mission scope and the communications architecture, discussed above, the key mission drivers are: launch availability, the production process, and radiation hardening. Though not strictly a design driver, the need for educational relevance in the Argus campaign strongly influences the manner in which the campaign is approached.

System reliability is **not** a design driver, given the low-power, passive nature of the spacecraft. More importantly, with potentially a dozen or more spacecraft to be flown the design team has opted for spacecraft-level redundancy rather than subsystem-level redundancy.

Launch Providers

Each Argus vehicle is scoped to fly as a secondary payload; the CubeSat standard was selected as the baseline to maximize the possible launches. The CubeSat standard brings additional benefits in terms of affordable COTS hardware and design constraints. Perhaps paradoxically, the constraints enforced by the CubeSat standard (e.g., no propulsion, very restricted volume) actual improve a student team's ability to field a capable flight-ready spacecraft; these constraints create reasonable expectations of system performance and, more importantly, prevent students from seeking out expensive, hard-to-manage solutions (e.g., propulsion and three-axis attitude control). Missions that meet the CubeSat scope are inherently easier to accomplish by student teams.

Production

Argus is being developed on a very aggressive schedule given that neither SSRL nor ISDE have flown a spacecraft before; how is it possible for the SSRL/ISDE team to be flight-ready in 20 months? First, scope is managed to enable very simple spacecraft to perform a very relevant mission. Second, interfaces are managed through very specific, limited interfaces between the payload and spacecraft; this limitation further manages scope and simplifies the design responsibilities on each side of the interface. Third, COPPER and Argus, use common practices for design, analysis, integration and test for subsequent student teams to follow, including the SLU Core Bus discussed in the next section.

Finally, we anticipate that this rapid production rate will improve an essential quality in student projects: ownership. On a short-duration project where students know that they will get to see their "own" spacecraft fly during their academic career, we anticipate that they will be far more willing to volunteer long hours and weekends to complete the project.

Radiation Effects Management

Argus is concerned with the effects of radiation on space electronics. Thus, the radiation-hardness of the spacecraft bus and science monitoring devices is of great importance; radiation science events could be obscured (or lost) due to radiation events occurring on the rest of the spacecraft!

The primary solution to this driver is through decoupling of the payload and bus. Event monitoring and data logging functions will reside on the payload itself; ISDE will use its knowledge of best practices in radiation-hardening in the design of the payload, and the payload-monitoring hardware will be built of older, known-to-be-radiation-hardened devices. Furthermore, the devices tested in Independence will be intentionally "soft" (i.e., expected to experience events at much higher rates than standard space systems). Thus, the science data will be protected to the greatest extent possible on-board the satellite.

Events on the bus may happen at a higher rate than science events. Latchup protection will be implemented, as will error-detection and correction for software. Still, provided that the radiation events are recoverable, the "soft" electronics on the spacecraft bus will be a potential annoyance, but will not be threatening to the mission.

Educational Relevance

The use of students as semi-skilled, unpaid labor has limited benefits as a labor solution. There needs to be an educational benefit to their efforts. In addition, there is a concern that a mass-produced spacecraft will cause students to miss the important educational benefits that come from practicing top-down requirements-driven systems engineering.

Yes, students involved in a mass-produced spacecraft program will have a diminished ability to perform the initial design steps. On the other hand, of the few schools that have a good top-down requirements-driven systems engineering program, most of them never complete their spacecraft, and thus never reach the fabrication, integration & test (I&T), launch and operations phases. Those that do reach those phases do so after many years, which means that the original design students graduate before I&T, and the I&T students weren't in school to do the design. In other words, every student misses some part of the design lifecycle, even in the "good" systems engineering programs.

The Argus team has decided that the lessons that students can learn from fabrication, I&T, launch and operations are worth the tradeoff of a less-outstanding requirements flowdown experience. If nothing else, requirements flowdown is covered in the students' capstone engineering class and, where possible, we will use the excess capacity in our 2U (Argus-High mission) and the senior design class to improve system performance and/or fly additional payloads. In addition, as SLU grows its graduate program, SSRL masters students will work with the teams to maintain continuity across the projects and over several years.

THE SLU CORE BUS

In order to complete two spacecraft in the next 18 months, SSRL has identified a core set of tightly-integrated subsystem components that provide sufficient performance for a range of missions. While this decision results in a "suboptimal" design with regards to the spacecraft bus meeting specific mission needs, it is a highly-optimized design with regards to achieving mission goals within the extremely constrained cost, schedule and personnel budgets at SSRL! The Core Bus is common to both COPPER and Argus.

The backbone of the SLU Core Bus is the modified PC-104 header definition used by the Pumpkin CubeSat Kit family of processors and the Clyde Space Electrical Power systems. The header sockets form the "wire harness" for the entire spacecraft. The communications components as well as the payloads are designed to plug directly into the sockets, making all devices instantly pin-compatible with one another.

For command & data handling, the Core Bus uses the CubeSat Kit PIC24-based processor with Pumpkin's SALVO real-time operating system. The electrical power system and lithium-ion battery are the 1U EPS system from Clyde Space. Student-built body-mounted solar panels, use two Spectrolab triple-junction cells per 1U panel.

The Core Bus communications architecture is based on NASA's GeneSat/PharmaSat approach: the MHX2420 series S-Band frequency-hopping transceiver and UHF Amateur radio packet beacon. Primary ground communications are via a dedicated station at SSRL, with automated receive-only stations to be distributed around the country.

The Core Bus occupies slightly less than 0.5U of height and 400 grams (not counting the structure). It consumes less than 1 W average power (much lower if the MHX2420 is power-cycled).

COPPER (NS-6 ENTRY, Commodore Payload)
The Close-Orbiting Propellant Plume Elemental Recognition (COPPER) mission is a 1U CubeSat (Figure 8). COPPER is SLU's first student-built spacecraft with 1.5 W nominal average daily power and mass 1300 grams. The launch is part of NASA's ELaNa-IV CubeSat flight on a Minotaur-1 in August 2013. COPPER utilizes the Core Bus and the Commodore payload as described above.

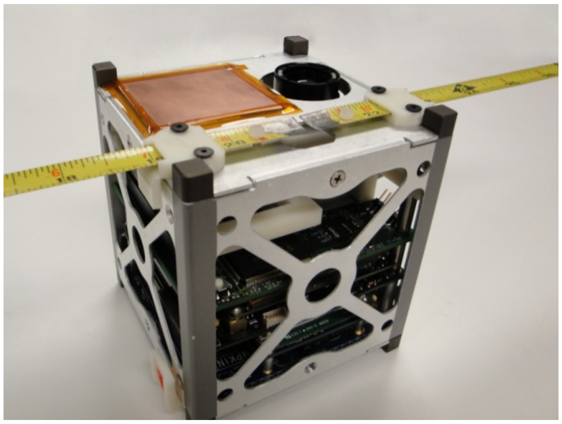

Figure 8. The COPPER Engineering Model

The primary instrument is the FLIR Tau, a compact uncooled microbolometer array sensitive in the 7-13 micron band. This will be the first orbital flight of the Tau. In addition to characterizing the Tau's performance for Earth observation, we are interested in using the Tau to observe the separation sequence from the launch vehicle. We believe that the Tau will capture evidence of thruster plume firing as the plumes interact with the plasma bubble around the vehicles[23].

Argus (NS-7 Entry, Independence Payload)
Argus is the second spacecraft in development at SSRL, carrying the Independence payload on a 2-year mission. As shown in Figure 9, the spacecraft is a very simple single-string system. It is nominally a 2U CubeSat, with approximately 0.5 U devoted to the spacecraft bus and the remainder to payload. It may be possible to reduce the entire spacecraft to the 1U form-factor; the 2U size was selected for the first Argus spacecraft in order to reduce development time and maximize the power, mass and volume available for the Independence payload. Future work will consider ways to reduce the volume to the 1U form-factor. Argus-High is intended to provide 3 W average daily power and have a total mass of 2.67 kg.

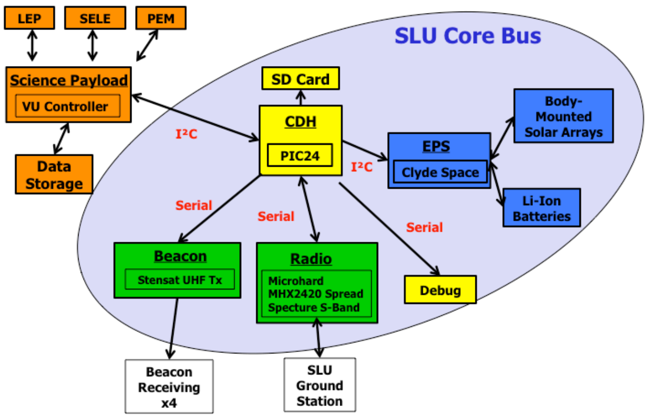

Figure 9. Argus Block Diagram

Argus development began in January 2011 under the University Nanosat-7 competition. Payload development began in September 2011; the Core Bus will be integrated with a functional version of the payload in Fall 2012, and flight integration will take place in February 2013.

SUMMARY

Argus meets an important need in the space industry: improving our understanding of the effects of radiation on space electronics. Because of CubeSats and their many opportunities for low-cost launch, it is now possible to consider serial spaceflight experimentation in the same way that we think of aircraft flight testing or repeated balloon experimentation. Argus is one such concept, depending on reflights of radiation-effects modeling experiments to advance scientific understanding in the field.

Argus is a mission concept that takes advantage of the CubeSat standard in two important ways: simple, cost-effective spacecraft and extremely short development cycles. The severe constraints imposed by the CubeSat standard are the very things that make it possible for small schools to build and fly spacecraft.

Argus benefits greatly from the complementary activities of the AFRL University Nanosat Program and the NASA ELaNa program. ELaNa provides launch opportunities for many more schools than can be supported by the UNP launch tempo, and UNP provides participating schools with a level of systems engineering overview and mission assurance reviews that can improve on-orbit reliability. As noted above, we believe that 50 kg is too much spacecraft for most universities to build – certainly within the time constraints of a student's college career.

Of course, we can only offer opinions on these subjects at the moment. The UNP/ELaNa combination has achieved the manifest of six UNP-sponsored missions in a very short period of time, but the actual results of those selected missions will have to wait until next year's conference to evaluate.

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