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High Altitude Radiation Detector (HARD): An Exemplary Means to Stimulate Electrical and Computer Engineering Undergraduate Research

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Abstract

This paper describes an undergraduate research project that has recently completed a two-year cycle for design, testing, integration, and revision of a near-space ballooning payload. Referred to as the High-altitude Radiation Detector (HARD), the scientific objectives of the payload were to measure the "east-west" asymmetry in cosmic-ray arrival direction at varying altitudes between the Earth's surface and near space, as well as to study how the intensity of cosmic rays changes with altitude, including a high-quality, long-exposure measurement at balloon-float altitudes. Correspondingly, the technical objectives were the implementation and successful operation of various electronic instruments to detect cosmic rays and collect data for the scientific objectives. In this paper, we 1) present brief descriptions and key revision points of individual subsystems, 2) identify key technical knowledge required for a successful design of the subsystems in reference to specific Electrical and Computer Engineering course contents, 3) briefly describe how the HARD 2013 is being used to develop further research opportunities and attract new members (primarily sophomores and freshmen) to undergraduate research, as well as the strategies to prepare new members to play key roles in future research opportunities, and 4) present and discuss assessment results on how these extracurricular project activities facilitate improving the student learning outcomes defined by the ABET (i.e., "a through k" student-learning outcomes).

Overview of the Project

The High Altitude Radiation Detection (HARD) is an extracurricular undergraduate research project to design a High Altitude Student Platform (HASP) payload to conduct experiments related to arrivals of cosmic-rays at the top of the atmosphere. The HASP is a support vehicle, based upon flight-proven hardware and software designs, that uses an 11 million cubic foot, thin film polyethylene, helium-filled balloon to carry multiple student-built payloads to altitudes of ~120,000 feet (~36km) for durations up to 20 hours [1]. The platform is designed to support eight small payloads of ~3 kg weight and four large payloads of ~20 kg weight (i.e. 12 experiment "seats"). A standard interface is provided for each student payload that includes power, serial telemetry, discrete commands and analog output. The Louisiana Space Grant Consortium (LaSPACE) HASP team and the Balloon Program Office (BPO) at NASA Wallops Flight Facility jointly issued a Call for Payloads (CFP) in December 2012 to solicit student groups to apply for a "seat" on the 2013 HASP flight. Any student group responding to this CFP was required to develop a proposal describing its payload, including science justification, principle of operation, team structure and management, as well as full payload specifications of weight, size, power consumption, mechanical interface, data requirements, orientation preference and drawings.

The HASP program requires and strictly enforces all student teams to 1) conform to the HASP payload interface specifications and schedule set out in the CFP [1], 2) complete in-depth technical documents such as Payload Specification & Integration Plan (PSIP) and Flight Operation Plan (FLOP), and 3) pass a rigorous ~8 hour-long thermal/vacuum test at NASA's Columbia Scientific Balloon Facility located in Palestine, TX. Some of the important milestones for the HASP program include i) Selection of student payloads (mid January), ii) Preliminary PSIP document (mid April), iii) Final PSIP document (late June), iv) Final FLOP document (late July), v) Student payload integration at CSBF (one week in late July ~ early August), vi) HASP flight preparation/launch/recovery/returning of the payloads to student teams (late August ~ early September), and vii) Final Flight/Science Report (mid December).

The High Altitude Radiation Detection payload #3 [2], or HARD-PL03, is a HASP payload that successfully met all requirements and milestones as per the aforementioned schedule and deliverables. The authors' student team had initially designed, built, and flown a similar payload for the HASP 2012 flight [3]. The HARD-PL02, however, revealed several design problems during flight that prevented it from collecting the desired science data. As some members of the HARD-PL02 had graduated, the student team was restructured in late November 2012, and the HARD-PL03 was constructed from all new materials for the HASP 2013 flight (instead of being a minor modification of the previous one), intended to fix the problems encountered previously. The primary science objective of HARD-PL03 was to investigate how the "east-west" angular asymmetry changes with altitude, as the cosmic ray flux transitions from mostly secondary particles near ground level to mostly primary cosmic rays near balloon-float altitudes. This asymmetry exists because the Earth's magnetic field deflects cosmic-ray trajectories from a straight line. Since cosmic rays are predominantly positively charged, more cosmic rays arrive from the west than from the east.

In September 2013, the HARD-PL03 payload was launched to an altitude of about 125,000 feet for approximately 10 hours of flight in collaboration with the LaSPACE HASP team and NASA's Columbia Scientific Balloon Facility (CSBF). The overall design of the payload was very similar to HARD-PL02, although lessons learned from the previous flight had been incorporated into the design (such as including a TTL to RS232 converter for serial communications). The payload was designed using a top-down approach, i.e., engineering requirements first established, followed by functional decomposition, and design/construction of subsystems, and unit/integration tests in the lab by the student team from the electrical and computer engineering (ECE) department.

Figure 1. Completed, sealed HARD-PL03

The team delivered monthly status reports on project progress from January 2013 to November 2013, a Payload Specification & Integration Plan (PSIP), and Flight Operation Plan (FLOP) as per the HASP schedule. In late July 2013, four student members traveled to the CSBF lab for the thermal/vacuum test and on-site payload integration. The completed payload, prior to integration and thermal vacuum test at the CSBF lab, is shown in Figure 1.

Student Design Activities for Payload Subsystems

The student team consisted of a total of six ECE undergraduate students, including one senior and five juniors (as of Sept. 2013), and two faculty advisors from the ECE and Physics departments. As an extracurricular undergraduate research activities, the student team members were required to commit a minimum of 5 hours per week to work on the project beyond their normal course work.

The functional block diagram of the payload is shown in Figure 2 and its physical specifications are shown in Figure 3. As with the 2012 payload [3], the key subsystems are the detector module, comparator module, coincidence detector, microprocessor/central processing unit (CPU), rotator module, and power module. While all members were collaborating toward the common goal of successfully completing all subsystems, the student members were largely split among three primary responsibilities: 1) electronic circuitry to detect cosmic-ray arrivals and generate corresponding digital signals for TTL logic with a threshold of ~2.4V (i.e., detector module, comparator module, and power module); 2) processing digital signals from the detectors and other required components (microprocessor/CPU, GPS, and serial communication module); and 3) physical construction of the payload and support frame to hold the rotator and detector modules. Below, some technical aspects are briefly described to elaborate on work done by student members.

In order to detect cosmic rays in the east-west plane, an array of four active detector elements was arranged in a square, as shown in Figure 4. Each active detector element consisted of a Photonique SiPM 0905V13MM silicon photomultiplier (SiPM) [4] attached via optical epoxy to a 3×3×1 cm^3 CsI(TI) scintillating crystal. The scintillating crystals emit light when traversed by

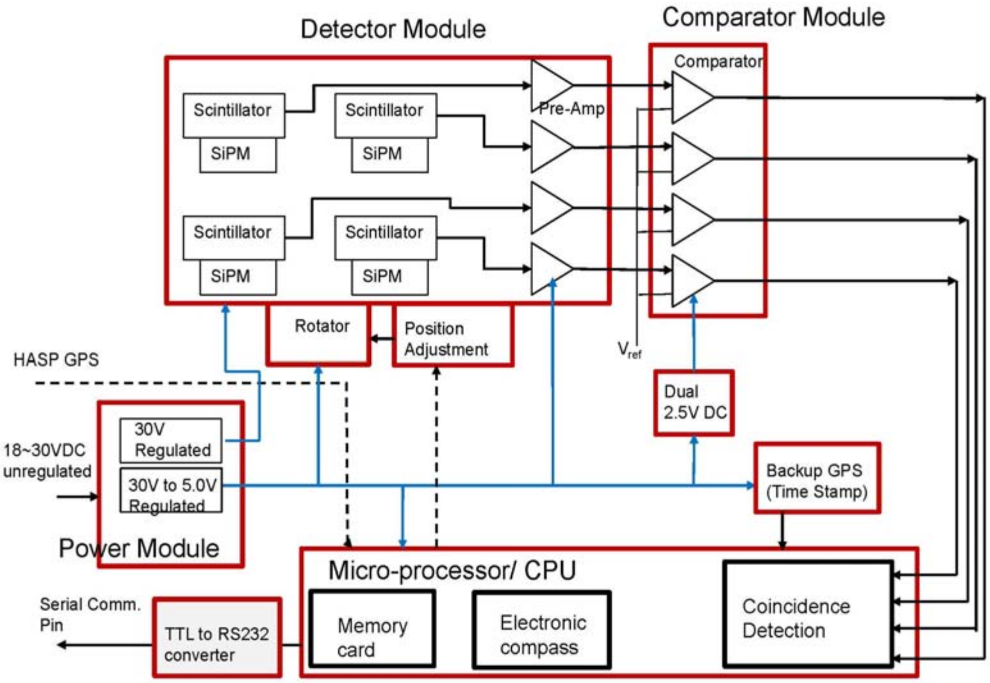

Figure 2. Overall functional block diagram of the HARD-PL03

a charged particle, which was then converted into an electric pulse by the SiPM.

A pre-amplifier [5] was used to amplify the small output signal of the SiPM into a negative pulse ranging from 0 to around -1 V, depending on the number of photons that hit the SiPM. Due to the long scintillation decay time of CsI(TI) crystals, the output pulses from the pre-amp were typically ~1 μs in duration (although the rise-time of the pre-amp was much faster, around 5 ns). Manipulation and detection of these short pulses required fast electronics, which drove many design decisions for the comparator and coincidence detector.

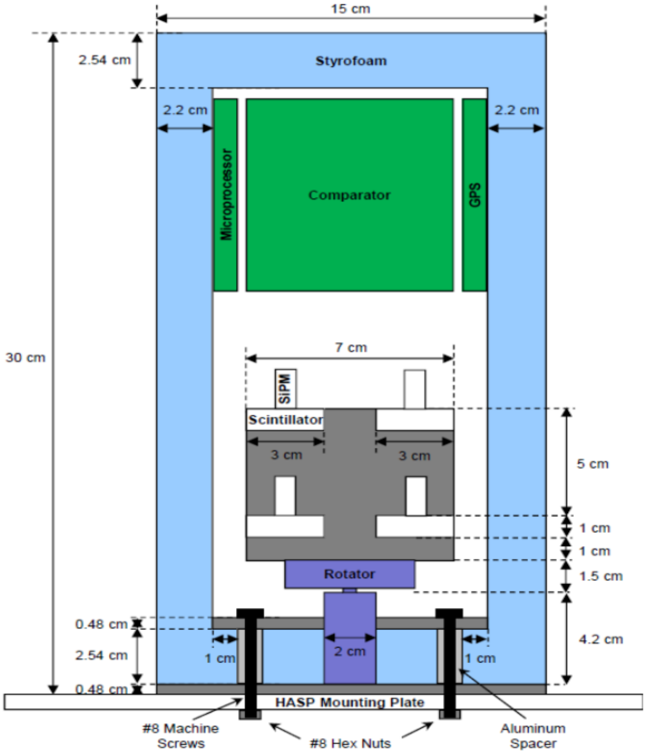

Figure 3. Physical specifications of the HARD-PL03 (front view)

The detector array needed to maintain an orientation in the east-west plane to detect the east-west asymmetry. An HMC6352 electronic compass [6] was used to determine the orientation of the detector module. When the orientation of the payload drifted more than 10° from the desired orientation due to rotation of the HASP platform, a servo motor (i.e., the Rotator module) was used to adjust the detector position.

The primary failure mode seen in the previous payload (i.e., continuous triggering even without a valid signal) was observed during bench testing of the detector module, pointing the main cause of the failure to the servo motor which draws a large amount of current while in operation. The servo was controlled using pulse width modulation, meaning that the angle of the servo was controlled by sending a pulse whose width defined the angle of rotation. The flight code resent this control pulse every 20 ms, even when the servo was in position, which sometimes caused the servo to attempt to slightly adjust its rotation. The anomolous trigger rate problem was solved by only sending the control pulse when the servo needed adjustment.

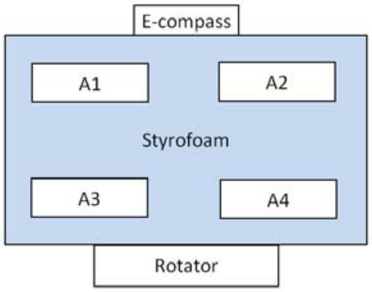

Figure 4. Diagram of the Detector module, including scintillator, rotator and e-compass

Since the SiPM amplifier outputs a negative voltage, four comparator circuits were constructed using AD8616 [7] inverting operational amplifiers with a high voltage gain to produce a TTL logic-level signal for input to the microprocessor, as shown in Figure 5. The coincidence module was implemented as one of several subroutines within the microprocessor/CPU. To monitor for a simultaneous coincidence in two or more SiPM modules, the microcontroller polled the digital input pins approximately once a microsecond to look for the coincidence of two or more of the SiPMs simultaneously returning a logical high. When this condition was met, the microcontroller recognized it as a successful “hit” (i.e., an event).

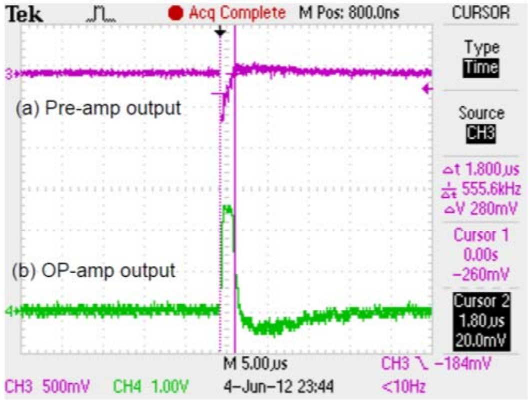

Figure 5. Output signals: (a) SiPM amplifier (b) OP AMP (comparator)

A chipKIT Uno32 Prototyping Platform [8] was used as the main microprocessor module. In addition to poling the digital I/O pins to determine whether a coincidence condition had been met as described above, the microprocessor provided a number of other functions. These included facilitating serial communication with HASP, collecting data from a temperature sensor attached to the 60V power supply, controlling the servo to adjust detector orientation, and collecting GPS time. A MAX233 line driver/receiver [9] was used to convert the TTL logic of the microprocessor to RS-232 logic as required to enable serial communication with HASP.

Since the HASP system provides an unregulated 30V power supply, DC-DC converters [10][11] were used to convert the supply voltage into the regulated voltages required by the payload (±2.5V, 5V, and 60V). Since each SiPM required a different voltage in the range of 30 ~ 40V, a four-branch resistor-based voltage-divider circuit was used to provide 34 ~ 38V to the SiPMs. Variable resistors were used in the divider chain to allow the bias voltage to each SiPM to be precisely adjusted as necessary.

Numerical Results and Discussions

The HARD-PL03 was flight-certified after a 2nd attempt to pass thermal/vacuum testing at the CSBF site. The payload launched at 2:57pm UTC on September 2, 2013, and terminated at 4:11 am UTC on September 3, 2013 after ~10.5 hours at float altitude. Our payload was turned on during climb out and transmitted data to the ground via serial communication with HASP for the entire flight duration, although there were some outages due to unknown communication interruptions. As part of the project requirements, student members, under the supervison of the faculty advisors, analyzed the flight data obtained during the flight via the serial communication from the payload to the HASP. A brief overview of the data collected during the flight is presented below.

During the flight, the internal temperature ranged from approximately -2°C to 44°C except for one anomalous data point at -50°C, as shown in Figure 6(a). The payload temperature was well within the safe operating limits of all payload components and remained fairly consistent throughout the flight. Figure 6 (b) demonstrates that the e-compass and servo were able to maintain a proper heading, as the e-compass never deviated from northward reading by more than 10 degrees (i.e., between the red dashed-horizontal lines), except for three times when the system was intentionally disabled around 500, 700, and 800 minutes into the flight. During these

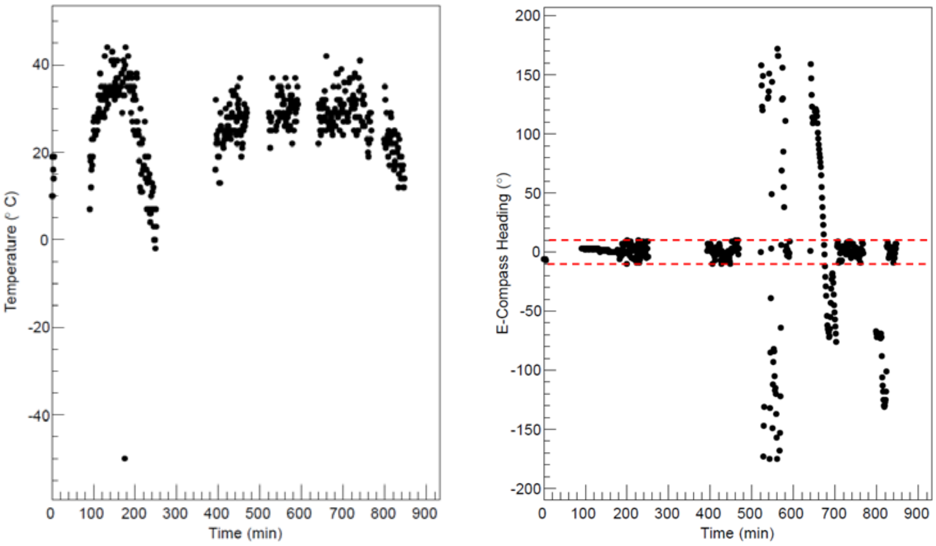

Figure 6. (a) Internal payload temperature during flight, (b) e-compass heading (red lines indicate deviation of 10° from due north).

times, the payload was rotated by 180° with the intention of gathering data pointing due south to better understand systematic errors, although swaying and rotation of the HASP structure caused the orientation of the payload to change dramatically while the auto-rotate function was off. A dedicated autorotation function for pointing south instead of north could be implemented on a future payload to eliminate this problem.

Figure 7(a) shows the total instrument event rate, which is the number of simultaneous coincidence events per minute. As expected, the rate starts from a few events per minute at ground level and increases rapidly as the balloon ascends through around ~40,000-50,000 ft. The instrument trigger rate at float altitude remained reasonably constant between 100 and 150 counts/minute for the remainder of the flight, except for around 650 minutes into the flight, where it briefly drops to about half.

The rates from specific combinations of scintillators are show in Figure 7 (b), and it is clear that detector module A3 or the associated comparator channel was not functioning at the start of the flight, spontaneously began working around 220 minutes into the flight, and briefly stopped functioning again near the end of the flight. The most-likely cause of this malfunction is a poor solder joint which began to function when either thermal stress (from the temperature change) or mechanical stress (from the instrument swaying) re-established electrical contact.

Enhancing Student Learning Experience

Relation between ECE Courses and Key Knowledge Required for HARD

As a complex project involving subsystem design, integration, and testing, successful completion of HARD-PL03 required a great deal of technical and non-technical skills beyond what students could generally acquire and/or polish during their course work. To relate student learning from

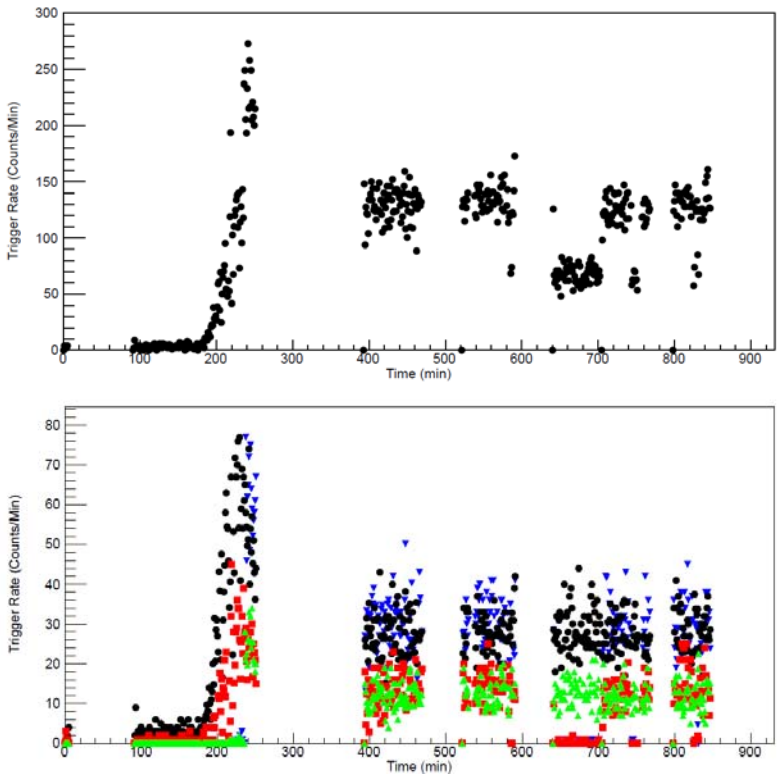

Figure 7. (a) Total event rate (in counts per minute) for all directions. (b) Event rate for downward events through A1 and A3 (blue downward triangles), downward events through A2 and A4 (black circles), east going events (red squares), and west-going events (green upward triangles)

this project and their course work in the ECE department at the University, we have reviewed how many credit hours of course work in the department would be directly related to this project. It should be first noted that students in the current ECE curriculum at the University are required to take a total of 131 credit hours (electrical engineering option, or EE) or 132 credit hours (computer engineering option, or CE). This includes (1) 48 credit hours of the Liberal Studies Core composed of theology, philosophy, ethics/moral responsibility, history, writing, speech, fine arts, literature, social science, science, mathematics, first-year seminar, leadership seminar, and senior capstone; (2) 20-23 additional credit hours of basic science and math; and (3) 60-64 credit hours of engineering courses. Based on a qualitative assessment, a list of key ECE courses that would provide students with technical knowledge directly related to the project is compiled in Table 1.

As shown in the table, about 50% (i.e., 30~31 crs. out of 60-64 crs.) of the engineering courses in the ECE curriculum contain materials that are directly related to this project. Participation in this or a similar project will therefore help students build or refine technical expertise from a large percentage of their courses via hands-on experience. It can also be noted that students who have completed two years of study in the ECE department would have acquired most of the technical knowledge needed to carry out the project and would be in a good position to actively engage in an undergraduate research project similar to the one described in this paper.

Table 1. Key ECE courses

	Fall Semester	Spring Semester	Credit hours
Freshmen	Eng Tools Applications (1 cr)	Intro. to C Programming (3 cr)	13 cr (for both EE and CE)
	Eng Tools Applications Lab (1 cr)	Digital Logic Design (3 cr)	
		Digital Logic Design Lab (1 cr)	
		Circuits I (3 cr)	
		Circuits I Lab (1 cr)	
Sophomore	Circuits II (3 cr) – EE only	Electronics I (3 cr)	14 cr (EE) 12 cr (CE)
	Circuits II Lab (1 cr) – EE only	Electronics I Lab (1 cr)	
	Prob Solving with Object-Oriented Programming (3 cr) – CE only	Data Structure & Algorithms (3 cr) – CE only	
	Test & Measurement (3 cr)		
	Microprocessor (2 cr)		
	Microprocessor Lab (1 cr)		
Junior	Electronics II (2 cr) – EE only	Rapid Prototyping with FPGA (3 cr) – CE only	3 cr (EE) 6 cr (CE)
	Electronics II Lab (1 cr) – EE only		
	Advanced Digital Design (2 cr) – CE only		
	Advanced Digital Design Lab (1 cr) – CE only		
		Subtotal:	30 cr (EE) 31 cr (CE)

Feedback on Student Learning Outcomes

To quantitatively assess the benefit of the HARD-PL03 project, a survey of 22 questions was developed and deployed in the end of Fall 2013 semester to ten ECE students including five on HARD-PL03 and five new members on a new but closerly related project. Nine students responded by the time the survey was closed. The "*(a) through (k)*" student learning outcomes defined by ABET/EAC [12] were the basis of the survey, as shown in Table 2. Odd-number questions asked if the project provided opportunities for the student to improve on these learning outcomes and the even-numbered questions asked if the student actually did improve by participating in the project. In addition, all even-numbered questions had a space for additional written comments. Survey results are summaried in Table 3. As can be seen, most students agree that the project has facilitated learning in the "*(a) through (k)*" categories, and they have improved their ability (or knowledge or understanding, as applicable) in those categories. For some questions, e.g., Q7 & Q8, Q11 & Q12, etc., one or two students responded with Neutral and/or Not Applicable, which might have occurred for some of the new team members.

Table 2. Survey Questions

Q#	**Description**
Q1	The extracurricular project activities provided me with an opportunity to improve my ability to apply knowledge of mathematics, science, and engineering.
Q2	Participating in the extracurricular project activities, I have improved my ability to apply knowledge of mathematics, science, and engineering.
Q3	The extracurricular project activities provided me with an opportunity to improve my ability to design and conduct experiments, as well as to analyze and interpret data.

Q#	Description
Q4	Participating in the extracurricular project activities, I have improved my ability to design and conduct experiments, as well as to analyze and interpret data.
Q5	The extracurricular project activities provided me with an opportunity to improve my ability to design a system, component, or process to meet desired needs within realistic constraints.
Q6	Participating in the extracurricular project activities, I have improved my ability to design a system, component, or process to meet desired needs within realistic constraints.
Q7	The extracurricular project activities provided me with an opportunity to improve my ability to function on multidisciplinary teams.
Q8	Participating in the extracurricular project activities, I have improved my ability to function on multidisciplinary teams.
Q9	The extracurricular project activities provided me with an opportunity to improve my ability to identify, formulate, and solve engineering problems.
Q10	Participating in the extracurricular project activities, I have improved my ability to identify, formulate, and solve engineering problems.
Q11	The extracurricular project activities provided me with an opportunity to improve my understanding of professional and ethical responsibility.
Q12	Participating in the extracurricular project activities, I have improved my understanding of professional and ethical responsibility.
Q13	The extracurricular project activities provided me with an opportunity to improve my ability to communicate effectively.
Q14	Participating in the extracurricular project activities, I have improved my ability to communicate effectively.
Q15	The extracurricular project activities provided me with an opportunity to broaden my education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context.
Q16	Participating in the extracurricular project activities, I have broadened my education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context.
Q17	The extracurricular project activities provided me with an opportunity to improve my recognition of the need for, and an ability to engage in life-long learning.
Q18	Participating in the extracurricular project activities, I have improved my recognition of the need for, and an ability to engage in life-long learning.
Q19	The extracurricular project activities provided me with an opportunity to enhance my knowledge of contemporary issues.
Q20	Participating in the extracurricular project activities, I have enhanced my knowledge of contemporary issues.
Q21	The extracurricular project activities provided me with an opportunity to improve my ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.
Q22	Participating in the extracurricular project activities, I have improved my ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

Table 3. Survey Results

Q#	Strongly Disagree	Moderately Disagree	Neutral	Moderately Agree	Strongly Agree	Not Applicable	# of Comments[*]	# of students answered
1	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	n/a	9
2	0.0%	0.0%	0.0%	22.2%	77.8%	0.0%	4	9
3	0.0%	0.0%	0.0%	11.1%	88.9%	0.0%	n/a	9
4	0.0%	0.0%	0.0%	33.3%	66.7%	0.0%	4	9

Q#	Strongly Disagree	Moderately Disagree	Neutral	Moderately Agree	Strongly Agree	Not Applicable	# of Comments*	# of students answered
5	0.0%	0.0%	0.0%	33.3%	66.7%	0.0%	n/a	9
6	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	4	9
7	0.0%	0.0%	11.1%	11.1%	77.8%	0.0%	n/a	9
8	0.0%	0.0%	11.1%	22.2%	66.7%	0.0%	4	9
9	0.0%	0.0%	0.0%	22.2%	77.8%	0.0%	n/a	9
10	0.0%	0.0%	0.0%	11.1%	88.9%	0.0%	5	9
11	0.0%	0.0%	0.0%	0.0%	88.9%	11.1%	n/a	9
12	0.0%	0.0%	0.0%	11.1%	77.8%	11.1%	4	9
13	0.0%	0.0%	0.0%	11.1%	88.9%	0.0%	n/a	9
14	0.0%	0.0%	0.0%	22.2%	77.8%	0.0%	5	9
15	0.0%	0.0%	0.0%	11.1%	66.7%	22.2%	n/a	9
16	0.0%	0.0%	0.0%	11.1%	66.7%	22.2%	3	9
17	0.0%	0.0%	0.0%	11.1%	77.8%	11.1%	n/a	9
18	0.0%	0.0%	0.0%	11.1%	77.8%	11.1%	3	9
19	0.0%	0.0%	11.1%	22.2%	44.4%	22.2%	n/a	9
20	0.0%	0.0%	11.1%	22.2%	44.4%	22.2%	2	9
21	0.0%	0.0%	11.1%	33.3%	55.6%	0.0%	n/a	9
22	0.0%	0.0%	11.1%	33.3%	55.6%	0.0%	5	9

* Some students took time to provide written comments in even-numbered questions, but those are intentionally omitted from this paper for space, as well as confidentiality.

Reflections

As mentioned previously, six undergraduate students from the ECE department, including one senior and five juniors (as of Fall 2013), participated in the project. One of the five juniors was involved in the design of HARD PL02 in 2012 and continued his involvement in 2013 for HARD PL03. The other four current juniors and one current senior joined the team in the beginning of Spring 2013. The student team met regularly for about 5 hours of lab work per week during the spring and fall semesters of 2013.

This project provided a great framework for undergraduate students in research and facilitated greatly enhancing students learning experience outside of the classroom as the survey results in Table 3 demonstrate. One of the challenges in carrying out the overall project activities was time management amid team member's schedules. Student team members normally carry 15~18 credit hours of course work each semester, as well as additional extracurricular activities. Weekly meetings were crucial for ensuring successful completion of the project by a set-deadline. The project was very helpful in teaching team members the concept of delivering a product on schedule, which is an essential workplace skill that cannot be easily taught in a class. It also facilitated close collaboration between students and faculty.

Students' travel to an off-campus site for intercollegiate collaboration, i.e., integration of the payload onto the HASP instrument at the CSBF site, was another great way to enhance their overall learning experience and enthusiasm for this project. The on-site lab activities also provided opportuities for the students to learn how to promptly respond to unforeseen real-world situations to successfully complete their mission.

Application to Promoting Undergraduate Research

As a way to broaden students participation in undergraduate research at the University, with the experience that the students acquired from HARD-PL02 (in 2012) and PL03 (in 2013), the HARD team has developed a new opportunity and, after forming a new team with additional student members, is currently developing a payload for NASA's Undergraduate Student Instrument Project (USIP) that is expected to take 18 months for completion and use a commercial balloon carrier. At the onset of the project, the team consists of two faculty members and 12 student members (i.e., 8 ECE and 4 science majors). The faculty advisors (who are the authors of this paper) have established designated project-activity hours, primarily in the ECE lab facilities, and interacted closely with student team members during lab hours to ensure that students have the knowledge and resources to complete the project. Furthermore, more experienced members of the team, such as those who have participated in the HARD project, serve as mentors for newer team members. Indeed, for preparatory training, five new ECE members (mostly freshmen and sophomores) of USIP have participated in post-flight testing of HARD-PL03 during Fall 2013, mentored primarily by the HARD (& USIP) team members.

By participating in this new research project, ECE students are expected to further develop competency in their specific discipline (electrical engineering, computer programing, etc.) by applying the skills learned in the classroom to a real-world problem. Even those students who do not have a physics or engineering background (i.e., team members from sciences) will benefit by gaining invaluable experience working as part of a large collaboration to achieve a complex and difficult objective. These collaborative skills cannot be taught in the classroom, yet are vital to success in industry and research.

Concluding Remarks

Built on the lessons learned from the previous year's payload, the HARD-PL03 was a success and was able to collect the desired cosmic-ray data. All other parts of the design, including serial communications, payload orientation, and temperature monitoring, functioned as expected.

Additionally, this project provided student team members with an excellent engineering opportunity that required both technical and non-technical skills to solve real-world problems. This project has effectively facilitated building a solid basis of technical expertise at the University, particularly in electrical and computer engineering and physics, and has created additional opportunities to engage a larger group of undergraduate students in research projects.

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