2006-1917: THE STUDENT SPACE SYSTEMS FABRICATION LABORATORY: AN APPROACH TO SPACE SYSTEMS ENGINEERING EDUCATION

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Abstract

The Student Space Systems Fabrication Laboratory (S3FL) is a student-led organization dedicated to providing students with practical space systems design and fabrication experience not readily available through the usual academic curriculum. S3FL's approach is to enhance education by coupling classroom knowledge with practicum experience involving real engineering design, analysis, test, fabrication, integration, and operation of actual flight vehicles and space payloads. Each year, S3FL involves over a hundred undergraduate and graduate students in activities ranging from balloon payloads to microgravity experiments to nanosatellites. By participating in the end-to-end development of complete space systems, students acquire knowledge and expertise that would otherwise take years of post-graduate experience to be achieved.

1 Introduction

A growing concern in recent years is that of the United States losing its strength in the science and engineering fields. Although the demand for workers with scientific and engineering backgrounds continues to grow, the number of undergraduate U.S. citizens training in these fields is declining, while at the same time many current members of the technical workforce are expected to retire within the next 20 years.[1, 2] These disturbing trends are particularly apparent in the aerospace sector, where former NASA director Sean O'Keefe has stated that NASA is struggling with a workforce crisis with three times as many science and technology workers over 60 years of age than under 30 years of age.[3] Other government agencies and the aerospace industrial sector are facing a similar problem, and this has far-reaching, negative implications for the country's economic welfare and national security.[4] For the U.S. to maintain and continue developing an effective and internationally competitive aerospace workforce, students must be both attracted to the aerospace field and provided the opportunity to rapidly climb the learning curve.

One response to this need is to more rapidly and better train students by means of realistic and intensive design-build-test activities. Since 1998, the Student Space Systems Fabrication Laboratory (S3FL) at the University of Michigan's College of Engineering has combined a formal design process with student creativity and spontaneity to train and provide students with opportunities for research in space system design and development.[5] This paper describes S3FL's resources and operations, outlines the lab's educational and design philosophy, and discusses the technical, teamwork, communication, and project management skills developed through S3FL. The paper also discusses how these traits combine to make students wiser engineers and better qualified to serve as the nation's future space workforce.

2 Lab Organization

All S3FL day-to-day activities, from personnel management to lab work to collaborative efforts with external entities, are student-run. Administrative support is provided by the student Executive Committee (Excom), composed of graduate and upper-level undergraduate students with prior project lead experience, and the faculty advisors. Excom plays an important role in determining the student projects, establishing project timetables, and allocating personnel and available funds among the student teams. Faculty advisors work with students to identify and suggest projects based on current research interests or external opportunities, provide guidance on technical issues, and act as reviewers in design reviews. They are also a valuable link between students and government, industry, and academia. For projects based on formal contracts and grants, the faculty advisors serve as the principal investigators.

2.1 Personnel

S3FL has grown to where now over a hundred students (e.g., about 140 this year) work on its projects. Depending on interests and capabilities, the students participate via the Undergraduate Research Opportunities Program (UROP), dedicated design or project experience courses, senior-level directed-study, major design experience credit, and work-study as well as volunteering. Table 1 shows the distribution of students for the 2005-2006 academic year.

Most freshman and sophomore students participate in the lab through UROP or as a result of having completed introductory engineering classes that serve as feeders to S3FL. While upper-level undergraduate students also participate through directed study, many of them are able to use S3FL projects for senior design coursework through the Aerospace Engineering, Electrical Engineering and Computer Science (EECS), and Mechanical Engineering (ME) Departments. The Master of Engineering in Space Systems program in the Atmospheric, Oceanic, and Space Sciences (AOSS) and Aerospace Engineering Departments is a source of graduate students who guide systems teams that oversee the general engineering trades within projects. Motivated by the desire to enrich their own educational experience or to supplement engineering skills, student volunteers comprise the remainder of S3FL's membership.

Field of Study	
Aerospace Engineering	62%
Atmospheric, Oceanic, & Space Science	4%
Electrical and Computer Science Engineering	16%
Mechanical Engineering	14%
Other (Physics, Industrial & Operations Engineering, etc.)	4%
Academic Level	
Undergraduate	94%
Graduate	6%
Participation Mode	
Credit (directed-study, design courses, work-study)	83%
Volunteer	17%

Table 1: *S3FL personnel statistics for 2005-2006 academic year.*

2.2 Facilities

S3FL is primarily housed within the College of Engineering's AOSS Department and has laboratory and office facilities within the Space Research Building, Wilson Student Project Center, and Aerospace Engineering Department. The AOSS's Space Physics Research Laboratory (SPRL) has clean room, thermal chamber, and vacuum chamber facilities; the EECS Radiation Laboratory provides radio-frequency antenna test facilities; and the ME Vibrations and Acoustics Laboratory has equipment for performing vibration and shock testing. Design and documentation efforts are aided by access to the University of Michigan's Computer Aided Engineering Network, including numerical modeling and computer-aided design software. For fabrication purposes, the Wilson Student Project Center and Engineering Programs Building provide machine shops and workspace.

2.3 External collaborations

S3FL maintains fruitful collaborative contacts with organizations sharing a common interest in enhancing engineering education and promoting aerospace workforce development. These organizations include student satellite groups at other universities, NASA centers, the Air Force Research Laboratory, and especially industry sponsors such as Lockheed Martin. Students interact with industry professionals via teleconferences, technical email exchanges, and formal design reviews. These exchanges enable students to experience the real world and to build professional contacts that enhance their career prospects. In addition, S3FL maintains a strong relationship with SPRL, whose professional engineers are valuable mentors who participate as reviewers in design reviews, offer training sessions, and provide guidance with test setups, hardware design, and software coding.

S3FL also has intramural relationships with other University of Michigan student groups such as the University of Michigan Aeronautical Science Association (MASA). As a student-run rocketry club, MASA provides S3FL with composite material fabrication expertise and flight opportunities aboard in-house hybrid rockets. These flights are valuable ways of testing telemetry systems and small hardware prototypes for launch environment survivability. S3FL also sends delegates to the University of Michigan Engineering Council, the student body's legislative group, to stay involved in campus events.

In addition to providing university students with real-world engineering experience, S3FL members strongly believe in the need to share the fun and excitement of mathematics, science, and technology with pre-college students. Therefore, S3FL works with the Michigan Space Grant Consortium (MSGC) to offer a variety of outreach programs for local students ranging from kindergarten through high school. Programs include presentations and tours of S3FL along with hands-on aircraft and rocketry workshops. These "beyond the formal classroom" learning experiences promote the aerospace field to pre-college students and encourage them to pursue higher education in engineering and the sciences.[6]

3 Education and Design Philosophy

A comprehensive education that prepares students to be strong contributors and leaders in their future careers requires an academic program of both classroom and practical components. Various forms of the classroom setting provide the foundations of engineering analysis, but they cannot substitute for practical, hands-on experience gained from real-world problem solving in end-to-end projects. S3FL gives students the opportunity to learn and practice sound engineering skills on real space systems projects while developing a systems engineering mindset. Furthermore, students are able to improve management and leadership skills by mentoring new lab members, thus providing a self-sustaining quality for S3FL.

3.1 Hands-on projects in real-world settings

Students are attracted to S3FL by exciting and challenging projects that reward them with the chance to fly experiments in microgravity or to see a product of their hard work fly into space. These projects allow students to directly apply the skills and knowledge learned in the classrooms to real engineering work. In particular, mechanical and aerospace engineering students perform the structural, thermal, and mechanism design, modeling, and analysis; electrical and computer engineering students code flight and ground support software while designing circuits, computer, control, and telemetry systems; operations engineering students perform risk analysis and quality control tasks; and students in the sciences perform the fundamental research that drive project objectives and work with science payload and instruments. With the lab's smaller, introductory projects, newer students are able to start project design and see their payloads launch within the same academic year, thus enabling them to evaluate their interests after going through the entire design-build-test cycle.

Unlike paper design exercises offered in a classroom setting, S3FL projects force students to confront and adapt to real constraints imposed by limited funds, external deadlines, and shifting requirements set by principal investigators or sponsors. The need to produce robust, functional hardware adequate for the task at hand as opposed to esoteric hardware approaches is also a consideration. As a result of these pressures, S3FL students are motivated to become team players thinking of the consequences their design trades have on the rest of the project. Along with the technical skills training and development, S3FL projects thus enhance engineering education and better prepare students for the tasks and problems they are likely to face upon entering the workforce.

3.2 Interdisciplinary environment

For projects that are continually more complex and interconnected, engineers must develop a systems-level perspective and the ability to communicate effectively with colleagues of diverse backgrounds in different disciplines. In S3FL, regular interaction among the subsystems is accomplished via concurrent design meetings. Recognizing that much design grief occurs at neglected interfaces between subsystems and inspired by industry models, concurrent design meetings bring subsystem members together for intense technical sessions to resolve cross-system issues. Through these meetings, students better understand the impact of system-level requirements in driving subsystem designs. Also, students become aware of such issues as the manufacturability of components, the feasibility of enhancing mission flexibility, and the trade-offs of increased payload robustness.

S3FL also offers interdisciplinary training to students through technical workshops. These training sessions permit students to broaden their perspectives and augment technical skills. Thus, students can enhance their engineering repertoire by learning how to lay out a circuit prototype, analyze a model in computer-aided design software, use machine shop equipment for hardware manufacturing, or conduct an integrated system test for flight acceptance and qualification.

3.3 End-to-end design cycle

S3FL projects are designed to be more than paper studies or construction of simple prototypes. The S3FL projects attempt to expose students to the entire end-to-end design cycle, from requirements definitions to post-flight data evaluation. Students become involved at the initial stages of a project by interacting with principal investigators or equivalent customers and outlining mission objectives and top-level requirements. Subsystem teams are responsible for performing the trade studies and analyses to converge on a specific flight configuration, and a dedicated machining team fabricates the necessary hardware. Emphasis is placed on prototyping as well as environmental and integrated system tests whenever possible to identify design flaws and minimize risk. Following mission completion, team members are responsible for performing data analysis, relaying flight results to the principal investigators, and documenting lessons learned that can be applied to future projects.

Throughout the design process, a regular series of internal and external design reviews are held. Modeled after professional design reviews in industry, these formal reviews help foster a culture of critical thinking in the lab to drive out design problems and enhance chances of mission success. “Red Team” reviews consisting of panels of faculty, professional engineers, visiting alumni, and experienced students are regularly held. In addition, project documentation is sent to contacts in government, industry, and academia for review. These reviews are important learning experiences for the students, who develop the skills necessary to present and defend their work in front of a panel of experts and peers. Furthermore, the design reviews reinforce the following engineering principles: traceability of requirements, iterative nature of trade studies, importance of back-of-the-envelope calculations to check simulation results, and necessity of using contingencies and margins to account for design uncertainties.

3.4 “See one, do one, teach one” paradigm

Major projects in S3FL can last for several years from the start of design to operations. The long project durations result in challenges with student retention and turnover; in particular, these top-tier projects must face the prospect of experienced team members graduating and leaving the lab prior to project completion. S3FL therefore provides a strong in-house mentoring system, which helps sustain continuity and project progress and train newer, less experienced students to take over responsibilities vacated by departing members. More experienced students provide leadership and serve as mentors for newer students in a variety of ways.

First, S3FL projects are typically divided into subsystem teams of four to ten students apiece. Student leads of these subsystem teams are responsible for overseeing and directing the day-to-day activities of the team: tracking and reporting its progress to the project management, preparing the team for design reviews, and providing guidance and resources for the team members. Serving as a subsystem lead gives students the opportunity to gain practical experience in managing small technical teams.

Second, each project has a student assigned to the role of project chief engineer. This student is responsible for the overall technical design and for overseeing all the subsystem teams of the project. Chief engineers usually have prior experience as subsystem leads, and they are nominated due to demonstrated outstanding technical and leadership ability. While serving as chief engineer, students learn and develop systems engineering and project management skills needed to lead large design groups.

Finally, more experienced students working on top-tier projects are frequently assigned as technical mentors for newer students working on the lab's smaller, introductory projects. With the lab's principle that the best way to learn is by teaching, mentors are able to solidify their own technical understanding while helping newer students come up the learning curve more quickly by relating past lessons learned. Furthermore, the student mentors provide vital guidance so that newer students do not become unduly frustrated or discouraged after making mistakes.

4 S3FL Projects

The projects summarized in this section illustrate the scope and depth of experiences S3FL provides. Projects range from large, multi-year designs involving dozens of students to small, months-long design projects intended as training programs for newer students and test platforms for prototype designs.

4.1 Top-tier projects

These major design efforts by S3FL include space shuttle science payloads and small satellites. The activity on these complex systems spans a number of years and involves dozens of students at any given time. Top-tier projects require substantial engagement from Excom and the faculty advisors to sustain funding levels and secure access to space; the projects also generally employ the lab's most experienced students to address the significant technical challenges.

*VO*rtex *R*ing *T*ransit *EX*periment (VORTEX)

VORTEX was the beginning of S3FL, which was formed as a result of the University of Michigan Students for the Exploration and Development of Space (UMSEDS) and its members' interest in flying a space shuttle Get Away Special (GAS) payload.[7] Over 70 UMSEDS students worked on the G-093 GAS payload called VORTEX with faculty advisor Professor Luis Bernal. This payload, shown in figure 1, flew in the cargo bay of the STS-89 (January 1998) and STS-88 (December 1998) missions and tested fluid vortex ring interaction with fluid interfaces in microgravity. Being entirely student-run, the VORTEX project demonstrated that student efforts can successfully develop and deliver space payloads.[8, 9] S3FL was thus motivated by the success and lessons learned during VORTEX.

Figure 1: *VORTEX flew twice aboard the space shuttle in 1998.*

Icarus student satellite

Icarus is the active endmass satellite designed for the NASA Propulsive Small Expendable Deployer System (ProSEDS) mission investigating the use of electrodynamic tethers for satellite deorbiting. The main objectives of Icarus for ProSEDS were to provide tether endbody location information using a GPS receiver and endbody attitude dynamics using an aspect magnetometer.[10, 11]

Shown in figure 2, Icarus began in the fall of 1998 as a concept in the Master of Engineering in Space Systems program's interdisciplinary design class. In January 1999, Icarus became the central project for an evolving S3FL and ultimately involved over a hundred students. The complexity of designing a fully autonomous satellite as part of a NASA mission motivated S3FL to collaborate with SPRL, whose professional engineers provided technical support and project management supervision to the student leads.

In 2000, S3FL delivered Icarus to NASA, and it was qualified for launch. Unfortunately, the Columbia accident in February 2003 resulted in the cancellation of ProSEDS, which had been scheduled for flight in March 2003, and Icarus was returned to the University of Michigan in April 2004.

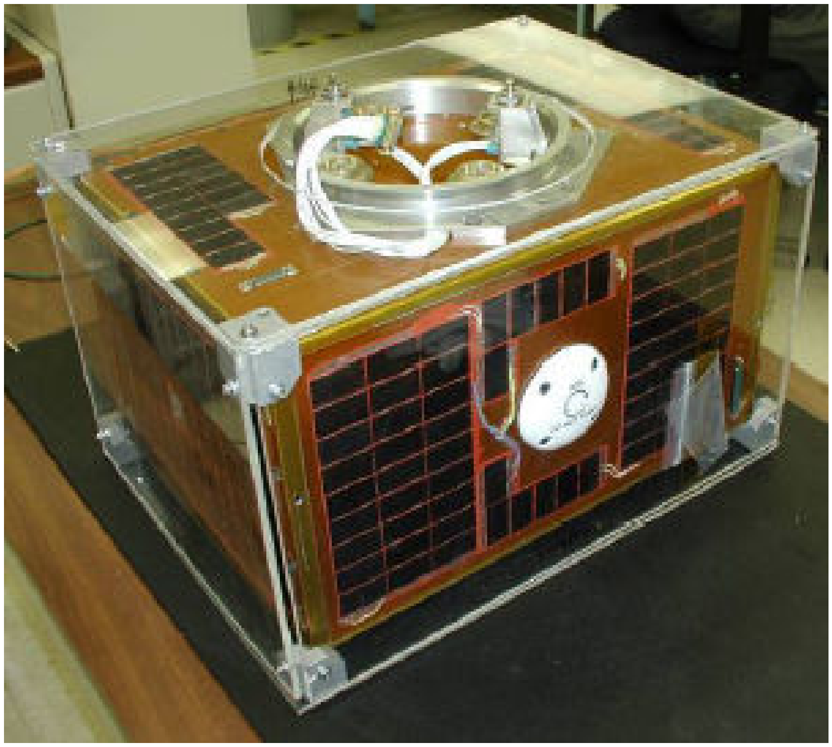

Figure 2: *Icarus is the first fully autonomous satellite built in S3FL.*

*F*ield *E*mission *G*et-Away-Special *I*nvestigation (FEGI)

FEGI was designed as S3FL's second GAS payload after the successful operation of VORTEX. The FEGI experiment was intended to demonstrate the feasibility of operating both commercially available and developmental field emission cathodes in a low Earth orbit environment.[12]

As GAS payload G-187, FEGI began development in early 2001 as a collaborative effort among three schools: the University of Michigan, Pennsylvania State University, and the Air Force Academy. As the project lead, S3FL was responsible for the program management and overall systems design, payload assembly and integration including that of the Small Vacuum Protective Enclosure (SVPE) in figure 3, and systems qualification. FEGI marked S3FL's first formal collaboration with other universities on the same project. Unfortunately, the Columbia space shuttle accident led to the official cancellation of the GAS program in spring 2005. Without the GAS program, the as-designed FEGI payload could not fly despite being a functional engineering design unit.

Although neither FEGI nor Icarus flew, these projects have provided valuable personnel training, systems design, test data, and assembled prototypes for later S3FL efforts. These projects include mFEGI (*m*odular-*FEGI*) and FENIX (*F*ield *E*mission *N*anosatell*I*te E*X*periment) as well as their evolved descendant, the *T*ether *SAT*ellite *T*estbed. Both FEGI and Icarus continue to provide useful examples and lessons for students working on current S3FL projects.

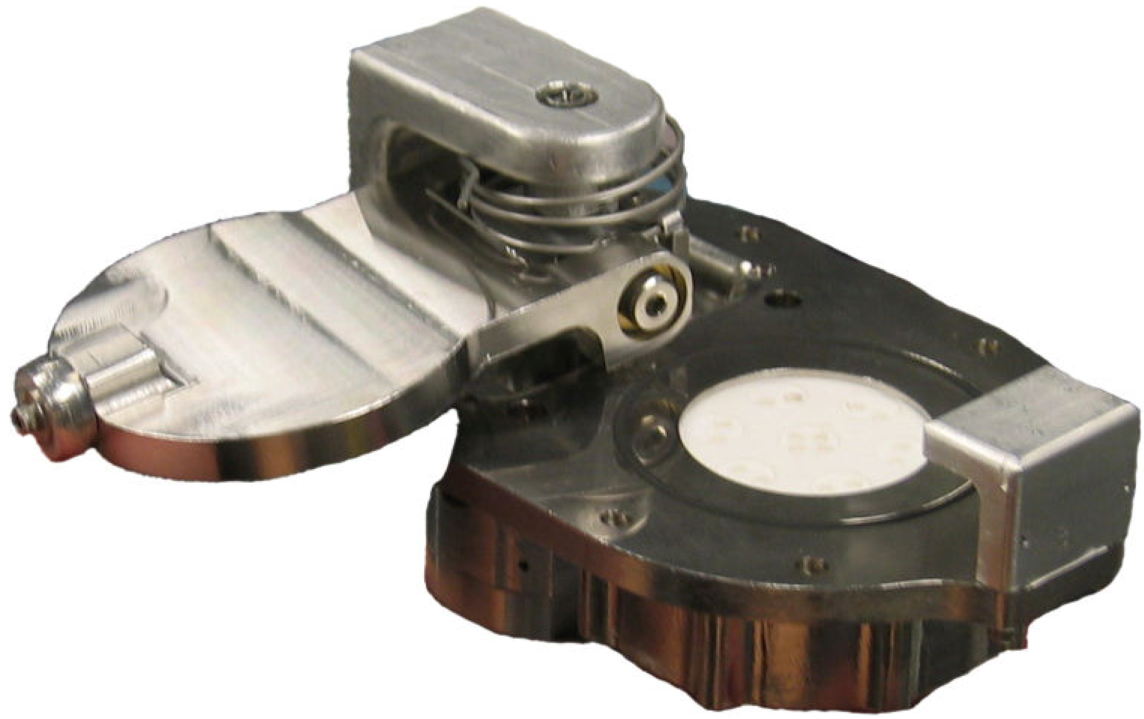

Figure 3: *S3FL designed and built the SVPE mechanism to protect FEGI's field emission cathodes from pre-launch and post-flight contamination.*

*T*ether *SAT*ellite *T*estbed (TSATT)

TSATT, S3FL's current primary project, leverages the knowledge base, trained personnel, and support infrastructure developed by the Icarus and FEGI projects. Sponsored by the Air Force and in collaboration with Tethers Unlimited Inc., TSATT in figure 4 will be a tethered nanosatellite pair (Maize and Blue) to demonstrate tethered systems as viable and cost-effective platforms for inexpensive calibration and validation of formation flying and rendezvous sensors. TSATT will also validate ground-based observation of tethered satellites and space situational awareness capabilities following its deployment from an expendable launch vehicle. With development beginning in 2005, TSATT currently involves over 50 undergraduate and graduate students on this single project.

To help validate the nanosatellite deployment system and initial tether deployment, TSATT team members are taking advantage of a microgravity flight opportunity through NASA Johnson Space Center's competitive Reduced-Gravity Student Flight Opportunities Program.[13] As with the VORTEX team, S3FL students will be using the microgravity conditions generated by the parabola flight profiles of a NASA airplane to test prototype designs. Specifically, S3FL students will be flying a microgravity experiment this summer with a scale model of TSATT to conduct its validation experiment under different deployment conditions.

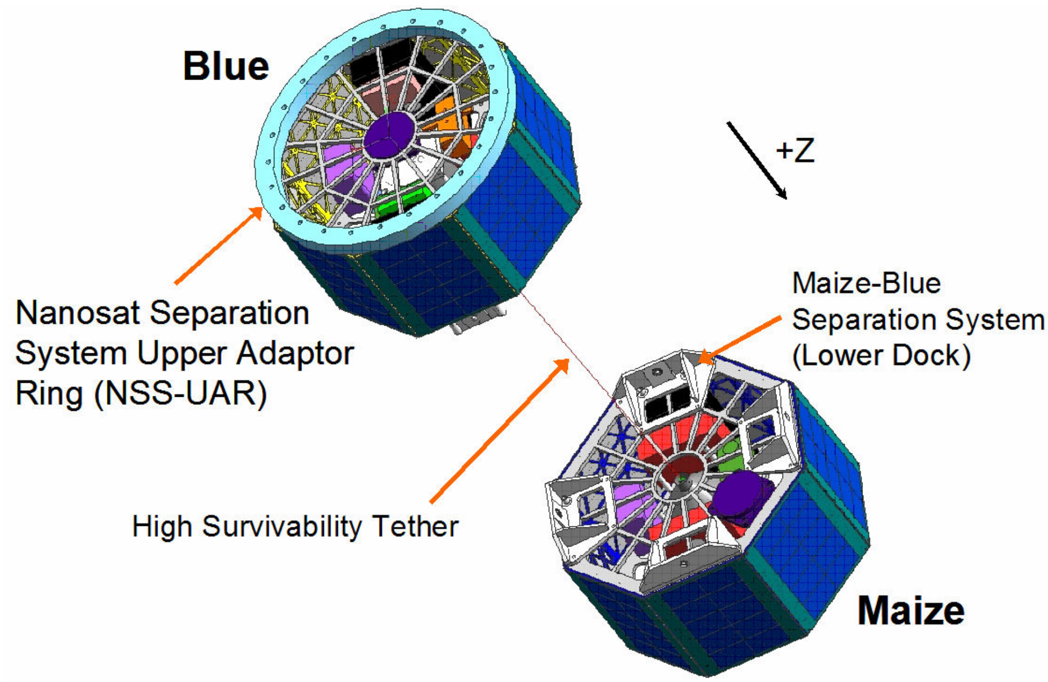

Figure 4: *TSATT in deployed configuration.*

4.2 Introductory projects

For the lab's newer, less experienced students, S3FL runs a number of smaller projects lasting between six to nine months. These projects of lower complexity and risk are tailored to maintain students' interest without overwhelming them. Working in teams of less than ten, students are allowed to develop engineering insights and teamwork tactics in a setting that permits them to make and learn from their mistakes. In addition, the introductory projects train the students in technical skills such as instrument calibration, computer-aided design, and circuit board prototyping. By introducing them to the complete design-build-test cycle, the lab provides newer students with valuable experience and skills that will be needed as they move on to the top-tier projects in later semesters.

Because the introductory projects can be fabricated relatively inexpensively, often at a few hundred dollars each, they also serve as low-cost technology demonstration missions for S3FL's top-tier projects. During the design of FEGI, S3FL made use of BalloonSat payloads launched in weather balloons as shown in figure 5.[14] This BalloonSat successfully tested the microprocessor and control algorithms for the SVPE. In the summer of 2005, S3FL students won the Annual CanSat Competition by launching a can-sized CanSat rocket payload to over a mile in altitude to test microcontroller and telemetry design concepts for the TSATT project.[15] These links with S3FL's top-tier projects give newer students a voice in the lab while encouraging the leads of the larger projects to provide mentorship support.

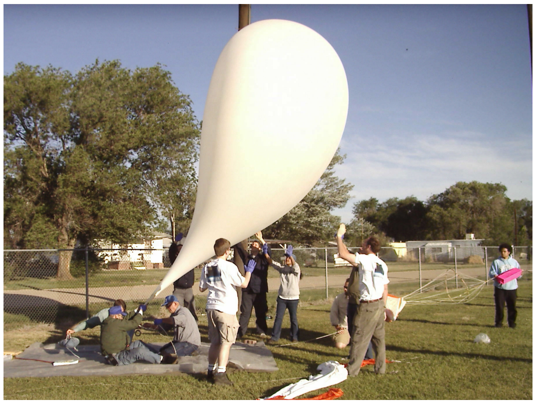

Figure 5a: *S3FL's second BalloonSat payload flew in June 2004 to test the operation of FEGI components.*

Figure 5b: *On-board camera captured this image of Earth at 100,000-ft altitude.*

4.3 Design competitions

S3FL has also diversified its lineup of projects in recent years to take advantage of various aerospace systems competitions. These competitions include systems concept studies and operational prototypes and have definite appeal to the S3FL student population. In 2005, S3FL participated in the NASA and Universities Space Research Association's Revolutionary Aerospace Systems Concept – Academic Linkage (RASC-AL) program with a design for a mobile radiation shelter to protect astronauts on the lunar surface.[16] This spring, S3FL students will again participate in the RASC-AL program along with an American Institute of Aeronautics and Astronautics (AIAA) competition with a concept to decelerate space capsules re-entering Earth's atmosphere using trailing tethers to provide additional drag. S3FL is also entering a beam-powered space elevator prototype in the Spaceward Foundation's Elevator 2010 competition.[17]

5 Conclusion

S3FL's mission is to provide university students with practical, hands-on experience in the design, analysis, test, fabrication, integration, and operation of space systems. Since 1998, S3FL's projects have generated student enthusiasm for the aerospace field and trained hundreds of students in technical, teamwork, communications, and management skills. Lab members have been motivated to attend graduate schools or obtain positions in the aerospace field, with employment at places such as NASA, Lockheed Martin, Boeing, Northrop Grumman, General Electric, AeroAstro, and others. These alumni form an important source for technical knowledge, corporate connections, and collaborative efforts. Indeed, alumni return to assist in design reviews and to directly convey their professional experiences. By working in real-world conditions, adopting professional techniques from the aerospace field, and utilizing lessons learned from the lab's past projects, S3FL makes students wiser engineers who are more resourceful, innovative, flexible, and savvy than they would otherwise be.

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