

## **Today's Students ... Tomorrow's Engineers and Scientists: Experiential Training in Space Engineering and Space Science at Montana State University**

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*The training and development of staff to become the future space scientists and engineers on which our field will depend, is of critical interest to COSPAR. Here we report on a new approach to training in the space arena, specifically describing an experimental program being adopted at the Space Science and Engineering Laboratory in Montana, USA. We present this as a case study, the experiences from which can be used as a model for other groups world-wide, and we report on how the scheme has allowed hands-on involvement in actual space hardware, in particular through the development and flight of CubeSats. Links with the first US satellite, Explorer-1, and James Van Allen have enhanced this program considerably and the successful flight of the so-called HRBE CubeSat has continued the Explorer-1 legacy.*

The Space Science and Engineering Laboratory (SSEL) established at Montana State University in Bozeman, Montana, USA 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 employment in high tech industries, with focus on spaceflight systems engineering and science. Collateral benefits include undergraduate student enrollment retention for the University, and the positive public relations for the University that ensue following satellite launch. Owing to 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. Additionally the program seeks to demonstrate the utility, and to advance the application of very small satellites for space research.

### **Program Goals**

The SSEL program has two equally important goals, namely, (1) to provide mentored hands-on training to university-level undergraduate and graduate students in the design, development, test, and operation of space flight systems for the purpose of training the next generation of space systems engineers and space scientists, and (2) to advance the capabilities of small spaceflight hardware systems and their application to scientific discovery through the application of advanced technologies.

As a result of addressing these two primary goals several peripheral outcomes result. By immersing them 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.

### **Specific Program Structure**

The Montana State University 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 United States 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, and 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.

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 laboratory. 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. We do note that since US 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 citizens 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 fourth 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-semester 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.

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 undergraduates and are pursuing an advanced degree.

### **Technical Activities**

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.

The kinds of technical activities most desired 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.



*Figure 1. 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.*

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 11-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.

CubeSats are 1.0 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 1, which is a rendering of Montana State University's Explorer-1 [Prime] CubeSat, has CubeSat-standard body dimensions of 10 x 10 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.

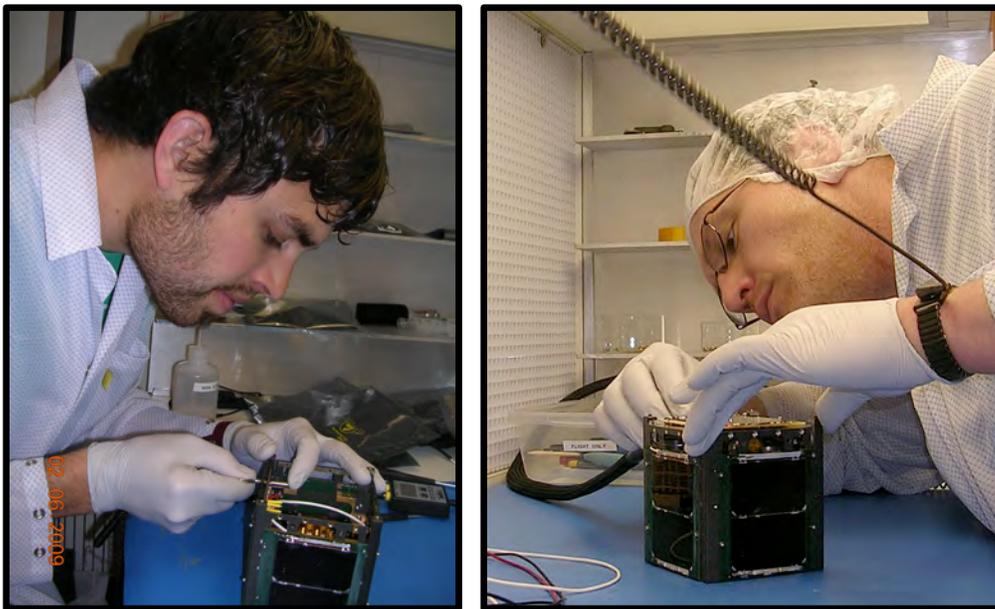
The problem of finding launch opportunities for small student-built satellites is no longer the hurdle that it once was. In the United States, for example, universities and other non-profit organizations can apply to NASA for the launch of CubeSats that fully comply with the CubeSat Design Standard. 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 Kazakhstan, 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.

### **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. Figure 2 shows students performing integration and test on Explorer-1 [Prime]. The satellites were built in two stages. Development began in the fall of 2006 following the loss of Montana's first CubeSat, the Montana Earth Orbiting Pico Explorer (MEROPE), in a 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 1/14<sup>th</sup> the mass of Explorer-1 and about 1/12<sup>th</sup> 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.

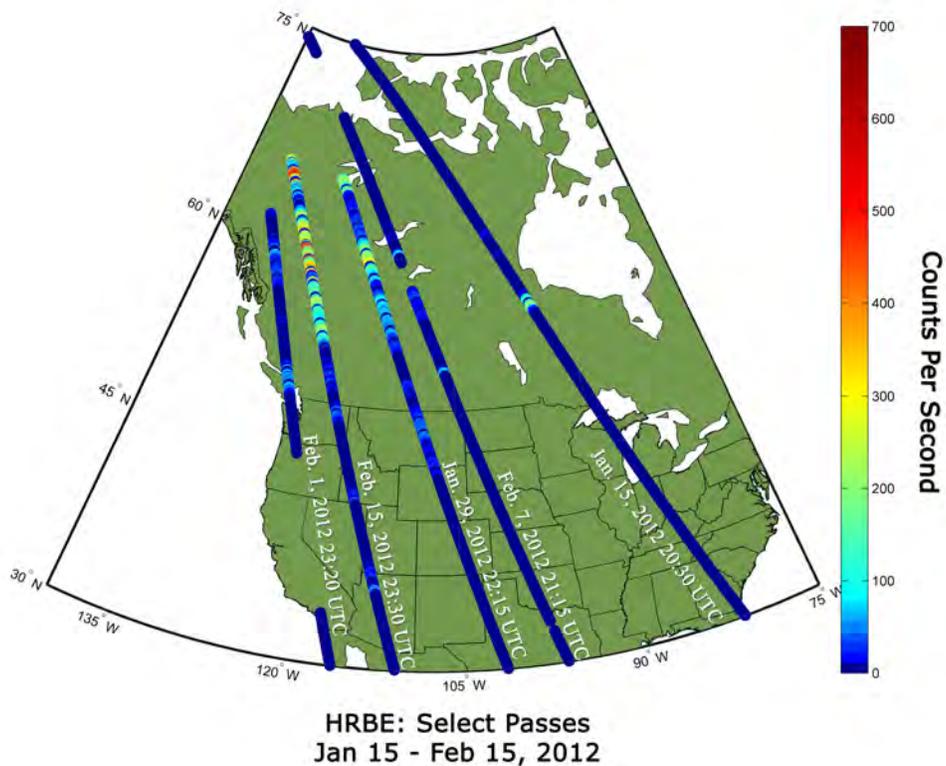


*Figure 2: Students at Montana State University performing integration and test of the Explorer-1 Prime CubeSats. Left Rubin Meuchel. Right Keith Mashburn.*

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 EIP 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, EIP 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 EIP 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 EIP 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 Vandenberg Launch Complex, and eventually installed on the Delta-II Launch vehicle.



*Figure 3. 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.*

Launch was a picture-perfect pre-dawn lift-off and ascent 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 EIP, 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 EIP. Over the ensuing minutes stations in Europe and the United Kingdom joined the growing list of Ham operators reporting strong EIP 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. Figure 3 shows radiation intensity data from several satellite passes over the western United States and Canada during January and February. Overlaid 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**

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.

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.

### **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. 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 almost always 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**

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. 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.

### **Acknowledgements**

The efforts of hundreds of students at Montana State University have made the vision of SSEL a reality. The Montana Space Grant Program has been a major supporter of the program and has provided substantial support for the development of the three 1-U CubeSats describe in this article. NASA, AFOSR, NSF, and many other entities have contributed to the support of the SSEL. Without the support of the NASA Launch Support Program's ELaNa Project, HRBE would not have been launched. Freshman MSU, student Matthew Handley created the plot shown as Figure 3.

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<b>About the Author</b>
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**Dr. David M. Klumpar, Montana State University, Research Professor of Physics and, Director, Space Science and Engineering Laboratory.**

Klumpar is an experimental space physicist with a 45 year background in Sun-Earth Connections system science. He received BA, and MS degrees in Physics from the University of Iowa in 1965 and 1968, and a Ph.D. degree, also in Physics, from the University of New Hampshire in 1972. He has authored/co-authored about 100 space research publications primarily involving electrodynamic coupling mechanisms at auroral latitudes in the ionosphere-magnetosphere system. He has developed instruments and led scientific analysis and interpretation investigations for NASA scientific missions, and over the past decade, has been developing scientific and technological capabilities of very small satellites ranging in mass from 1 to 30kg. As founding Director of the Space Science and Engineering Laboratory at Montana State University he has led the development of CubeSat missions, three of which have been launched. Klumpar is co-Principal Investigator for the twin 1.5U CubeSats FIREBIRD mission for the National Science Foundation. FIREBIRD has completed PDR and CDR and is in development for launch readiness in 3<sup>rd</sup> Q CY 2012.