AC 2012-4313: IONOSPHERIC ROCKET PAYLOAD DEVELOPMENT: PROJECT AND COURSE

Prof. Dimitris Vassiliadis, West Virginia University

Dimitrios Vassiliadis received his Ph.D. in plasma physics, University of Maryland, College Park, in 1992. Following that he was a Postdoctoral Fellow under the National Research Council program at NASA/Goddard Space Flight Center for two years. He went on to work for NASA/Goddard as a contractor scientist in magnetospheric and ionospheric physics until 2007, when he moved to West Virginia University as a Research Associate Professor. His interests and teaching experience are in the fields of plasma physics and engineering, nonlinear signal processing, forecasting and control theory, microcontrollers, and MEMS applications.

Dr. D.J. Pisano, West Virginia University

Department of Physics

Dr. Yu Gu, West Virginia University

Yu Gu was born in Huainan, China, in 1975. He received a B.S degree in automatic controls from Shanghai University in 1996, a M.S. degree in control engineering from Shanghai Jiaotong University in 1999, and a Ph.D. degree in aerospace engineering from West Virginia University in 2004. Since 2005, he has been a Research Assistant Professor in the Department of Mechanical and Aerospace Engineering at West Virginia University, Morgantown, W.V. His main research interests include sensor fusion, flight control, and small unmanned aerial vehicle (SUA V) design, instrumentation, and flight testing.

©American Society for Engineering Education, 2012
IONOSPHERIC ROCKET PAYLOAD DEVELOPMENT: PROJECT AND COURSE

D. Vassiliadis, Y. Gu, and D.J. Pisano

(1) Department of Physics, West Virginia University, Morgantown, WV 26506
(2) Department of Mechanical and Aerospace Engineering, West Virginia University, Morgantown, WV 26506

Abstract. Starting in 2009 a senior-level design project has been developed at WVU with the goal of having STEM students become familiar with space engineering concepts and development of basic payloads. The project is related to the national RockSat program through which the payloads are launched on NASA suborbital rockets. To facilitate participation by students from different backgrounds, the instructors have designed a special-topics course on principles of space engineering to complement the hands-on, open-ended lab experience of the project. Payload designs are evaluated by RockSat mission managers and the payload design must pass through a series of reviews before being accepted on the flight. Students document the development in technical reports and telecons with RockSat and other student teams. At the end of the spring semester, the student team participates in testing and integration at NASA’s Wallops Flight Facility. The launch is followed by work on data analysis and preparation of a final report. A brief description of the course procedures is given along with an overview of the experiments conducted. A brief discussion of educational goals and positive outcomes of this activity for individual students and annual teams is presented. Finally the lessons learnt in organizing the project and course are summarized since they may be useful for schools and organizations planning to develop such programs.

1. Introduction

The Department of Physics at West Virginia University has sought to integrate project-based learning with a regular classroom-based curriculum. One such project, developed in collaboration with the Department of Mechanical and Aerospace Engineering and the West Virginia Space Grant Consortium, has focused on development of simple payloads for suborbital rocket missions provided by a NASA education program. The vehicle carrying the payloads is a two-stage rocket launched from NASA’s Wallops Flight Facility (WFF) located in Chincoteague, VA. The project and the accompanying course are developed from a systems engineering perspective and payload development is presented as an integrated process starting with a concept for an experiment, and followed by mechanical and electrical design, sensor selection, construction, and testing. The end-to-end approach is intended to benefit junior- and senior-year students from a variety of engineering and science backgrounds who have accumulated a large number of credit hours and developed several technical skills, but may not have had the opportunity to practice and integrate these skills.

The payload development team participates in the RockSat program administered by the Colorado Space Grant Consortium. RockSat was proposed by a small number of universities and space grant programs led by the Colorado and Virginia Space Grant Consortia in response to NASA programs for student low-cost access to space. It consists of several activities including the “RockOn” introductory workshop and a payload-management program. RockSat coordinates participating college teams during the development process, conducts regular reviews, and prepares the final payload manifest for the flight. The WVU effort started in June 2009 by a small team attending RockOn, an annual week-long introductory workshop which covered basic payload design, including experimental and programming
techniques and prepared a basic payload. The payloads constructed during the workshop were launched on a Terrier Orion rocket (Fig. 1) together with advanced experiments by returning (“RockSat”) teams.

Fig. 1. A Terrier-Orion rocket at NASA’s Wallops Flight Facility, similar to the vehicle used for the RockSat launches.

The vehicle reaches between 115 and 130 km (Fig. 2) well above the stratosphere and within the ionospheric E region; actual inclination and apogee vary each year. The rocket reaches its apogee at about 3 minutes while the duration of the flight is approximately 15 min. Historically such suborbital vehicles were called sounding rockets because one of the goals of the first such missions was to rapidly scan, or “sound”, the layers of the ionosphere and neutral atmosphere. The payload portion descends via parachute, and is retrieved from the Atlantic Ocean within a few hours. After de-integration and partition into the individual college payloads, students work on data analysis and final reports. The recovered payload is useful for mission evaluation and serves as a starting point for the following year’s instructional and design phase.

2. Course on Rocket Propulsion and Payload Development

It was recognized early on that an essential part of this project was to organize the payload engineering and science in the form of lab exercises. The format would provide a framework for the diverse theoretical and empirical knowledge base and it is useful for students in practicing existing and new skills before they can apply them to payload development. Most students are mechanical-, aerospace-engineering, or physics majors. In some cases team members have electrical and computer engineering and computer science backgrounds. Students are juniors or seniors although a few sophомores have joined as well. The students were initially trained by means of lab exercises, while brief lecture notes, or instruction sheets, were also handed out.
A special-topics course was offered in spring 2010 which focused on basic electronics and programming in C++ with applications in embedded computing. About half of the students have taken only basic electricity and magnetism courses so brief surveys on specific topics had to be presented in the lab. Examples were drawn from standard lab and electronics textbooks. Most students were familiar with basic data analysis, but not with related topics such as error analysis. In addition, informal discussions and notes were added on the physical environment such as on basic notions of radio communications, atmospheric and plasma physics, and cosmic-ray physics. The course was slightly revised the following year.

In fall 2011 the course material was expanded and reorganized. The course was renamed Introduction to Rockets and Payloads and was divided in 3 units:

1. Rocket dynamics and propulsion including a discussion of Earth’s space environment.
2. Analog and digital electronics with an introduction to radio-frequency circuits.
3. Programming in C++ with an emphasis on embedded applications.

The first part of the course was taught from a primary textbook as well as auxiliary texts for rocket dynamics and propulsion, engine design and space science. A number of exercises were created for homework sets and exam problems. The second part used standard texts with portions from other special-topics books. The material included a review of basic linear electronics and emphasized nonlinear elements such as transistors and op amps. Radio frequency electronics and an introduction to basic antenna theory were in the last lectures of the second part. The final part on C++ programming was based on a popular textbook with exercises drawn from it. Since only a small part of the language could be covered, the emphasis was on its input/output features used in data acquisition, and flow-control and time-dependent features (timers, interrupts, pulse width modulation) necessary for efficiently operating the payload sensors. Since embedded programming was practiced on NetBurner’s MOD5213, application notes written for this microprocessor were used as a source of examples and exercises.
Homework sets and exams were similar in structure and complexity to a typical sophomore- or junior-level engineering course. Exercises for these were drawn from the above textbooks and other resources (Fig. 3). Starting in fall 2011, about 10% of the exercises on many subjects (rocket dynamics, propulsion, electronics, and programming) were based on experimental and telemetry data of earlier RockSat flights.

![Nozzle flow analysis](image)

**Fig. 3.** Nozzle flow analysis from a homework problem on engine design.

### 4. Educational goals and methods

In an effort to go beyond traditional instruction environment, a number of other techniques were tried and several of them were found to be useful for a hands-on, project-based educational activity. These techniques included student-to-student instruction, collaboration with external advisors with specialties on individual payload subsystems, and a diversity of payload experiments and educational objectives.

Student-to-student instruction was adopted almost from the beginning of the course. Several undergraduate students stood out for their above-average lab experience through courses and/or similar design projects. Such individuals were quick to identify opportunities and risks in the payload design, and research and contribute new designs or components. They were leaders of their teams and advisors to new students. One of these individuals returned to the team twice after the original flight and helped teach the lab portion of the class in the academic year 2011-2012. In addition, at least one research graduate student (in aerospace, physics, or electrical engineering) was a team member every year and could help with aerospace or physics modeling, and in some cases, C++ programming. Such student-experts would provide valuable detailed feedback although their time in the payload lab or in report preparation was kept to a minimum.

Specialist advisors helped in varying degrees with individual payload subsystems. The specialists were asked to join the team for experiments related to astrophysics, cosmic-ray physics, fluid dynamics, and plasma physics. The specialists visited the classroom or lab a few times per semester to give a limited number of lectures or inspect the design; more commonly students would meet with them to discuss revisions and problems.

In contrast to other payloads which had typically one or two major engineering or science goals, the WVU payload was designed to address a number of science questions at varying degrees of complexity. The diverse payload allowed students to identify with one or more subsystems and brought out their
Vassiliadis et al., Rocket Payload Development

Expertise and skills. Individual experiments were designed to have a variety of complexity levels so that even if they were not completely successful, there was a tangible outcome such as the response to the programming, a video, or an actual set of measurements. The payload diversity exposed the students to a number of engineering concepts and tools, and in particular demonstrated the need and usefulness of systems engineering.

Finally, many payload subsystems were repeated from year to year and students were asked to review earlier mission data and component choices and learn from the successes and failures of their predecessors. In addition the legacy components formed a useful base on which the current team was asked to build. Innovation and revision were encouraged.

5. Payload Design

A payload is divided into smaller functional units called subsystems. For RockSat each subsystem comprised one or more experiments and/or tests (Fig. 4). One of the subsystems was command and data handling (CD&H), or software development. In the third year, the power distribution was identified as its own subsystem which served as a power hub for all other physical subsystems. Also in the third year and later, subsystem names started to be referred as two-or three-name abbreviations.

Subsystem design followed standard aerospace engineering procedure. After the concept was formulated, a functional block diagram was created indicating major pathways of power, control, and data flow. Mechanical drawings were prepared using 3D CAD tools SolidWorks and ProEngineer (Fig. 5) which allow the integration of subsystems in a single “assembly” drawing. Other designs were prepared for auxiliary structures such as the canister holding the payload, interfaces to the rocket skin and to the rocket ports. The third phase centered on electrical circuit (schematic) design using SPICE and similar tools, and PCB design using ExpressPCB, Eagle, and Altium. While some of these custom circuits were based on RockOn designs and vendor and textbook examples, they evolved significantly over the semester (Fig. 6). The mechanical and electrical drawings were presented along with other project information in three major design reviews each fall semester: a) the conceptual design review, focusing on the experimental goals and representing subsystems as functional block diagrams; b) the preliminary design review, featuring detailed subsystem design; and c) the critical design review, including evolved subsystem representations.

![Fig. 4. Functional block diagram of the second WVU payload (2010).](image-url)
6. Payload Construction and Testing

In the early offering of the course the discussion of theoretical concepts and lab work took place in each session. Starting in the 2011-2012 academic year, classroom and lab work were separated physically and in time. In the fall semester an hour of classroom lecture and recitation was followed by an hour of lab work. Currently (spring 2012) the class involves lab work only, dedicated to payload construction and testing.

Payload construction, revision, and testing as well as the challenges they present to the practitioner, has been undoubtedly the most valuable offering of this educational activity to students. While the coursework is useful for setting the stage for the payload design and development, the actual work introduced students to the concepts of systems engineering and demonstrated the challenges and rewards of a real-world project. Each subsystem was constructed and assembled, and finally all subsystems were
integrated and operated as a system. The final integration was performed at WFF with the supervision of NASA staff (Fig. 7).

Testing was a critical component of this activity. Students became familiar with several types of testing methodologies: mechanical, vibration, spin, thermal, electrical, functional, and programming-related. A strong effort was made to have students think critically and be inventive for solutions to design problems. Also most students took the class with little experience on data analysis and were trained to basic modeling and error analysis with test and actual flight data.

An important part of the project has been the ATK collaboration which has enabled the team to test the payload at the end of each spring semester. The off-campus tests included vibration, thermal, electrical, functional tests as well as circuit inspections (Fig. 8), and were a valuable experience for the students visiting the ATK facility. ATK engineers identified potential problems and offered suggestions and in some cases immediate fixes.

Students learnt from their mistakes and difficulties, and in many cases this was a more valuable experience than the theoretical part of the project. Individual students or teams encountered difficulties with or failure of the design which required major revisions and repeated tests. For instance, original designs were usually unrealistic in terms of physical size of components, sensor selection, and electrical power requirements. In terms of estimating the physical fit of the payload, the standard RockSat container is cylindrical and measures 9.0” in height and 10.5” in diameter. In most flights WVU has access to ¼ or ½ of this volume, although a full canister has been requested for the 2012 mission. Additional, time-consuming revisions were necessary in electrical circuit design, PCB design, and estimates of power requirements. In situations where students were unfamiliar with relevant physical principles, multiple design errors were made before an acceptable solution was reached. In such an example, a radio receiver needed for ionospheric plasma sounding was constructed by adopting a textbook design for an active filter. However the use of standard op amps led to instabilities in the circuit. These persisted for several versions of the design until component tests showed they had to be replaced by RF-compatible op amps with appropriate slew rates and gain-bandwidth features. Eventually the receiver design progressed by replacing the op amp design with a simplistic, but stable, LC filter.

Adhering to basic lab practices was necessary for maximizing effectiveness and providing a safe working environment; wherever these practices were not followed inefficiency and errors resulted. As
Vassiliadis et al., Rocket Payload Development

Fig. 8. Vibration testing was part of the test procedures conducted at ATK/ABL in spring 2011.

mentioned above, students had different backgrounds and lab experience so it was necessary to review with them safe handling of electrical components and radioactive sources. In some instances the appropriate fabrication or testing equipment was not available so students had to identify appropriate resources. The Chemistry department glass maker manufactured various containers for the capillary motion experiment in 2011. Similarly other components were requested or donated by external collaborators. For instance ATK staff pointed out that the cosmic-ray assembly should be mounted on a base and then proceeded to fabricate one. In these situations student teams had to be inventive and self-reliant to ensure reliable operation of their payload subsystems.

Students learnt to document their progress through designs, printouts and drawings, code output, and photographs. During the fall semester they prepared the three design reviews mentioned in Section 5. However during the construction phase in the spring semester they had to prepare and file more than 15 reports and presentations. The team presented the design reviews and other documents in telecons with RockSat management and students had to learn quickly how to file information for easy retrieval and how to respond to criticism and feedback on their payload designs.

In addition to design and construction stages with multiple revisions, logistics posed smaller, but important problems. Delivery delays from domestic and especially foreign sources could be critical for a construction phase limited to one semester. Such a case arose in early spring 2011 during the construction of a basic cosmic-ray detector, consisting of an array of four Geiger counters. A sample one-counter detector was built and tested in February of that year. However before the remaining components could be ordered, a major nuclear accident took place at a power plant in Fukushima, Japan, on March 2011. The ensuing contamination in East Asia and the Pacific Rim, and the concern for contamination in North America led to a several-month-long worldwide shortage for radiation detectors and their components. The cosmic-ray experiment was placed on hold and only after negotiations with a vendor did the team receive the remaining components approximately a month before launch.

In summary, the challenges imposed by project constraints (physical-size, flight-related, electrical, functional, programming, and logistical) were considered a valuable experience for students. These obstacles along with the weekly management of finances and communications provided students with potentially useful perspectives on real-world problems and corresponding risk management practices.
**Fig. 9.** Cosmic-ray experiment measurements with flight stages indicated (2010).

**Fig. 10.** Radio sounding of ionospheric plasma (2011). Left: transmission of a MHz pulse and recording of the reflected pulse amplitude (active sounding). Right: fluctuations of the undisturbed plasma (passive). The amplitude of the recorded pulse is plotted versus time from launch. A third mode (not shown) used two GHz frequencies tuned so that their beat frequency of a few MHz resonated with the plasma.
7. Payloads Flown

Since 2009 a number of subsystems and experiments have been constructed and flown on WVU payloads. Several have been reflown since they provide useful data (e.g., flight dynamics experiment), failed to function properly (capillary motion experiment), or their design is revised and expanded (radio sounder). They are summarized in Table 1 below and selected data are presented in Figs. 9 and 10.

<table>
<thead>
<tr>
<th>Flight dynamics variables</th>
<th>2009 (workshop)</th>
<th>2010</th>
<th>2011</th>
<th>2012 (planned)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle acceleration (1D)</td>
<td>3D acceleration, 2D rotation</td>
<td>3D acceleration, 2D rotation</td>
<td>3D acceleration and rotation</td>
<td></td>
</tr>
<tr>
<td>Earth observation</td>
<td>-</td>
<td>-</td>
<td>Video camera (optical)</td>
<td>-</td>
</tr>
<tr>
<td>Astrophysical observations</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>UV camera</td>
</tr>
<tr>
<td>Earth’s magnetic field</td>
<td>-</td>
<td>3D field</td>
<td>3D field</td>
<td>3D field</td>
</tr>
<tr>
<td>Canister thermal changes</td>
<td>Pressure and temperature</td>
<td>Board temperature</td>
<td>Board temperature</td>
<td>Board temperature</td>
</tr>
<tr>
<td>Atmospheric properties</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Temperature; CO$_2$, H$_2$O, and O$_3$ density</td>
</tr>
<tr>
<td>Liquids in microgravity</td>
<td>-</td>
<td>-</td>
<td>Capillary motion (failed)</td>
<td>Capillary motion</td>
</tr>
<tr>
<td>Ionospheric properties</td>
<td>-</td>
<td>Plasma density via radio sounding (failed)</td>
<td>Plasma density via radio sounding</td>
<td>Density/ temperature: radio sounding, probe</td>
</tr>
<tr>
<td>Plasmas in microgravity</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Simple plasma discharge</td>
</tr>
<tr>
<td>Cosmic rays</td>
<td>Particle flux</td>
<td>Particle flux</td>
<td>Flux as a function of energy</td>
<td>Flux as a function of energy</td>
</tr>
</tbody>
</table>

Table 1. Summary of experiments on the 2009-2012 payloads.

8. Project Outcomes

The rocket payload development project has been rewarding to most stakeholders, namely students, instructors, departments, and supporters on and off campus. Although the program started with one student in its first year, it has by now involved close to 20 undergraduate (mostly aerospace engineering) and 3 graduate students. Juniors and seniors became familiar with the systems-engineering perspective applied to a project which often seemed open-ended. Many students used this experience as a starting point for learning more about aerospace applications and the space environment in general. One of the best students went on to work as a summer intern at NASA’s research rocket team at Goddard Space Flight Center for two successive summers. Using the experience from the payload and earlier projects he worked on circuit and sensor designs for an experiment called FireStation which is scheduled to operate on board the International Space Station in early 2013. Following this experience, the student returned to lead the WVU RockSat team twice, transferring knowledge obtained in his Goddard tenure. A second student, who worked on the radio sounder experiment, has started doctoral studies in plasma physics. Other students have gone on to industry and government internships and related summer jobs.
The departments supporting this program together with the WV Space Grant Consortium have had significant visibility in the press and media. Numerous campus articles have featured this project and it was covered on the WV Public Radio in August 2011. Two side projects have been started to support the rocket payload project including an advanced soldering and electronics workshop at a level similar to J-standard. As a result of these and related activities, a NASA IV&V research group currently designing a microsatellite mission has invited the rocket development group to contribute concepts and materials for payload and infrastructure components. The first such pair of microsatellites is scheduled for launch in August 2012.

9. Concluding Remarks

This paper has presented a senior-level design project on development of simple rocket payloads through which West Virginia University student teams participate in the RockSat mission providing low-cost access to space. The project provides a platform where STEM undergraduate and graduate students can be involved in educational and research activities on a number of engineering and science topics.

Acknowledgments

The authors are grateful to Physics department chairman Earl Scime and WV Space Grant Consortium director Majid Jaridi for supporting this project, and thank the students of all WVU teams, especially M. Gramlich, for their work and dedication. DV thanks ATK engineers Chuck Durney, Mark Solberg, Mark Rudy, Craig Kesner and many others for reviewing the payload designs and providing helpful suggestions. DV also thanks Goddard researchers Douglas Rowland and Robert Benson, and University of Iowa researcher Scott Bounds for their comments on the plasma sounder. Suggestions for individual experiments from WVU faculty Mark Koepke, Alan Barnes, and Lloyd Carroll are appreciated.

Bibliography