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CubeSat Lessons Learned: Two Launch Failures Followed by One Mission Success
(Subtitle: What can go wrong will go wrong.)

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ABSTRACT

Montana State University's small satellite team just keeps on learning and keeps getting better through experiences gained and through careful attention paid to lessons learned. After all, that is a fundamental goal of experiential training. The Space Science and Engineering Laboratory at Montana State University engages university undergraduate students in the design, production, testing, and flight operations of spaceflight systems as a highly effective hands-on training methodology for the next generation of space researchers. Additionally the program seeks to demonstrate the utility of, and to advance the application of very small satellites for space research.

Both through launch failures (two in succession); and through mission success, we continually add to our institutional list of lessons learned. These lessons learned are by no means unique to our program, which means that others may benefit from our experiences. Launch failures are outside the control of the satellite developer but even then there are lessons to be learned. Even in success there are lessons to be learned. This paper describes how the Montana State program small satellite program has capitalized on lessons learned to further the educational advancement of tomorrow's space scientists and space engineers and to further the technological capabilities of very small satellites for application to space research.

PROGRAM INTRODUCTION

The Montana State University (MSU) initiated a space research program in 1992 with research focused on the dynamic Sun to understand the physics of the sun's upper atmosphere and its corona. In late 2000 the Space Science and Engineering Laboratory (SSEL) was founded at MSU to complement the solar and space physics research program by providing the additional capability to build space flight hardware in Montana, both to support solar and space physics research and to train the next generation of space scientists and space engineers. While having experienced our share of the same trials and tribulations that not uncommon for any start-up venture the Laboratory has successfully met its founding goals. The SSEL's students and staff are designing, building, testing, and flying space flight hardware. The Laboratory has involved hundreds of students at both the undergraduate and graduate levels in the development of space flight hardware, launching many of these students into challenging and exciting careers in the aerospace industry. We have built and delivered active instrument packages that Shuttle astronauts mounted to the external payload carrier on ISS's Columbus Module, and subsequently retrieved and returned to Earth after months of space exposure; and we have been operating our own free flying satellite on orbit since October 2011 from our satellite tracking station on campus.

Our experience at developing and growing a space flight hardware development center within a mid-sized public university has led to many lessons learned that may be of value to others seeking to establish similar programs, whether within the university environment or within private industry.

This paper describes some of the many lessons learned that have accumulated over this first decade or so of the Space Science and Engineering Laboratory. There are lessons learned regarding the management approach of involving undergraduate students in this type of activity, there are lessons learned with respect to financing the laboratory, there have been regulatory lessons learned, and there have been many many technical lessons learned. Among the most difficult lessons to have learned are those that involve the same 'out-of-your-control' experiences that everyone in the 'space hardware business' has faced during their career. Together this accumulation of diverse experiences is what makes the graduates of the SSEL program such valued employees as they enter the aerospace industry or take employment in government laboratories following graduation.

Achieving the student training goal

The Space Science and Engineering Laboratory (SSEL) established at Montana State University in Bozeman, Montana in 2000 engages university undergraduate students in the design, production, testing, and flight operations of spaceflight systems as a highly effective hands-on training methodology for the next generation of space researchers. This active learning program prepares university students for immediate meaningful employment in high tech industries, with focus on spaceflight systems engineering and science. Collateral benefits of this experiential training program include undergraduate student enrollment retention for the University, and the positive public relations for the University that ensue following satellite launch and successful mission operations. Owing to their participation in the program, students make long-lasting career decisions early in their undergraduate studies. Strong pedagogic value of the program results from early application of formal classroom learning to real-life, exciting, and challenging scientific and engineering problems through active hands-on learning. This synergistic multiplication of formal classroom learning represents a huge advantage of the program as an adjunct to traditional undergraduate education. The evidence is simply that as a training methodology, it works.

Figure 1 shows MSU undergraduate student Rubin Meuchel at Montana State University performing integration and test of the Explorer-1 Prime CubeSat.

Several peripheral outcomes result in addressing the primary student training goal. By immersing higher education students in genuine career practice students decide early in their undergraduate tenure if their prospective career choice is personally right for them. The program succeeds even for those students who discover that they are not cut out for a career in the aerospace discipline. For these students, this early discovery occurs at a time when they still have the flexibility to change academic majors before investing too heavily in an education that is not right for them. In contrast, for those students who find the involvement motivating and exciting, their career skills grow at tremendous speed as they are continually challenged by the application environment. These students often learn fundamental STEM (Science, Technology, Engineering, and Mathematics) skills before they are encountered in the formal classroom. The active learning process is enhanced by the student's frustration of having encountered a technical challenge in the laboratory without having the technical knowledge to address the problem. Later, when the underlying technical concept is presented in the classroom, the student immediately grasps its importance. This preconditioning for learning greatly enhances the student's intellectual advancement.

For the students in the SSEL at Montana State the program is operated as an extracurricular activity that takes participating students beyond the traditional academic track pursued by all students. Student participants do not receive traditional formal classroom training within the program. Instead, the program augments formal classroom instruction, often through preconditioning, as described above, and through immediate application of newly-learned classroom skills by providing genuine problems to be solved, thus reinforcing the newly gained knowledge. In this environment students more readily grasp the importance of the academic concepts being presented in the classroom. Additionally, under the guidance of professional mentors, students are exposed to, and put to practice, the formal processes and procedures required to build successful space flight hardware. Such aerospace industry procedures and practices include the development of appropriate documentation, the use of configuration management and control procedures for engineering changes, hardware travelers, formal design reviews, and formal written procedures for assembly, integration, and test of hardware. This discipline-specific training is essential in head-starting the students' careers in the space industry.

Because the program is voluntary the students that become involved have a very high level of self-motivation – students become involved primarily because they have a strong desire to engage in this type of activity. Most of our students had not predetermined that they might make a career of aerospace engineering or space science before entering the program; but most have had some long lasting interest in, or fascination with space. The vast majority of participants at Montana State University discover this program during their undergraduate tenure after they have arrived on campus, and only then do they begin to envision the reality of a career that connects with an enduring childhood interest. Since the institution does not offer a degree-level program in aerospace science or aerospace engineering, students who enroll at Montana State University are not those who have selected aerospace as a career during or before high school. This program thus puts college and university students on aerospace career tracks after formal programs at the K-12 precollege level have failed to reach them. The author believes that the heavy investment in government-sponsored programs that seek to entice youngsters at the elementary and secondary education levels into science and engineering programs, an investment that essentially ends at the high school level in the United States, is not as effective as would be a more balanced approach that would continue the enticement to the collegiate level where most students make their final and lasting career choices. See Figure 2.

Figure 2: Keith Mashburn an MSU SSEL Physics graduate is shown putting final touches on the Explorer-1 [Prime] CubeSat.

There are no formal requirements for admittance into the SSEL program. Most undergraduate students are initially brought into the program as unpaid interns. These are strictly volunteer positions where the students are exposed to the activities taking place in the lab. The new volunteers are invited to student-led project meetings where they learn about the projects being conducted by the other students. They are encouraged to get involved in an activity that interests them and are given every encouragement to become involved. Interns are given open access to the laboratories. (side note: since satellites are governed by US government International Traffic in Arms (ITAR) regulations, and technical data related to satellites and satellite design is export controlled, only US citizen are taken into the program). The volunteer internship program serves multiple purposes. Firstly it gives the student an opportunity to discover if their desire to be involved in the aerospace industry is durable once they are able to see what the work involves. Secondly, the internship period provides the opportunity for the student to learn the language and become familiar with the terminology. During this period SSEL faculty and staff are becoming familiar with the individual student's capabilities and assessing their potential placement within the program. Following the internship the students who continue with the program are most frequently hired for hourly pay. For those students who need to work part time during their schooling, working in the SSEL is more relevant to their career aspirations than menial employment off-campus.

Students have other means of remuneration. Academic credits are available to those students who wish to enroll in an academic department for undergraduate research. Such students undertake independent research projects that require scholarly research and independent study. The students meet periodically with their mentor for guidance. Monthly progress reports are submitted each month, and a final project report is due at the end of the semester. The student may also be required to present an oral project summary. One to three academic credits may be earned through such an independent research activity. Students who are being paid hourly are eligible to enroll in independent study, but their academic project must clearly distinct and separate from the activity undertaken for pay.

Another avenue for students to receive academic credit under SSEL involvement is by participating in SSEL-sponsored senior design projects. Three to four students, usually forth or fifth year engineering students, engage in a project that has been defined by, and is sponsored by SSEL. The student is enrolled in the formal senior design course offered by the academic department of the college. During the two-semesters of senior design, while working to an SSEL specified requirements document, the students first design, then build, and finally demonstrate the functionality of their project under close supervision of their faculty advisors and SSEL engineering staff.

A strong goal of the SSEL active learning program is that individual students become engaged over the course of two years, or more. No one or two-semester course can offer the depth and breadth of training that SSEL students achieve by being durably involved during much of their undergraduate tenure. One additional outcome of the undergraduate experiential program is the relatively high number of program graduates who enroll in graduate school and receive advanced degrees. Many of the program participants make the graduate school decision only after having been involved for a significant amount of time as an undergraduate in the program. This long-term involvement by individual students has many benefits, including enhanced peer-to-peer knowledge transfer.

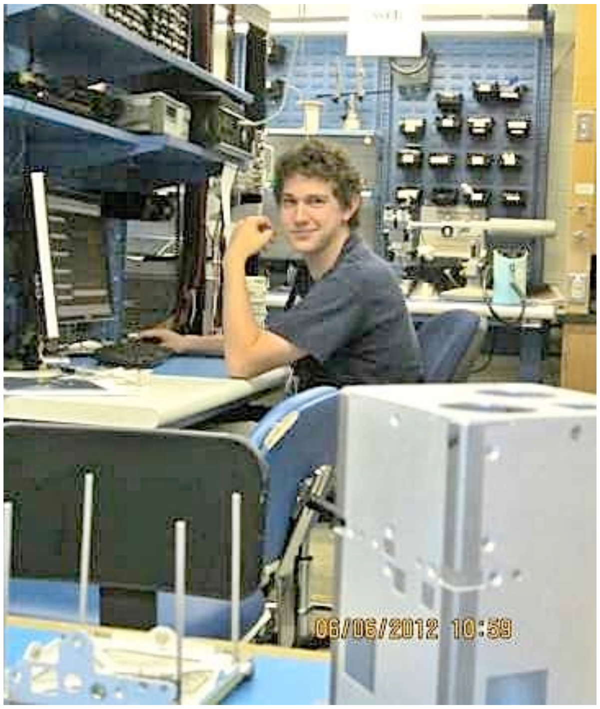

Figure 3. Sophomore SSEL student Matthew Handley takes a break while developing software for MSU's FIREBIRD mission. A FIREBIRD satellite structure is in the foreground.

Peer-to-peer learning is a very important characteristic of the program that enriches the training of all students. Students who have participated in the program over a period of time, and have learned many of the requisite skills are put in the position of transferring their knowledge to the newer participants. The double benefits of this peer-to-peer knowledge transfer is that the new students absorb knowledge and learn the practices more quickly through this interaction, and the more experienced student reinforces his or her knowledge through the opportunity to impart it to others, and acquires leadership and management skills in the process. An additional benefit of this peer-to-peer active learning setting is that a relatively small professional staff of mentors can manage larger numbers of students. The more experienced students include both undergraduates who have been in the program for one to three years, or graduate students who have come up through the program as undergrads and are pursuing an advanced degree.

Achieving the technical goals

What kinds of space science and engineering activities are undertaken?

The most desirable kinds of technical activities are those that present thought-provoking engineering challenges, typically involving numerous interacting and interdependent subsystems, thus requiring the application of systems-level engineering for their successful completion. Additionally, the projects chosen for development invariably involve several of the traditional engineering disciplines as well as computer science, mathematics and physical or biological sciences requiring the student development team members to bring their individual skills together in an interdisciplinary working environment in order to reach closure. As a result every member of the team, in fact, has a valued contribution to make and achieves ownership in the result.

It is absolutely essential that ultimately each project leads to hardware development and a flight opportunity, because the rigorous discipline required to test the product through space flight qualification and to demonstrate robustness to operate in the flight environment is a huge element of the active learning process. The author believes that this is one of the key features that distinguishes Montana's Space Science and Engineering Laboratory program from so many others that conclude with only a paper design study and a formal presentation. Educational programs that end following design, without implementing the design in hardware, seriously short change the participants by giving them a false sense of accomplishment. It has been the author's experience that most initial student designs, when actually implemented in hardware, fail to achieve their technical objectives. It is clear to this writer that the real learning takes place only after the student is forced to reexamine his or her design, implement modifications, often multiple times, and finally demonstrate the robustness of the hardware against failure while operating under the harsh conditions present in the space environment. The iterative cycle of design, build, test, rebuild, retest, and fly is where the true learning takes place.

The focus of the laboratory is on space science and space engineering. Thus virtually all projects involve space flight hardware development. While the laboratory has taken on a wide variety of space-related projects over the course of its 12-year existence, the design and development of small free-flyer satellites and their science payloads provide the ideal set of attributes for student hands-on training. Satellites present unique engineering challenges owing to the harsh conditions under which they must operate. They consist of a multiplicity of subsystems that encompass both digital and analog electronics, computer engineering, mechanical and thermal engineering, computer science, physics, and systems engineering, and project management skills. Rigorous design practices must be adhered to, and thorough testing in the simulated space environment is required to assure reliable operation. It is the author's strong conviction that the value to the student comes from his or her participation in the full cradle-to-grave process, including conception of the project, design, development, assembly, integration and test of the hardware in preparation for launch, and participation in on-orbit operations. Development of very small free flying satellites involves all of these attributes. They can readily be launched, as discussed below, and can be built and operated on a budget that is achievable within the university research environment. A particular enabler that has facilitated the ability to conduct small satellite development projects has been the worldwide acceptance of a standard small satellite form factor, the CubeSat, along with an accompanying orbital insertion system, the P-POD that can be (and has been) accommodated on most rocket launchers. See Figure 4.

Figure 4: Rendering of Montana State University's Explorer-1 [Prime] satellite as it might appear to an observer in space. Produced by a Montana State University undergraduate student.

CubeSats are one to 4.5 kg satellites that conform to a particular standard and are built to a controlled form factor [1]. The CubeSat shown in Figure 4, which is a rendering of Montana State University's Explorer-1 [Prime] CubeSat, has CubeSat-standard body dimensions of 10 x10 x 10 cm. Their common size and shape allows them to be carried into orbit within a launch dispenser that interfaces simply to almost any launch vehicle [2]. This standardization is the key in the availability of frequent launch opportunities. CubeSats are most often launched as secondary payloads on a space-available basis and almost always utilize a very small portion of the unused lift capacity available to the primary. While there is a well-defined CubeSat Design Specification (CDS) that controls the size and total mass, and requires a specific interface to the launch dispenser, the CDS levies few additional constraints on the satellite developer [1]. Thus the developer is given wide latitude to design and implement their individual CubeSat as they see fit. Within the student training environment the design and development freedom allowed by the CDS allows the student engineers ample opportunity for innovation.

The problem of finding launch opportunities for small student-built satellites is no longer the hurdle that it once was. In the United States , universities and other non-profits can apply to NASA for launch of CubeSats that fully comply with the CubeSat Design Standard. Under this Educational Launch of Nanosatellites (ELaNa) program CubeSats are being flown as secondary payloads on launches carrying NASA science missions. To date under the ELaNa Program nine CubeSats have been launched. Three university CubeSats, including Montana State University's Explorer-1 [Prime] were launched with NASA's Glory spacecraft on March 3, 2011. The launcher failed to place any of its satellites into orbit. The second ELaNa launch carried six CubeSats into orbit as secondary payloads on the Delta-II carrying NASA's Suomi NPP mission. Montana State's Hiscock Radiation Belt Explorer CubeSat is one of the six. In Europe, the recently developed Vega launcher has recently been used to launch university-built CubeSats. Seven CubeSats from European universities were launched on Vega's maiden flight from Kourou, French Guiana on February 12, 2012. Other CubeSats have been launched on the Dnepr from Kazakhastan, on the Indian PSLV, and by JAXA for Japanese universities.

In large part the increasing opportunities internationally for CubeSat launches is due to the acceptance of the P-POD CubeSat dispenser as a low risk secondary payload carrier that provides a high degree of protection to both the primary satellite and to the launch vehicle. The fact that it has been qualified on a large variety of launch vehicles attests to its ease of integration and its acceptance by launch vehicle providers.

LESSONS LEARNED

The following paragraphs discuss various experiences leading to lessons learned during the 12-year development of the SSEL. These include the unique challenges of managing a student workforce; developing a suitable level of document control; managing relationships both with local upper management and with federal and international rules and regulations; learning how to deal with and survive through deleterious experiences that are beyond your control. In addition there are uncountable technical lessons learned during the design, fabrication, and testing process of building spaceflight hardware that will not be described in this venue.

Managing a mobile and somewhat distracted workforce

Managing a student-based workforce requires a more tolerant and forgiving approach than managing paid professional employees. Despite many differences from industry, one management practice stands out owing to its similarity to professional circles. Each individual is treated with respect and is valued for what they can contribute. Each individual is treated as a professional peer, and each is tasked at a rather high level to produce results, and is not subjected to micro-management. All students and employees participate in frequent project wide meetings so that each individual has a good grasp of the top-level goals of the project, yet each person is expected to perform his/her tasks, and comes to realize that other members of the team are depending upon them, and that the success of the project depends upon the successful completion of a multitude of small tasks.

The program achieves its active learning goals by intimately involving the students in every aspect of the space systems development cycle and by empowering participating students with the authority to make programmatic and technical decisions that materially impact the outcome of the project. The operating principal here is that students must be given authority if they are to take ownership in the project. It is the act of taking ownership in the project that produces results.

Unique challenges arise in managing a student-based workforce. Students have many demands on their time including academic studies, classes, and a rich social calendar, leaving only limited time available for this extracurricular active learning activity. Individual students are not necessarily in the laboratory at the same time hindering the flow of information among team members. Studying for exams and preparation for other academic deadlines takes the student employees out of commission at irregular intervals, and sometimes for days at a time. Additionally the workforce is ephemeral; student tenure at the university is limited to four or five years at best. A student develops valuable skills and carries a wealth of project information in his or her head, and then graduates and disappears. Some participants discover that the type of work is not suited to them and leave after a few weeks or months in the lab. There is constant turnover in the workforce.

Solutions to these management challenges include doubling up students so that no one individual holds all of the knowledge on a particular subsystem. Requiring that each participant fully document trade studies, decisions, designs, and implementation decisions is even more critically important than in a more professional setting.

By experience we learned that it is essential to operate the laboratory on a year round basis. By employing the students over the summer months in a full time capacity we are able to make significantly more progress during the short three summer months than during the nine academic months. Nevertheless, having continuity throughout the calendar is also critical, even though technical progress is much slower during the academic terms.

Document management and document control lessons

The aerospace discipline and other high tech endeavors require a high level of document discipline. It is critically important that student trainees learn and adapt to this requirement right from the beginning. Students hate writing down what they have done. In the university environment described above, with the somewhat ephemeral nature of the participants, it is at least as important as anywhere else in the industry that rigorous documentation is performed. We have adopted documentation standards and procedures that parallel those in the industry as a whole, tailoring them to a level appropriate to the class of instruments and satellites we build.

Understanding and adhering to federal and international rules and regulations

Satellites and satellite-related hardware and related technical data are subject to export controls regulations in the United States. Additionally, RF transmissions to and from satellites are regulated by international agencies, and, in the U.S. by the Federal Communications Commission (FCC). Additionally U.S. law governs orbital debris and requires active orbital debris mitigation if a satellite is expected to remain in orbit 25 years after completion of its mission.

It is essential that all satellite developers, including university developers know the applicable rules and regulations and adhere to them. Owing to the international nature of radio frequency transmissions from satellites, multiple agencies are involved and the rules and regulations can be rather daunting to achieve full compliance among all of the agencies. This is normally a process that up to 12-months, or more, to complete.

Any deviation from the prescribed rules of the road can lead to serious consequences, which resulted in a strong lesson learned when a ruling came down that our satellite (and other secondaries) could not launch. It is October 2011, that spare satellite has been completely tested and qualified for spaceflight and now sits atop the venerable Delta-II launch vehicle, the vehicle is on the pad, your bird is a very tiny secondary payload accompanying a very big mission on a very large rocket, and it is three days before the scheduled launch. What do you do when you are emphatically told by a government agency that your satellite cannot fly because you haven't complied with international treaties by submitting all of the documentation to achieve full international compliance to transmit from space? You pay attention!

The result is a lesson learned in making sure you have followed all applicable rules and regulations and that you have all required approvals in place in timely fashion.

Lessons learned from events that are beyond your control including launch failures.

Things happen that are beyond your control. Get over it. Despite the fact that in the 53 years since the Explorer-1 launch in 1958, launch attempts have been made in the U.S. resulting in hundreds of satellites being placed into orbit; during that same period there have been many many launch failures resulting in the loss of satellites. Some launch vehicles have rung up success records numbering in the tens to even more than 100 consecutive launches. Delta-II for example has achieved a long string of successful launches (more than 150) and no failures since 1997. European, Japanese, Russian launchers have similar launch reliabilities. Nevertheless launch failures still occur.

What do you do when: you are in Kazakhstan standing in a scorpion-infested field watching the launch of your group's very first satellite, the one that your student team has sweated over for 5 years, the launch vehicle leaves the ground in a blinding flash and thunderously roars toward space, and 73 seconds into the flight the engine shuts down?

When we launched our first CubeSat, the Montana Earth Orbiting Pico Explorer (MEROPE), in July 2006 on the Dnepr launch vehicle that at the time had a success rate approaching 99% out of more than 100 launches, a launch failure was the last thing on our minds. We were wrong to have discounted that outcome! The countdown: "pyat', chetyre, tri, dva, a'deen, launch!!". The silo-launched rocket soared into the night sky. 73 seconds into first stage burn a malfunction, later attributed to a motor gimbal, caused the vehicle to veer off course, and shut down. The flash of light on the horizon a couple of minutes later confirmed our worst fears; our CubeSat (along with 17 other satellites) had ended up in Geosynchronous orbit at 1 Earth Radius. Pictures showing the resulting crater created in the Kazakhi desert were indeed impressive. Lesson learned: You learn to persevere, and you vow, "next time I'll build a spare".

Not to be deterred, the students who had built MEROPE picked themselves up, having learned two valuable lessons: 1) Don't take anything for granted. 2) build a flight spare of your satellite.

Almost five years later, March 2011. Now you have secured have a US-soil launch through NASA's Educational Launch of Nanosatellites Program (ELaNa). We are mounted atop Orbital's Taurus XL, sharing the ride into space with NASA's Orbiting Carbon Observatory (OCO). How could anything go wrong – after all both NASA and Orbital had scrubbed that rocket exhaustively after the previous launch attempt for NASA's Glory satellite had failed, because the nose fairing did not deploy. An interesting quirk of fate, here – we had initially been manifested to fly as a secondary payload on that Glory launch, but owing to the need to exercise extreme caution on what would be NASA's first launch of university-built secondary satellites, the schedule could not accommodate the three university CubeSats and we were remanifested on the OCO vehicle. What do you learn, this time, 5-years following that first launch failure, while standing on a concrete bleacher at Vandenburg, California watching your second satellite speed toward space atop a return-to-flight launch vehicle, while Launch Control calls out mission milestones, and then, after what seems like an eternity of silence, you hear over the PA "the vehicle is under performing"?

You recall the lesson of perseverance learned five years earlier, and you note that you are thankful that your team has built a spare.

What do you do when you finally reach orbit (the third time's the charm), your satellite deploys, autonomously (as planned) begins beaconing from orbit, and ham operators from Africa and then Europe announce receipt of strong telemetry. You jump with joy. Your satellite is operating perfectly, but then what do you do a couple of weeks later when one of the other satellite teams contacts you suggesting that your satellite is "very very close to theirs, so close that they may even be stuck together in orbit". You pay attention. This potential lesson learned is ongoing. Data from various sources seems consistent with the hypothesis that MSU's HRBE 1U CubeSats (described below) has become attached, in orbit, to the CubeSat that was launched adjacent to it in the P-POD. If, after all of the analysis is completed, this turns out to be the case it might mean that more attention is warranted when placing CubeSats containing permanent magnets into the P-POD. As will be described below the HRBE satellite continues to operate after more than seven months on orbit and shows no evidence of having a "close" companion.

THE WILLIAM A. HISCOCK RADIATION BELT EXPLORER

By example, the Hiscock Radiation Belt Explorer (HRBE) is SSEL's most recently launched satellite. HRBE was built in the SSEL between 2006 and 2011. It was one of two nearly-identical CubeSats measuring 10 x 10 x 10 cm designed and built at Montana State during this period whose scientific objective is to measure variations in the location and intensity of energetic trapped electrons in the high latitude horns of the Earth's Van Allen Radiation Belts. Figures 1 and 2 show students performing integration and test on Explorer-1 [Prime]. The satellites were built in two stages, first one, followed later by the second. Development began in the fall of 2006 following the loss of Montana's first CubeSat, The Montana Earth Orbiting Pico Explorer (MEROPE), in the July 2006 launch mishap when a Russian Dnepr, launched from Kazakhstan failed to place its 18 satellites into orbit. More than one hundred students at Montana State University were involved in the design and development of the two Explorer-1 [Prime] (E1P) CubeSats. During the first development stage, a single flight model was designed, built, tested, and eventually flight qualified in preparation for launch. The name of the satellites derives from the desire that their launch would commemorate the fiftieth anniversary of America's first satellite Explorer-1 launched on February 1, 1958. Explorer-1 made the first measurements that foretold the presence of intense zones of radiation durably trapped in the Earth's magnetic field now known as the Van Allen Radiation Belts. Those measurements were made with a simple Geiger-Mueller detector instrument prepared by James A Van Allen and his colleagues and students at the University of Iowa. The significance of the Montana implementations of Explorer-1 would be that a satellite built using today's technologies, primarily using commercial-off-the-shelf parts could be built in a fraction of the volume and a fraction of the mass of Explorer-1. E1P has 1/14th the mass of Explorer-1 and about 1/12th the volume. The additional significance of MEROPE and the Explorer-1 [Prime] satellites was that the bare Geiger Tube detectors at the heart of their payloads were spare Geiger counters donated to us by Dr. Van Allen; left-overs from the early days of space research that had been carefully stored in the back of a desk drawer for decades in Van Allen's office. Van Allen pointed out the age of the tubes and instructed us to perform diligent testing on them to assure their flight worthiness before we considered flying them. Reassuringly he noted, however, that similar Geiger tubes on Pioneer 10 had operated faithfully for over 30-years in deep space and were still operating during last contact with the spacecraft.

The first launch opportunity for E1P arose when in 2008 E1P was selected to proceed toward launch under the pilot program of NASA's Educational Launch of Nanosatellites (ELaNa) project. The Montana team worked diligently with the NASA Launch Services Program team during the next two years to work out the procedures by which university-built CubeSats would be allowed to accompany primary NASA scientific missions on their ride into space. Finally, after thorough review E1P and two other university CubeSats were manifest for launch on with NASA's Glory mission. Launch occurred on March 4, 2011. Once again for the Montana CubeSat team, the launch vehicle failed to place the satellites in orbit, and despite reaching space at more than 550 km altitude, E1P plunged back to Earth before being activated. In the meantime the second of the two satellites had been under development.

Explorer-1 [Prime] Flight Unit 2 was selected by NASA for participation in the CubeSat Launch Initiative in August 2010 and was intended to be placed into orbit on a subsequent launch to form a mini-constellation with E1P FU1 to simultaneously monitor variations in the Van Allen radiation belts at different longitudes. Unit 2 had been manifested on ELaNa-III and the Montana team had been working that mission with NASA beginning in the fall 2010. Following the March 2011 launch failure E1P Unit 2 was brought to flight readiness by the MSU student team. Full spaceflight qualification testing was performed during summer 2011, and the spaceflight qualified unit was delivered from Montana for the last time in August 2011 for integration into the P-POD, and final integrated P-Pod level testing in California. In early October the P-POD with its three CubeSats was delivered to the Vandenburg Launch Complex, and eventually installed on the Delta-II Launch vehicle.

Launch was a picture perfect pre-dawn lift-off and assent to orbit on October 28, 2011. Follow well after deployment of the primary spacecraft, NASA's Suomi NPP, the CubeSats were ejected from their P-PODs. Six CubeSats were carried in three PODs and released at 100-second intervals. The ejection process immediately initiates operation of E1P, which then cruises along in a semi-dormant state for 60 minutes to allow the batteries to charge. After 60-minutes the satellite fully activates, deploying its stowed communications antennas, and begins to beacon data packets every 15-seconds. Deployment occurred over Northern Central Africa and within minutes the university tracking station at University of Vigo (Vigo, Spain) reported receipt of strong signals from E1P. Over the ensuing minutes stations in Europe and the United Kingdom joined the growing list of Ham operators reporting strong E1P signals from low Earth orbit.

One week after launch Explorer-1 [Prime] Unit 2 was officially dedicated to the memory of William A. Hiscock, founding director of the Montana Space Grant Program and Professor of Physics at Montana State University. Bill, who was a huge supporter of our small satellite program, passed away in April 2010. The satellite has been named The William A. Hiscock Radiation Belt Explorer, or HRBE as it is commonly called.

HRBE has been a complete success. On February 16, 2012 the satellite met its orbital lifetime goal by exceeding the 111-day lifetime of the original Explorer 1. HRBE continues to return data from the horns of the radiation belts, and students at Montana State University continue to operate the satellite from the on-campus tracking station during 4-5 passes per day as shown in the photograph to the right. Figure 6 shows radiation intensity data from several satellite passes over the western United States and Canada during January and February. Overlain on the satellite ground track are color-coded count rates from the Radiation Payload as the satellite passed through the horns of the Van Allen Radiation Belts. Variations in the intensity and location (in latitude) of the energetic particles reflect variations in the intensity of precipitating particles from the radiation belts due to geomagnetic activity. The unidirectional detector is viewing locally mirroring energetic electrons and protons.

THE SCIENTIFIC PROMISE OF VERY SMALL SATELLITES

While at first glance it may seem that a satellite so small that it can rest in the outstretched palm of one's hand would not be large enough to accomplish any useful purpose. CubeSats are frequently employed as technology test beds to obtain flight heritage for newly developed miniature technologies. In space science, owing to their diminutive size, it is clear that CubeSats will not host large instruments that require large apertures, consume 10's of watts of power, and require multiple 10's of megabits per second of downlink telemetry. On the other hand many subdisciplines of space research do not require such instruments. One should not consider whether very small satellites might eventually replace larger traditional satellites. Rather one should ask how this potential new tool might be used advantageously to complement more traditional space research approaches.

Figure 5. SSEL summer intern Jordan McIntyre, a Computer Science student from Rocky Mountain College in Billings, Montana, operating the HRBE satellite from the satellite tracking station on the MSU campus during a recent pass.

Perhaps the greatest scientific advance that very small low-cost satellites will enable is the ability to make many simultaneous synergistic measurements from multiple observing locations. When dozens of cooperating satellites are deployed to address a scientific objective that requires, for example multiple viewing directions, or that requires distributed measurements of spatially complex and/or temporally dynamic phenomena, the scientific community will be in a position to acquire entirely new perspectives on scientifically baffling phenomenon. Constellations of small low-cost satellites carrying, perhaps, relatively unsophisticated instrumentation targeted at specific measurements represent a new research tool that will be complementary to more the traditional approach where a single satellite carrying very sophisticated instruments makes very detailed measurements but is unable to reveal the big picture or unravel complex dynamics.

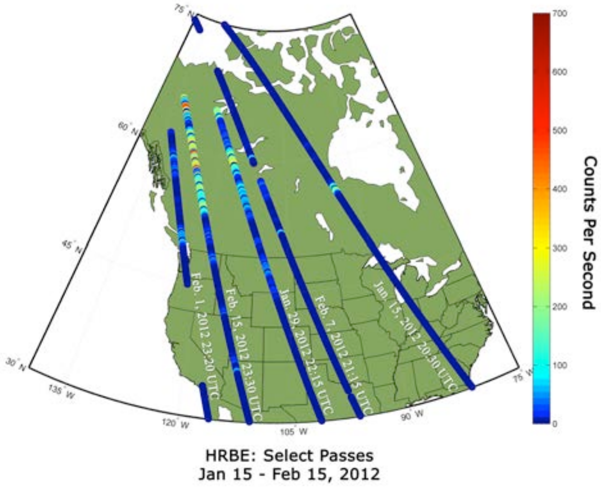

Figure 6. Count Rates measured by the unidirectional detector on the Hiscock Radiation Belt Explorer (HRBE) CubeSat for selected passes between January 15 and February 15, 2012. The detector responds to locally mirroring electrons > 50 keV and protons > 500 keV.

OUTCOMES

More than 400 undergraduate students have been involved in the Space Science and Engineering Laboratory's student hands-on flight program since its founding in 2000. Student currently in the program are benefiting from their predecessors and from the many valuable lessons-learned over the years. Students who graduate from this program have achieved a high level of competence in the practice of space flight hardware development. They have put their engineering education to work to develop genuine space flight hardware at the earliest possible point in their careers. The students learn systems engineering. They learn proper aerospace industry practice and discipline by direct participation. Graduates from the program are highly sought by government and aerospace industry laboratories. Program graduates are invariably offered starting salaries well above common entry-level positions. These highly trained individuals represent an economic advantage to the employer in that they require much less on-the-job training than most new hires, and they are able to be productive from the first day on the job. This is good for the new hire, and is good for the industry.

Additionally, by focusing on the development of miniature, low power, low-cost, COTS-component-based spaceflight systems there is growing evidence that non-traditional approaches to scientific spaceflight hardware development might play an increasing role in the future of space research.

SUMMARY

Montana State University's small satellite team just keeps on learning and keeps getting better through experiences gained and through careful attention paid to lessons learned. The Space Science and Engineering Program at Montana State University produces college and university graduates that have developed special skills in space sciences and space engineering while designing, building, testing, and operating space flight hardware. The key elements to the program's success are that students are intimately engaged in the cradle-to-grave process of design, development, test and flight of space flight systems over a significant portion of their undergraduate training period. It is an essential element of the training process that mistakes will be made along the way, but that lessons-learned from the participatory nature of the process are taken to heart and incorporated into the corporate knowledge of the Laboratory. No training program that does not position students in responsible and authoritative roles in the hands-on development of space flight systems can compete in its ability to train the next generation of space explorers. The lessons never stop coming. That's why we all love the space business.

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