CUBESATS AS RESPONSIVE SATELLITES

Armen Toorian
Mechanical Systems Lead, Graduate Student
atoorian@calpoly.edu
(805) 756 - 5087

Emily Blundell
Graduate Student
eblundel@calpoly.edu
(805) 756 - 5087

Dr. Jordi Puig Suari
Aerospace Engineering Department Chair
jpuigsua@calpoly.edu
(805) 756 - 6479

Aerospace Engineering Department
California Polytechnic State University
San Luis Obispo, CA 93407

Robert Twiggs
Director Space Systems Development Laboratory
bob.twiggs@standford.edu
(650) 723 - 8651
Stanford University
Stanford, CA 94305

ABSTRACT

California Polytechnic State University, in coordination with Stanford University, has developed the CubeSat standard to provide inexpensive and timely access to space for small payloads. These picosatellites, built mostly by universities, are 10 centimeter cubes with a mass of 1 kilogram. Of the 40 or so participating universities and private firms, more than 60% of CubeSat developers reside in the United States. Our goal is to make launching these satellites easy and cost effective by coordinating launches and providing a reliable deployment system. This paper will discuss Cal Poly's role in the CubeSat program, and the characteristics of the project which create practical, reliable, and cost-effective launch opportunities.

TABLE OF CONTENTS

1 INTRODUCTION

The CubeSat Program is a collaborative effort between California Polytechnic State University, San Luis Obispo (Cal Poly) and the Space Systems Development Laboratory (SSDL) at Stanford University. The objective of the CubeSat Program is to provide a standard platform for the design and launch of a new class of picosatellites - CubeSats.[1]

The CubeSat Program is designed so that space missions can be completed in two years or less (the average collegiate lifetime of a graduate student). This accelerated schedule allows students to be involved in the complete life cycle of a mission. Specifically,

- Mission and requirements planning
- Design, analysis, & testing
- Fabrication, assembly, & quality control
- System level testing
- Integration and launch
- Ground based satellite operations

A unique feature of the CubeSat Program is the use of a standard deployment system. Through the Poly Picosatellite Orbital Deployer, or P-POD, standardization is used to reduce mission cost and accelerate development time. Cal Poly's current roles are to maintain the CubeSat Standard, coordinates launch opportunities, and continue to develop and fly the P-POD. This framework allows universities and organizations worldwide to develop and launch CubeSats without directly interfacing with launch providers (LP).

2 THE DEPLOYMENT SYSTEM (P-POD)

Additional hardware, such as a deployment system, usually only increases complexity. For CubeSats, however, addition of this hardware is critical to mission success.

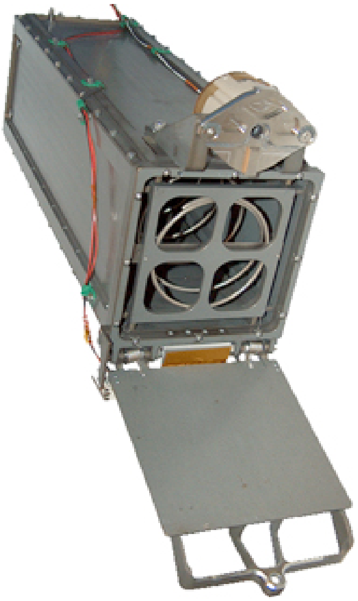

Figure 2-1: P-POD with door open.

2.1 Objectives

The functions of the P-POD are to protect the launch vehicle (LV) and primary payload, to provide a safe and reliable deployment system for the CubeSats, and to maintain flexibility in compatible LV options.

2.1.1 Protect Primary Payloads and the LV

Low cost missions usually imply high risk. Therefore, it is imperative that the P-POD minimize risk to the LV and primary payload.

The P-POD must maintain its own structural integrity and offset any failures that CubeSats may have during launch. Encapsulation of CubeSats within the P-POD, mechanically and electrically isolates CubeSats from the rest of the LV, reducing risk of damage due to

- Accidental activation of electronics
- Debris produced by structural damage
- Prematurely deployed antennas/booms

2.1.2 Protect CubeSats

Assuring the safety of the CubeSats is an important but secondary objective of the P-POD. The P-POD should still provide a safe environment for the CubeSats during launch, and maintain a high level of reliability. Also, the P-POD should not introduce large spin rates to the CubeSats during deployment.

The P-POD also serves as a storage bin between integration and launch, protecting CubeSats from hazardous environmental factors such as dust, ESD, and damage due to mishandling or good-intentioned "last minute tuning" by engineers.[2] Once integrated, CubeSats may charge batteries and undergo diagnostics through an access port, but will otherwise remain in a dormant mode until being deployed in space.

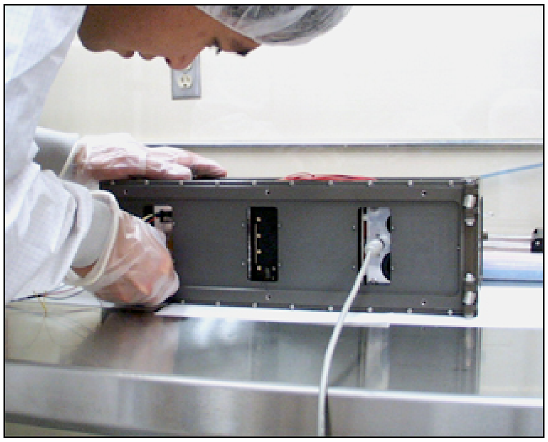

Figure 2-2: P-POD Access ports.

2.1.3 Provide LV Flexibility

Published secondary payload envelopes played a large role in defining the P-POD's size and shape. As a result, the P-POD is compatible with a wide variety domestic and foreign LV.

Table 2-1: Some compatible launch vehicles.

Delta II[3]	Pegasus
Delta IV – SAM	Taurus
Delta IV – ESPA[4]	Falcon I
Atlas V – ESPA[4]	Rockot (Russian)
Space Shuttle	Dnepr[5] (Russian)

Though the small size of the P-POD allows for many interface possibilities, launch providers (some Russian LP excluded) are not willing to squeeze secondary payloads wherever they can find extra room. Therefore, only the most conservative secondary payload envelopes were considered viable options.

2.2 P-POD Design

The P-POD's design is extremely simple, and purposefully so. It is an aluminum box with a spring, a door, and a mechanism to open that door. CubeSats are stacked inside the P-POD and constrained by a set of hard anodized, teflon-impregnated rails. These rails provide a low-friction surface for the CubeSats to slide against during deployment.

The P-POD's only task is to open the door (at the right time) and push CubeSats out. The philosophy of simplicity was adopted very early on because the P-POD has to do its task extremely well. After all, the owners of a newly disintegrated $90million mega-satellite probably will not be very accepting of their loss due to a secondary payload failure (even if the students do learn a valuable lesson).

2.2.1 Modularity

The P-POD can hold a number of different CubeSat configurations, totaling a length of 340.5mm (the length of three standard sized CubeSats). Double (227.0mm long), and triple (340.5mm long) CubeSats can also be integrated without modification to the P-POD.

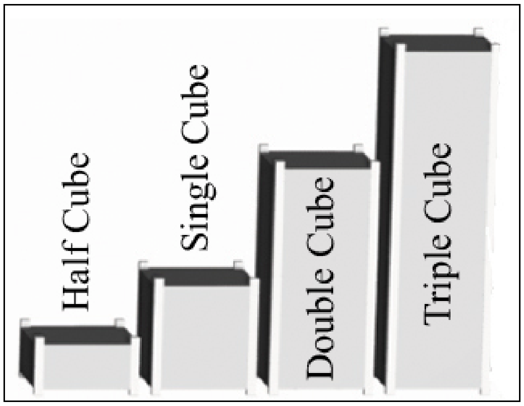

Figure 2-3: CubeSat configurations.

2.2.2 Simplicity

Due to its simplicity, working on the P-POD is a painful exercise in restraint for an undergraduate engineering student. However, less time spent designing, means more time spent testing.

Minimizing the number of mechanisms allows those mechanisms to be designed carefully, and parts to be chosen meticulously. Furthermore, reducing the number of mission critical components, affords those components a larger portion of the budget. The P-POD has three such mechanisms.

2.2.3 Critical Components

The Starsys Qwknut 3k is used to release the P-POD door. It is a non-pyrotechnic bolt release system[6] with redundant electric circuitry (no electronic components). It is very reliable, and as a result, more expensive than the cost of every other P-POD component combined.

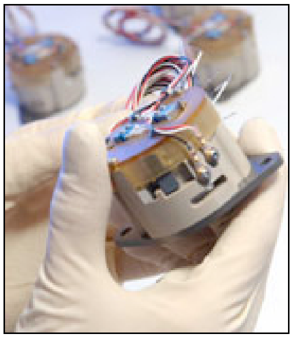

Figure 2-4: Starsys Qwknut 3k.

The Qwknut 3k was chosen over less expensive, or student-designed, components to offset concerns about the P-POD's reliability and limited flight heritage. In addition, the Qwknut is user resettable, which allowed us to perform deployment tests to our hearts' content.

Two torsion springs are used to open the door of the P-POD. These springs provide enough torque to quickly move the door out of the CubeSats' path. The design allows positive mating of the door and release mechanism to reduce stress. Appropriate geometry and lubrication are used to prevent binding of the door.

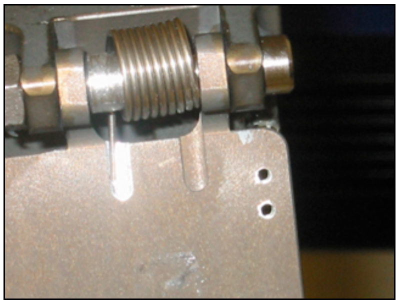

Figure 2-5: Torsion spring for opening door.

An internal compression spring and plate assembly ejects the CubeSats from the P-POD. There is no direct contact between the CubeSats and the spring; only the plate guides the CubeSats throughout the length of the P-POD. The spring is customized based on the required ejection parameters for a given mission. The Dnepr 04-05 mission requires CubeSats to be clear of the P-POD within one second of receiving a deployment signal, but limits their velocity to 2 m/s relative to the upper stage.[5]

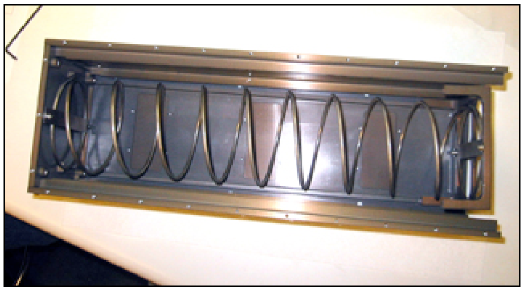

Figure 2-6: P-POD main compression spring.

3 THE CUBESAT STANDARD

A broad objective of the CubeSat Program is to learn which attributes of a spacecraft can be standardized, and which cannot. The CubeSat Design Specification[7] is defined based on some practical requirements, the dimensions of the P-POD, and a number of safety issues.

3.1.1 General Specifications

Even the most basic spacecraft will need a computer, some kind of power generation and storage system, a communication system, and payload. A CubeSat is a cube-shaped spacecraft, measuring 10 cm per side, with a mass of up to 1kg. It is based on the following considerations.

- The market offers a number of solar cells about 30 x 70 mm. CubeSats should be able to body mount at least two solar cells per face to generate enough voltage to support common microcontrollers (3 to 5 volts).
- A wide variety of cylindrical and prismatic cell batteries of various chemistries are available in compatible sizes.
- Most CubeSats will use amateur radio frequencies (around 437 MHz) and low gain antennas. The CubeSat must generate and store enough power for periodic transmissions from low earth orbit (LEO).
- 1 kg is a convenient number in terms of defining cost. Many universities can afford to launch a 1 kg spacecraft. The number of willing and able participants drops dramatically with even a slight increase in mass.

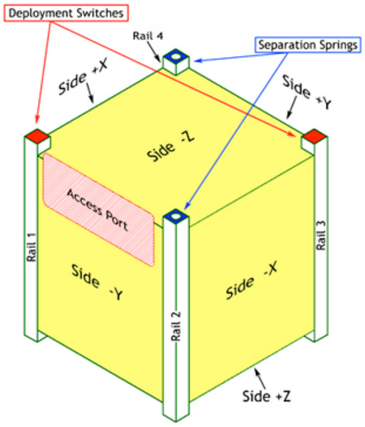

Figure 3-1: Excerpt from CubeSat Specification.

3.1.2 Specifications Due to the P-POD

Likewise, some standards were set based on the shape and size of the P-POD.

- The center of mass of a CubeSat must be within 2 cm of its geometric center to minimize spin rates produced during deployment.
- The location of access ports on the P-POD determines areas on the CubeSats that can be used for diagnostic ports and remove before flight (RBF) pins.
- CubeSat rails should be smooth, flat, and hard anodized to prevent cold

welding due to the launch environment and minimize friction while deploying.

- Thermal expansion of the CubeSat should be similar to that of aluminum 7075-T73 (P-POD material).
- Tolerances in the specification are based on P-POD materials, dimensions and tolerances.

3.1.3 Specifications Due to Safety

A major benefit of the P-POD is that it allows CubeSat developers to take risks without endangering the LV or primary payload. A number of safety features are required on all CubeSats to minimize risk to other CubeSats.

- Incorporated separation springs ensure timely separation between CubeSats.
- At least one deployment switch must physically disable the electronic systems of the spacecraft while depressed (when inside the P-POD).
- A delay of several minutes must be implemented before deployment or activation of any antennas, booms, or transmitters.
- A RBF pin is required to keep the CubeSats inactive during integration.

Finally, the most important aspect of the CubeSat Specification Document is its maintenance by an objective third party. This detachment is essential to successfully enforcing the standard and meeting launch provider requirements.

4 LAUNCHING CUBESATS

In the CubeSat Program, everything is considered a component of a larger system. Understanding the interactions between these systems is crucial to flying secondary payloads.

4.1 Testing Philosophy

A "test as you fly" approach is used throughout the CubeSat Program. Integrated tests are performed to identify any problems caused by unknown interactions between specific CubeSats, and between those CubeSats and the P-POD.

The P-POD itself is designed to withstand very harsh environmental conditions. However, in the event of a failure of one or more CubeSats, the P-POD must protect the primary payload and launch vehicle. Therefore, even flight P-PODs are tested above and beyond LP requirements.

Design level testing, following any modification or addition to the P-POD, is much more stringent. Since dynamic loading due to vibration is the biggest concern, multiple P-POD engineering models have been successfully tested to random vibration levels of 14.1 Grms for 10 minutes per axis, compared to 1 minute per axis required by NASA GEVS[8] documentation. P-PODs are also designed to operate between -45°C and +65°C.

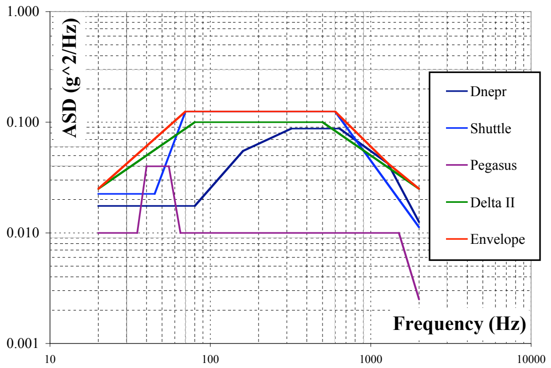

Figure 4-1: Various random vibration profiles.

CubeSat developers can choose to design and test to elevated environmental conditions as well. This qualifies a developer's CubeSat for any launch opportunity with equivalent, or more lenient, requirements. CubeSat developers are urged to think of their spacecraft as one component in a larger family of systems. The quality of their work can have tremendous impact on other CubeSats as well as the success of the mission.

4.2 Advantages of Repetition

Once the P-POD and interface have been flight proven, minimal work is required for subsequent launches on the same LV. This strategy eliminates a large portion of mission specific design, analysis, and testing.

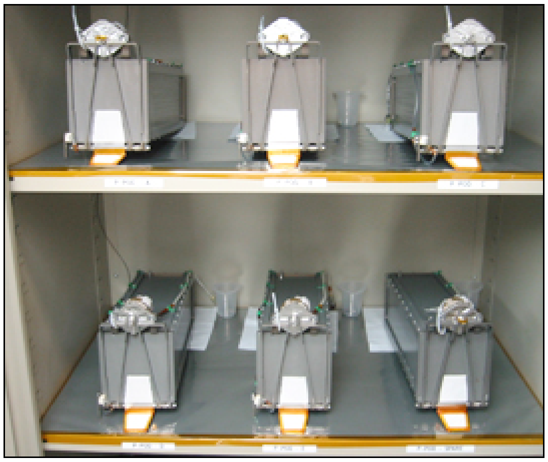

Figure 4-2: Integrated P-PODs (Dnepr mission).

As the CubeSat Program evolves, it is feasible to develop a catalog of prequalified P-POD/LV interfaces. The large number of developers worldwide creates the necessity for frequent launches. This means flight heritage can be established quickly, since every mission provides more experience with the same system, and most missions require multiple P-PODs. Additionally, P-POD components can be ordered in large quantities, and therefore, with quantity discounts. Eventually, the early stages of a CubeSat mission might be:

1. Assemble a group of nearly completed CubeSats
2. Conduct a survey of near-term launch opportunities
3. Choose a preexisting P-POD/LV interface
4. Begin negotiating secondary payload accommodations with the LP

4.3 Multiplexing Spacecraft

Without sacrificing robustness, the P-POD has been carefully optimized for mass. One empty P-POD for the Dnepr 04-05 mission has a mass of 2.5 kg, and carries a 3 kg payload.

If a P-POD was designed for one CubeSat, its mass would roughly be 1.75 kg. Combining multiple CubeSats into one P-POD increases risk for CubeSats, but decreases the total mass of the deployment system by over 50%. Also, each developer is now only paying for one third of a very expensive release mechanism.

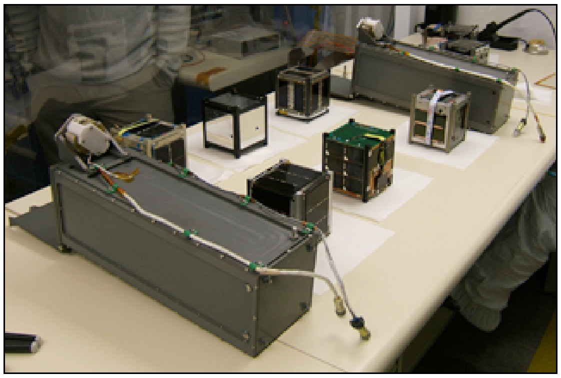

Figure 4-3: Group of 6 CubeSats and 2 P-PODs.

Due to cost and the large number of developers looking for access to space, it became apparent that three CubeSats per mission would not be efficient. However, with a dozen or so participants, total mission launch costs of half a million dollars become manageable for university projects. Launch costs to the developer include

- Cost to launch 1 kg of CubeSat
- Cost to launch 1/3 mass of the P-POD
- P-POD and LV interface development, manufacturing, and testing
- Licensing and administrative costs

4.4 Building Block Approach

At one point, the P-POD endured many design iterations to increase capacity to more than three CubeSats. The result was, instead, to mount multiple P-PODs in small clusters. This way, groups of CubeSats can easily be added to or removed from a mission as necessary. Risk is also mitigated in this way, since a malfunction of one P-POD does not mean a failure for the entire mission.

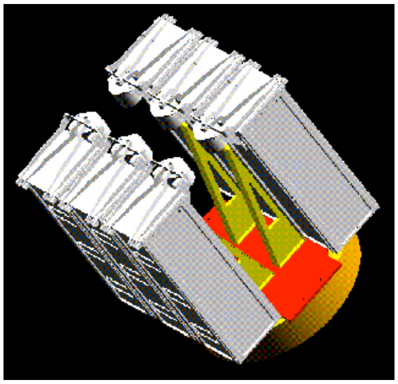

Figure 4-4: Interface for SAM and ESPA.

Additional hardware is required to group P-PODs in this way. Usually, this additional hardware is also the interface between the LV and P-PODs. Available secondary payload envelopes and mass requirements determine the number of P-PODs per cluster.

Sometimes one cluster of P-PODs does not provide the required capability. In this case, multiple clusters can be mounted to the launch vehicle. The final package – composed of CubeSats, P-PODs, and P-POD clusters – is then delivered to the launch provider. The goal is to make intermediary systems transparent to the LP so that the delivered hardware can be treated as a single, non-separating payload.

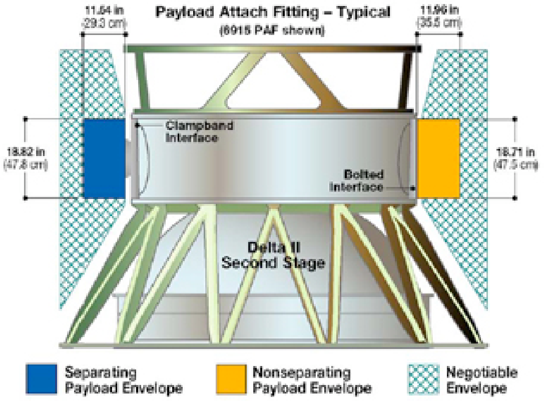

Figure 4-5: Delta II secondary accommodations.

5 THE RESULTS

In June 2003, a Rockot launch vehicle (LV) launched one commercial and 5 university CubeSats into orbit from Plesetsk, Russia. A second CubeSat launch, scheduled for the summer of 2005, will place 14 CubeSats into orbit using a Dnepr LV and five P-PODs. Concurrently, a third launch is planned to accommodate six P-PODs in December 2005. After only three missions, there will be more than 30 CubeSats in low earth orbit. Based on current capabilities, the CubeSat community can easily sustain one or more launches per year, with multiple P-PODs on every mission.

Around 600 students currently participate in CubeSat projects worldwide. As a result, there is a large community of developers working to solve similar problems. Students can learn from others' past experiences and pose questions in an open forum.

Since few S-class parts fit into a 10 cm cube, CubeSats use a wide variety of COTS components, due to their size, cost, and short lead times. Consequently, a number of "ad hoc" standards are emerging within the CubeSat community. Laptop and cellular phone parts are very popular, and many developers choose to use COTS components that have shown success and reliability on other CubeSat missions (Pic™ processors, Lithium Polymer batteries, etc.)

Additionally, CubeSat developers are likely to have internal standards. Often, developers use identical or similar components and systems on multiple missions. A number of developers design their spacecraft bus generic enough to support a wide variety of payloads.

By participating in a launch coordinated by Cal Poly, developers can focus on design and development rather than interfacing with the launch provider. The level of handholding required between LPs and universities with little or no space experience, greatly increases integration time and costs.

To alleviate these issues, Cal Poly acts as a launch coordinator, working with developers to solve problems without stealing precious time from the launch provider. As a result, the LP interacts with one organization and one piece of hardware. The process is fairly transparent to both the CubeSat developers and the launch provider.

6 CONCLUSION

With a single launch of two P-PODs and six CubeSats (three of which were successful), the quantity of CubeSat launches and operational successes is small.

Even with such small numbers, some claim that CubeSats have already proven themselves as disruptive technology[9]. In the six year history of the CubeSat Program, a standard has been defined, has gained widespread recognition, and has been adopted by over 40 organizations worldwide. Through standardization, launch costs have been reduced, and mission life cycle has been accelerated to acceptable levels for university projects.

With some experience behind us, and some opportunities quickly approaching, the CubeSat Program is in a position to offer low cost access, to space to a large customer base at regular intervals. Because of its low cost, rapid mission life cycles, and flexibility[10], the CubeSat Program has shown significant success as a responsive space program.

7 ACKNOWLEDGMENT

Dr. Jordi Puig-Suari, who continually guides, encourages, and provides insight. His work to secure funding for and establish facilities to research, design, construct, test, and operate CubeSats at Cal Poly has been fundamental to the success of the project.

Our "coordinator in chief", Simon D. Lee for answering heaps of emails organizing meetings, dealing with ITAR, making those phone calls, and always taking one for the team.

Our late night pal, Wenschel Lan who worked on the Delta II P-POD adapter design concept. She also produced four very "trendy" mass models for our upcoming Dnepr 04-05 launch, which are currently spending some much needed vacation time in the Ukraine. We love to keep a plaque of all her achievements.

Roland Coelho, for his time and effort in keeping up our thermal vacuum chamber in order to perform necessary qualification testing. As well as agreeing that some analogies just don't make sense.

The PolySat team, for putting up with the CubeSat standards and CubeSat team members.

Bob Twiggs, for his guidance and advice. Also thank you to all participating universities helping to make the CubeSat Program a success.

Special thanks to Raytheon, the Solar Turbines & Bently Nevada Vibrations Lab, Cal Poly Mechanical Engineering Department, Northrop Grumman, Agilant Technologies, Boeing, Cal Poly Aerospace Engineering Department, California Space Authority, Lockheed Martin, and the AMSAT community.

The Multidisciplinary Space Technologies Laboratory for providing all of us a place to work and sleep.

8 REFERENCES

---

[1] Schaffner, J, "The Electronic System Design, Analysis, Integration, and Construction of the Cal Poly State University CP1 CubeSat" 16th AIAA/USU on Small Satellites Conference, Logan, UT, October 2002, pp. 1-2

[2] Fleeter, R., "The Logic of Microspace," Microcosm, El Segundo, CA, 2000, pp. 146.

[3] Boeing Company Launch Services, "Delta Launch Vehicle Secondary Payload Planner's Guid for NASA Mission" <http://www.boeing.com/defense-space/space/delta/docs/DELTA II PPG 2000.PDF>

[4] DOD Space Test Program, "Secondary Payload Planner's Guid for Use on the EELV Secondary Payload Adapter," Version 1, June 2001. <http://cadigweb.ew.usna.edu/~midstardownloads/structures/ESPA Payload Planners Guid.pdf>

[5] International Space Company Kosmotras, "Interface Control Document of EgyptSat-1, SaudiSat-3, SaudiComsSat, AKC-1, AKC02, containers P-POD with CubeSat spacecraft and SS-18 Intercontinenal Ballistic Missile (modified as the Dnepr Launch Vehicle)," Dnepr-2004-2.3.6061.103, November 2004.

[6] Starsys Research Corp., "Operation Manual, Qwknut," Gen 1, January 2005. <http://starsys.com/catalog/pdf/src 33.pdf>

[7] CubeSat Program, "CubeSat Design Specification," <http://cubesat.calpoly.edu/ new/documents/cubesat spec.pdf>

[8] Milne, J.S., Garvin, J., Baumann, R., "General Environmental Verification Specification for STS & ELV Payloads, Subsystems, and Components," NASA Goddard Space Flight Center, GEVS-SE Rev A, Greenbelt, MD, June 1996.

[9] Swartwout, M., "University-Class Satellites: From Marginal Utility to 'Disruptive' Research Platforms", *18th Annual AIAA/USU Conference on Small Satellites Conference*, Logan, UT, August 2004.

[10] Correll, Randall, "Responsive Space Transforming U.S. Space Capabilities," Washington Roundtable on Science & Public Policy, George C. Marshall Institute, Washington, D.C. November 2004, pp. 2-5

AUTHOR INFORMATION

Armen Toorian *is a graduate student in the Aerospace Engineering Department at CalPoly, San Luis Obispo. He is enrolled in a blended program and expects to graduate with both his B.S. degree in Mechanical Engineering and M.S. degree in Aerospace Engineering in June 2006. His thesis work includes the development and testing of the Poly Picosatellite Orbital Deployer (P-POD) for launching on a Dnepr rocket.*

Emily Blundell *is a graduate student in the Aerospace Engineering Department at CalPoly, San Luis Obispo. She is enrolled in a blended program and expects to graduate with both her B.S. and M.S. degrees in Aerospace Engineering in December 2005. Her thesis work includes the design and analysis of interfaces between the P-POD and a number of domestic launch vehicles such as the Delta IV and Atlas V.*

Jordi Puig-Suari *received B.S., M.S., and Ph.D. Degrees in Aeronautics and Astronautics from Purdue University. In 1993 he was a visiting assistant professor in the Department of Aeronautics and Astronautics at Purdue University. From 1994 to 1998, he was an Assistant Professor in the Mechanical and Aerospace Engineering at Arizona State University. In 1998, Dr. Puig-Suari joined the Aerospace Engineering Department at CalPoly, San Luis Obispo as an Associated Professor where he is charged with leading the development of the astronautics program. Currently he acts as Department Chair and adviser to the CubeSat Program. His research interests include spacecraft design, low-cost space systems, vehicle dynamics and control, and tethered satellites.*

Robert Twiggs *is a consulting Professor in Aeronautics and Astronautics Department. He established the Space Systems Development Laboratory (SSDL) in January 1994 at Stanford University with both formal classes and laboratory classes for the development of microsatellites. The laboratory had its first microsatellite OPAL launched in Jon January 26, 2000. The second microsatellite SAPPHIRE will be launched August 31, 2001 on an Athena from Kodiak, Alaska. There are three other microsatellites under development for a shuttle launch in 2003. The Stanford group is now developing a picosatellite called CubeSat. This 1 kg 10cm cube will provide students in many universities with a low-cost, quick-to-launch project that will give them and other space experimenter's easy access to space. The first launches of these CubeSats is scheduled for May 2001on the Russian Dnepr ELV. Professor Twiggs received a BSEE degree from University of Idaho and an MSEE degree from Stanford University.*