University-Class Satellites: From Marginal Utility to 'Disruptive' Research Platforms

Michael Swartwout
Department of Mechanical and Aerospace Engineering, Washington University in St. Louis, St. Louis MO 63130
(314) 935-6077, mas@me.wustl.edu

Abstract. The last ten years have seen a tremendous increase in the number of student-built spacecraft projects; however, the main outcome of these programs has been student training and, on some occasions, extremely low-cost space access for the university science community. Because of constrained resources and an inherently-constrained development team (students), universities have not been in a position to develop 'disruptive' space technologies; in order to secure launches, they are forced to build low-capability, high-margin systems using established design practices.

However, universities have one inherent advantage in developing 'disruptive' space systems: the freedom to fail. Experimental failure is a basic element of university life, and from the university's perspective a failed spacecraft is not necessarily a failed mission. Because of this freedom, universities can take risks with spacecraft that no sensible professional program would dare attempt. The tremendous reduction in the size and cost of electronics are making possible 'disposable' spacecraft that function for only weeks, but whose very low cost and short development cycle make their launch and operation affordable. Universities are uniquely poised to take advantage of disposable spacecraft, and such spacecraft could be used to develop 'disruptive' satellite technologies.

This paper briefly reviews the history of student-built spacecraft, identifying general trends in spacecraft design and university capabilities. The capabilities and constraints of university programs are matched against these emerging technologies to outline the kinds of unique missions and design methodologies universities can use to contribute to the small satellite industry. Finally, this paper will provide examples of these 'disruptive' technologies.

INTRODUCTION

Over the past ten years, there has been an increase of spacecraft production at schools around the world, with 30 university-built spacecraft launched. However, despite the claims and expectations of many of these new participants (the author among them), university satellites have not "disrupted" industry practice in favor of small spacecraft.

There are three ways in which universities typically participate in space missions:

1. As **principal investigators** for the science experiments on board the spacecraft.
2. As **technology developers** for future spacecraft components.
3. As **spacecraft designers, integrators and operators** for a complete (usually school-sponsored) mission.

Universities have primarily participated in the first two categories. This is because of the historical research role of universities and because, until recently, spacecraft components were necessarily large and very expensive. The electronics revolution at the end of the 20th century spilled over into spacecraft development, giving universities the opportunity to build much smaller vehicles at a much lower price.

This change in opportunity led to a very different type of participation. In the first two categories, universities participate as members of a larger development team, receiving significant funding and significant programmatic and technical assistance; they must also make significant contributions towards the flight mission. When a university opts to start a spacecraft bus program, however, it often does so on its own with only some (or no) assistance from government or industry.

However, as noted above, missions in this third category have not revolutionized the space industry; with a few notable exceptions, university-built spacecraft have been low-cost, marginal-performance vehicles.* Students are, by definition, untrained personnel, and thus a truly student-built spacecraft is (and should be) subjected to particular scrutiny by a professional launch provider and its paying customers. Therefore, university spacecraft are forced to be low-capability, high-margin systems following established design practices. Similarly, if students are to be involved in development, then the constraints of an academic cycle force universities into low-performance, short-duration missions. These constraints make it

* A new, slightly pejorative, term has been coined to describe these "no-payload" spacecraft: BeepSat.

exceedingly difficult to develop systems that would disrupt the current market for spacecraft.

However, despite these obstacles – or, more to the point, because of these obstacles – university-class spacecraft possess the ability to become "disruptive" research platforms, introducing technologies and practices to change both the small and large satellite industries. Universities can pursue high-risk, high-reward missions because their primary mission (education) gives them greater tolerance for flight failure. And, the tremendous reduction in the size and cost of electronic components has introduced the possibility of "disposable" spacecraft – systems that function for only weeks or months, but whose very low cost and development cycle make their launch and operation affordable. Universities are uniquely poised to take advantage of disposable spacecraft, and it is such spacecraft that could be used to develop disruptive technologies and missions.

Before proceeding, three terms used in this paper require careful definition.

Disruptive Technology

As defined by the conference organizers, a ***disruptive technology*** is one that fundamentally alters the way in which a task is carried out: electronic mail and cell phones are disrupting society's approach to business and communications, as did television did fifty years ago. This paper is an investigation of whether university-built small satellites will disrupt our approach to space missions. It should be noted that, in this paper, "disruptive" has positive connotations.

University-Class Satellite

The term "university-class satellite" is preferred over "student satellite" because the latter has become nonspecific through overuse; multimillion-dollar science missions and 3-kg Sputnik re-creations are both called "student" spacecraft. For the purposes of this paper, a ***university-class satellite*** has three distinguishing features:

1. It is a self-contained device in Earth orbit with its own independent means of communications and command; it can be bolted onto another vehicle and even draw power from it.
2. Untrained personnel (i.e. students) performed a significant fraction of key design decisions, integration & testing activities, and flight operations.
3. The training of these people was as important as (if not more important) the nominal "mission" of the spacecraft itself.

Therefore, the significant distinction of a university-class satellite (as opposed to a space mission with strong university participation) comes from programmatic issues, not cost or performance; while university-class satellites have traditionally been low-cost and low-performance, this is a logical consequence of the way the missions have proceeded, not an inherent part of their nature. (In fact, there is a mistaken belief that university-built spacecraft are a low-cost alternative to "professional" satellites; this will be further discussed, below.) The purpose of university-class missions is to train students in the design, integration and operation of spacecraft, and this is accomplished by giving students direct control over the progress of the program.

Many spacecraft with strong university connections do not fit this definition, especially those where the university contributes the primary payload. Similarly, while some spacecraft in the amateur radio service are university-class, there are many with the OSCAR designation that do not fit the definition.

Exclusion from the "university class" category does not imply a lack of educational value on a project's part, not does it imply that such programs cannot contribute to "disruptive" spacecraft development; this definition is simply a way to limit the discussion in this paper to a specific class of university missions. The author recognizes the incomplete nature of the information used to determine which spacecraft are university-class, and regrets any mistakes.

Finally, it should also be noted that NASA's University Explorer (UNEX) program sometimes calls its spacecraft "university-class missions;" none of the UNEX missions to date fit the above definition of university-class (though they are not categorically excluded).

Freedom to Fail

The third concept to define is the "freedom to fail," which is so fundamental to the operation of a university (and at odds with the workings of industry) that it is often overlooked. Experimental failure is a basic element of university life; many hypothesis cannot be tested except through experiment, and it is to be expected that some hypotheses (and thus some experiments) will "fail." Since the primary role of a university is to advance learning, a "failed" experiment still yields significant benefits. In the case of student engineers, the sting of experimental failure is often the best (or only) teacher.

Thus the term ***freedom to fail*** connotes a university's inherent freedom to test new concepts within the context of a learning environment, and the freedom to employ unusual or risky practice in an attempt to develop new technologies. However, freedom to fail does not imply that a university should pursue unsound

practice for the sake of being adventurous (or simply low-cost); experimental freedom is not incompatible with reasonable, careful development. It does mean that a failed experiment (up to and including the loss of the mission due to failure of the experimental components) is acceptable.

Up until now, the cost of space missions has severely limited the missions in which universities could exercise this freedom. The implications and limitations of a university's freedom to fail in the context of space missions will be discussed in more detail, below.

Paper Overview

The remainder of this paper is devoted to a discussion of the role of universities in providing disruptive small satellite missions and technologies. First, a review of university-class spacecraft launched since 1981 is provided, including trends in spacecraft design and performances. These trends are extrapolated to consider near-term (5-year) university-class missions. The capabilities and constraints of university programs are matched against these emerging technologies to outline the kinds of unique missions and design methodologies universities can use to contribute to the small satellite industry. Finally, this paper will provide two examples (and one counter-example) of disruptive university-class missions.

REVIEW OF UNIVERSITY-CLASS SATELLITES

A list of university-class spacecraft launched between 1981 and 2003 is provided in Table 1. Because the inclusion or omission of a spacecraft from this list may prove to be a contentious issue – not to mention the designation of whether a vehicle failed prematurely, it is worth discussing the process for creating these tables.

First, a list of all university-related small satellites that reached orbit (i.e. not lost to rocket failure) was assembled from launch logs, the author's knowledge and several satellite databases.[1,2,3,4] Missions that did not meet the definition of "university-class" as defined above were removed from this list. The remaining spacecraft were researched regarding mission duration, mass and mission categories, with information derived from published reports and project websites as indicated. A **Tech** mission flight-tests a new component or subsystem (new to the satellite industry, not just new to the university). A **Science** mission creates science data relevant to that particular field of study (including remote sensing). A **Comm** mission provides communications services to some part of the world (often in the Amateur radio service). While every university-class mission is by definition educational, those spacecraft listed as **Edu** missions lack any of the other payloads and serve mainly to train students and improve the satellite-building capabilities of that particular school. Finally, a spacecraft is indicated to have failed prematurely when its operational lifetime was significantly less than published reports predicted and/or if the university who created the spacecraft indicate that it failed.

This list of spacecraft and their respective details is complete to the best of the author's ability; certain aspects are known to be incomplete and are noted as such. For example, the listed launch masses should be considered approximate, as the variance in mass among different published records can reach as high as 50%. Also, many spacecraft are considered to be "operational" even when most or all of the primary payloads and communications equipment are failed or barely functional; the loss of many spacecraft occurs without any acknowledgement from their operators. Therefore, the listed mission duration in months is approximate.

Finally, a special explanation is required regarding the spacecraft built/supervised by Surrey Satellite Technology Ltd. (SSTL). This organization has trained dozens of spacecraft engineers through the design, integration and operation of spacecraft. These missions appear to fit the definition of university-class satellites. However, because of the resources invested, the capabilities of the spacecraft and the specific training processes used, most SSTL-class missions fall outside the intended meaning of "university-class satellite." To simplify the discussion, SSTL missions are not included in Table 1, except for four which fit the university-class definition (UoSAT 1 & 2, KITSAT-1 and Tsinghua-1).

There have been 46 university-class spacecraft launched between 1981 and 2003 by 28 universities in 15 countries, including 25 spacecraft launched since 2000. In reviewing this list several issues become immediately apparent. The first is that most university-class spacecraft are very small (under 50 kg); with the recent arrival of CubeSat-class spacecraft driving the averages very low. The second immediate observation is that university-class spacecraft are less reliable than their industry counterparts, with about one-third experiencing significant (or complete) loss of performance within a few months of launch. Third, most university-class spacecraft missions could be categorized as educational or amateur communications; the 21 missions carrying science or technology (i.e. potentially-disruptive) payloads tend to be developed by universities with strong government support.

One other observation is relevant to the discussion: of the 28 universities to have participated in developing a university-class spacecraft, only 9 have developed a second (a few more schools may join this list before the end of 2004). It would appear to be very difficult to build a sustainable spacecraft program.

Table 1. University-Class Spacecraft Launched Between 1981 and 2003 (references 1,2,3,4 unless noted).

Launch	Spacecraft	Primary School(s)	Mass (kg)	Mission Duration (months)	Primary Mission Type	Ref
1981	UoSAT-1 (UO-9)	University of Surrey (UK)	52	98	Science	5
1984	UoSAT-2 (UO-11)	University of Surrey (UK)	60	247	Comm	
1985	NUSAT	Weber State, Utah State University (USA)	52	20	Tech	6
1990	WeberSAT (WO-18)	Weber State (USA)	16	97	Comm	
1991	TUBSAT-A	Technical University of Berlin (Germany)	35	157	Comm	7
1992	KITSAT-1 (KO-23)	Korean Advanced Institute of Science and Technology	49	78	Tech	8
1993	KITSAT-2 (KO-25)	Korean Advanced Institute of Science and Technology	48	98	Comm	9
1994	TUBSAT-B	Technical University of Berlin (Germany)	40	1	Tech?	
1994	BremSat	University of Bremen (Germany)	63	12	Science	
1996	UNAMSAT-B (MO-30)	National University of Mexico	10	0.03	Comm	
1997	Falcon Gold	US Air Force Academy	18	1	Tech	
1997	RS-17	Russian high school students	3	2	Edu	10
1998	TUBSAT-N	Technical University of Berlin (Germany)	9	46	Tech	11
1998	TUBSAT-N1	Technical University of Berlin (Germany)	3	20	Tech	11
1998	Techsat 1-B (GO-32)	Technion Institute of Technology (Israel)	70	52	Science	12
1998	SO-33 SEDSAT	University of Alabama, Huntsville (USA)	41	12?	Tech	13
1998	PO-34 PANSAT	Naval Postgraduate School (USA)	70	68?	Comm	14
1999	Sunsat (SO-35)	University of Stellenbosch (South Africa)	64	23	Comm	15
1999	DLR-TUBSAT	Technical University of Berlin (Germany)	45	62	Science	16
1999	KITSAT-3	Korean Advanced Institute of Science and Technology	110	62	Tech	17
2000	ASUsat 1	Arizona State University (USA)	6	0.03	Edu	18
2000	Falconsat 1	US Air Force Academy	52	1	Edu	
2000	JAWSAT (WO-39)	Weber State, USAFA	191	1?	Tech	
2000	Opal (OO-38)	Stanford University (USA)	23	53	Tech	19
2000	JAK	Santa Clara University (USA)	0.2	0	Edu	20
2000	Louise	Santa Clara University (USA)	0.5	0	Science	20
2000	Thelma	Santa Clara University (USA)	0.5	0	Science	20
2000	Tsinghua-1	Tsinghua University (China)	50	48?	Edu	
2000	SO-41 Saudisat 1A	King Abdulaziz City for Science & Technology (Saudia Arabia)	10	40?	Comm	
2000	SO-42 Saudisat 1B	King Abdulaziz City for Science & Technology (Saudia Arabia)	10	40?	Comm	
2000	UNISAT 1	University of Rome "La Sapienza" (Italy)	12	??	Edu	21
2000	Munin	Umeå University / Luleå University of Technology (Sweden)	6	3	Science	22
2001	PCSat 1 (NO-44)	US Naval Academy	12	33	Comm	
2001	Sapphire (NO-45)	Stanford, USNA, Washington University (USA)	20	33	Edu	
2001	Maroc-TUBSAT	Technical University of Berlin (Germany)	47	33	Science	11
2002	Kolibri-2000	Space Research Institute (Russia)	21	2	Edu	23
2002	SO-50 Saudisat 1C	King Abdulaziz City for Science & Technology (Saudia Arabia)	10	17?	Comm	
2002	UNISAT 2	University of Rome "La Sapienza" (Italy)	17	18?	Edu	24
2003	AAU Cubesat	University of Aalborg (Denmark)	1	2	Edu	
2003	CanX-1	University of Toronto (Canada)	1	0	Edu	
2003	CUTE-1	Tokyo Institute of Technology (Japan)	1	12	Edu	
2003	DTUsat	Technical University of Denmark	1	0	Edu	
2003	MOST	University of Toronto (Canada)	60	12	Science	25
2003	QuakeSat	Stanford University (USA)	3	12?	Science	
2003	XI-IV	University of Tokyo (Japan)	1	12	Edu	
2003	STSAT-1	Korean Advanced Institute of Science and Technology	100	9?	Tech	6

Still operational
Semioperational
Nonoperational
Premature loss of operations (or severely degraded operations)

Future University-Class Missions

Within the United States, two approaches for university-class missions now dominate the field: the 1-kg class CubeSat (with its standard P-POD launcher) and the 15-30 kg class Nanosat. More than 50 schools are pursuing the former (including many schools around the world) and about two dozen schools are involved in building satellites in the latter category.

The list of planned launches for 2004 shown in Table 2 indicates the near-term trend in university-class spacecraft: CubeSats. Almost all of the planned university-class launches for 2004 (and beyond) are for these spacecraft, whose launch costs are on the order of $100,000 for each cube. If this second wave of CubeSats is successful (3 of 6 CubeSats from the 2003 launch were either never contacted or failed very early), then many, many CubeSats can be expected in the next few years. In addition, the overwhelming majority of

proposed CubeSats are pursuing Edu missions, and thus the CubeSat community still needs to demonstrate the ability to perform research on this platform.

The Nanosat category is supported by AFRL and NASA through design competitions; these schools attempt to gain government launch sponsorship for a secondary flight. A team from the first competition, 3CornerSat, will fly several of its spacecraft constellation on an upcoming Boeing Delta 4 test flight. The winner of the University Nanosat 3 competition will get a flight in early 2006.

Outside the U.S., schools are either participating in CubeSats or, in the case of a few national universities (Tsinghua, Technical University of Berlin, University of Rome, KACST, among others), they possess sufficient government and industrial sponsorship to continue developing their series of spacecraft.

The continuing trend of smaller components has aided the development university-class spacecraft, especially in terms of MEMS sensors and processors; these components will approach the performance abilities of their larger professional counterparts. However, the schools have already encountered important constraints in terms of communications and power, as the antennas, batteries and solar cells have not (or cannot) follow the trends of other electronics; in fact, it is not mass as much as volume that constrains the performance of future small spacecraft. For the near future, the 10 cm CubeSat appears to be the practical limit for traditional spacecraft architectures, and thus the practical limit for university-class spacecraft using traditional architectures.

ARE UNIVERSITY-CLASS SATELLITES DISRUPTIVE?

To date, no one could argue that university-class spacecraft have disrupted the approach to space missions. (One possible exception has been the UoSATs, which led to the creation of SSTL and a very successful string of missions. However, the success of UoSATs and SSTL has created an important niche for their company, but has not translated into other successful programs – yet.) The reasons for the lack of disruption are apparent: university-class spacecraft are almost always built with high margins of flight safety and low margins of performance using established design practices. Such spacecraft do not lend themselves to disruption, because they do not support new payloads, flight technologies or, most importantly radically new mission architectures.

Many universities pursue spacecraft projects because of internal motivation; their own faculty and students see spacecraft as an exciting and relevant way to teach engineering. The payload (if there is one) is often defined after the project's inception, and thus the payload exists to justify the spacecraft, not the other way around.

Those universities attempting to fly "real" payloads face a different chicken-and-egg problem: the developers of real payloads are justifiably hesitant to risk their components on these new spacecraft, yet without a real payload, the universities cannot the gain flight experience necessary to attract real payloads. And even with a real payload, universities still have the challenge of finding an affordable launch.

Table 2. Planned University-Class Launches in 2004.

Spacecraft	Primary School(s)	Mass (kg)	Launch Date
Naxing-1 (NS-1)	Tsinghua University (China)	25	April
CP1	Cal Poly San Luis Obispo (USA)	1	August
CP2	Cal Poly San Luis Obispo (USA)	1	August
HAUSAT-1	Hankuk Aviation University	1	August
ICE CUBE1	Cornell University (USA)	1	August
ICE CUBE2	Cornell University (USA)	1	August
ION	University of Illinois (USA)	1	August
KUTESat-Pathfinder	University of Kansas (USA)	1	August
Mea Huaka'i	University of Hawaii (USA)	1	August
MEROPE	Montana State University (USA)	1	August
Ncube	Norwegian Universites	1	August
Rincon	University of Arizona (USA)	1	August
SACRED	University of Arizona (USA)	1	August
SEEDS	Nihon University (Japan)	1	August
UNISAT 3	University of Rome (Italy)	12	July
SaudiSat 2	KACST (Saudia Arabia)	15?	July
3 CornerSat: Sparky	Arizona State University (USA)	15	September
3 CornerSat: Petey	New Mexico State University (USA)	15	September
3 CornerSat: Ralphie	Colorado University - Boulder (USA)	15	September

The underlying issue in all of these obstacles is cost: access to space is extremely expensive. Because the cost-per-kilogram of launching spacecraft is so high, spacecraft must be extremely reliable and have a compelling mission. Proper development, integration and testing require significant infrastructure. Therefore, it has been extremely difficult for universities without significant (usually government) sponsorship to complete and launch their own spacecraft.

In the 1990s, the electronics revolution allowed the development of moderately-capable small spacecraft using commercial-grade electronics. Universities were deeply involved in developing these electronics and their implementation in communications, robotics, and other systems. At this time, the belief began to circulate that university-built spacecraft could be low-cost alternatives to professional vehicles. This belief has not proven to be true. University-class spacecraft (i.e. missions where student training is paramount) are not low-cost alternatives because of the resources spent to train the students, and because of the unavoidable mistakes and delays that come from student involvement. While students work considerably more cheaply than professional engineers, their productivity per man-hour is considerably lower, and their work schedule suffers from a significant number of breaks and distractions (e.g., exams).

Therefore, lacking compelling payloads and lacking the resources to attract compelling payloads, most university-class spacecraft have marginal science or engineering return, focusing instead on student training. Clearly, there is nothing wrong with this approach; many students (the author included) have benefited greatly from hands-on engineering experience on these "payload-less" missions. However, as shown in Table 1, most universities with education-only satellites have only built one spacecraft; whatever time, money, personnel and enthusiasm came together to create the first spacecraft were not available to try a second, and the program ended.

While several university programs do have sufficient credibility and sponsorship to pursue traditional research payloads, these projects have tended not to be disruptive; in order to secure a launch these spacecraft carefully follow the traditional constraints of reliability, cost, and performance. In other words, these programs are part of the traditional (i.e. non-disruptive) approach to space missions. There is nothing wrong with this approach, either; they simply aren't pursuing disruptive research.

Could University-Class Satellites be "Disruptive?"

So, is it at all possible for university-class spacecraft to disrupt the spacecraft industry? To answer that question, let us first examine the three main types of payloads carried by university-class missions:

1. A ***simple, low-to-moderate-utility payload*** that has little interest outside the program (except for possible amateur use). Low-resolution commercial cameras and environmental sensors are examples of this category. Most university-class satellites fall into this category (for lack of resources, as discussed above).
2. A ***traditional science payload***, such as a high-resolution telescope. Few university-class spacecraft have carried such payloads, lacking the performance (e.g. pointing control) and/or reliability.
3. An ***experimental component*** or concept to flight qualify. This category is the engineering analog to the previous category, and suffers from the same constraints.

However, as mentioned above, none of these approaches are necessarily well-suited to creating disruptive space missions; they are traditional missions pursued by university students (and thus often subject to even stricter flight-safety constraints than their professional counterparts). Therefore, it is not surprising that these university spacecraft look and behave like less-capable versions of traditional spacecraft.

Because of these constraints, one should not expect university-class spacecraft to "disrupt" the space industry on their own. Student-built systems cannot be built on the same scope or scale as professional spacecraft; students and programs that can do so end up starting their own professional spacecraft companies (and abandoning the constraining university-class spacecraft approach). The most effective way for universities to contribute to the disruption of the space industry is by building research platforms for disruptive concepts and technologies, particularly high-risk/high-return missions and novel architectures.

Universities are in a unique position to pursue high-risk missions because of their freedom to fail; any university-class mission "succeeds" when students gain practical education in spacecraft engineering. Thus, a high-risk spacecraft that fails in orbit still succeeds from the university perspective; success of the flight experiment would be an added bonus.

As with the other mission types, the fundamental obstacle to using university-class spacecraft for high-risk research platforms is cost; universities can afford to fly a failed mission, but launch sponsors cannot. Unless the cost of building, launching and operating university-class spacecraft can be dramatically reduced, there will be only limited opportunity for universities to

participate in disruptive spacecraft development. Such reductions have four requirements: very small spacecraft, common launch interfaces, short-duration nominal missions and large operational margins. These will be discussed in turn.

Small spacecraft. Generally speaking, the lower the spacecraft mass, the lower the cost of the launch. However, this is only true for orders-of-magnitude changes in launch mass (1000 kg vs. 100 kg vs. 10 kg) and for primary payloads; a 10 kg spacecraft may not cost any less to fly in a secondary opportunity than a 30 kg vehicle, and the real launch costs for very small vehicles are driven by integration, flight safety and documentation expenses. Still, spacecraft less than 50 cm on a side and under 30 kg have a wider range of secondary launch opportunities than larger spacecraft.

Also, a smaller spacecraft improves mission reliability; a small vehicle means fewer parts and fewer interfaces, which improves the ability to comprehensively review and test every design, component and interface before launch. Structural performance benefits from the smaller frame; natural frequencies increase and bending moments decrease with decreased size. Therefore, it is easier for a very small student-built spacecraft to pass flight safety reviews.

Common launch interfaces. The spacecraft-to-launch vehicle interface is one of the most reviewed and risk-prone aspects of the mission, especially for university-class spacecraft. Costs can be significantly decreased and reliability significantly increased through the use of common interfaces and form factors across university missions.

For these reasons, common interfaces have already been developed for several types of university spacecraft. Extremely small (1 kg) spacecraft have two standardized interfaces: the P-POD launcher for CubeSats and the DoD launcher built for the MEPSI program. AFRL and NASA have required the standard use of Lightband for their Nanosats.

Very short duration missions. Choosing missions that can be accomplished in short durations (90 days or less) has two benefits. The reduced scope allows for higher-risk, lower-cost/mass components and higher-risk practices that are consistent with a short mission. For example, powerful and inexpensive COTS processors tend to be radiation-sensitive; reduced mission times will reduce their potential exposure. On the education side, a shorter-duration mission tends to be simpler from both a development and operations side, which gives students greater opportunities to see an entire mission from concept through operations. Both of these effects tend to make the spacecraft smaller and less expensive, further improving the launch performance.

Large operational margins. These are student-built spacecraft, which means that design and fabrication errors may exist, and these are high-risk spacecraft, which means that conceptual errors may exist. It is essential to mitigate the effects of these errors by building spacecraft with significant margins in mass, power, computation, pointing and communications. Students should not be expected to design and build spacecraft that push the state-of-the-practice in performance without giving them significant margins in cost, schedule and flight operations.

EXAMPLES OF 'DISRUPTIVE' MISSIONS

Three examples of university-class satellites (two in flight, one in development) will help illustrate the kinds of missions that are well-suited for disruptive university-class research programs.

Disruptive Mission - Opal

The Orbiting Picosatellite Automated Launcher (OPAL, or, as commonly used, Opal) mission began in 1994 at Stanford University, and was launched in January 2000 on a Minotaur rocket as part of the JAWSAT mission.[19] Shown in Figure 1, Opal is a 23 kg hexagonal prism made of aluminum honeycomb carrying COTS electronics. Opal's primary mission was to demonstrate deployable spacecraft technologies; six hockey-puck sized "picosatellites" (PICOSAT 1 & 2, StenSat, Thelma, Louise, JAK) were deployed from Opal several days after launch. In addition to its primary mission, Opal conducted magnetometer hardware testing and acted as an Amateur radio repeater.

Figure 1. Opal [courtesy Stanford SSDL].

The "disruptive" contribution of the Opal mission has two aspects. First, the picosat launcher was a research experiment for potentially disruptive technologies; the PICOSAT spacecraft were the first flight of a DARPA/ Aerospace Corporation program for extremely small spacecraft and MEMS communications technologies. The success of the Opal mission was followed by another PICOSAT flight on MightySat 2.1 and led to the MEMS-Based PICOSAT Inspector (MEPSI) flight program, which will develop "on-board, on-call" miniature inspectors to improve long-term operations. Since MEPSI is still in development, it is impossible to know how MEPSI-class inspectors will affect the future of spacecraft development. However, Opal was an important, low-cost "proof of concept" experiment that enabled this program to proceed.

On the university side, Stanford and Cal Poly teamed to improve Opal's picosat launcher concept for future university-class spacecraft, resulting in the P-POD launcher concept for 10 cm cube, 1-kg CubeSats.[27,28] A half-dozen CubeSats were launched on one Dnepr rocket in 2003, with more than a dozen CubeSats planned for a 2004 launch.

The CubeSat project has already "disrupted" the way that university-class missions are pursued. Only 28 universities have built their own spacecraft since 1981 (including 4 building CubeSats); almost every one of the 10 schools intending to fly CubeSats by the end of 2004 are building their first spacecraft, and more than 50 schools around the world are in the process of building their own CubeSats. Because of Opal, many more universities are using spacecraft projects as classroom teaching tools.

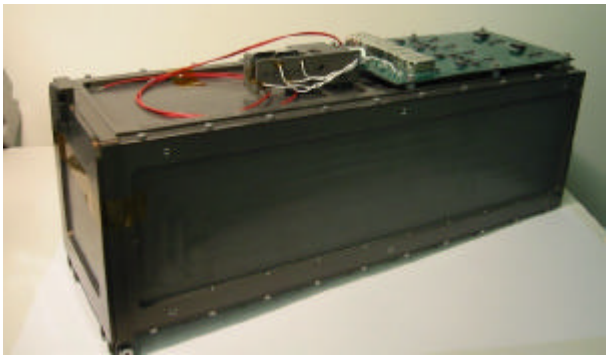

Figure 2. P-POD [courtesy Cal Poly].

Non-Disruptive Mission – Sapphire

In contrast to Opal, the Sapphire satellite has not proven to be a "disruptive" mission. Sapphire was also a Stanford project, started in 1994 and completed in 1998. Lacking a launch sponsor or compelling payload, Sapphire, was donated to the U.S. Naval Academy as a training tool in 2000 and selected by the DoD for a launch in 2001 as part of NASA's Kodiak Star mission. The author served as Sapphire's project manager at Stanford and is Sapphire's primary operator.

Shown in Figure 3, Sapphire is a 20-kg satellite whose primary flight mission was to flight-test a set of MEMS infrared detectors. A student-modified COTS camera and voice synthesizer were also included, and Sapphire carries software to perform autonomous health management.[29]

Sapphire is an example of the traditional university-class spacecraft, where the primary reason to create the spacecraft was the student training itself. Sapphire's lack of compelling flight mission led to the 3-year delay in securing a launch, and its primary function on-orbit has been as spacecraft operations training tool for students at many universities. While the student training is an important mission, it is not disruptive.

Figure 3. Sapphire.

Potentially Disruptive Mission – Bandit

The third example mission is in development at Washington University in St. Louis (WU), where the author serves as principal investigator. In many respects, this mission builds on the lessons learned from Sapphire and Opal. The Bandit program has been scoped in size and purpose to maximize student learning and flight opportunities. The Bandit mission is to demonstrate key enabling technologies for inspector spacecraft: repeatable docking, close

maneuvering near a parent vehicle, and automatic, image-based navigation. These technologies will be tested in phases, with total flight time on the order of hours.[30] The docking structure for the conical Bandit inspector is shown in Figure 4.

Bandit is the lead experiment for WU's Akoya nanosatellite, which is part of the AFRL/NASA University Nanosat 3 competition. Since Bandit will operated in and around the WU-built Akoya spacecraft, mission designers have greater freedom to incorporate high-risk (but low-cost, low-mass, high-reward) designs. For example, the all-WU mission gives Bandit more tolerance for possible impacting, tumbling and other effects of missed docking. In other words, Bandit's "freedom to fail" extends to its potentially damaging effects on the parent spacecraft. Such freedom is unlikely to exist when another party owns the parent vehicle, but is essential for initial flight demonstrations.

The Bandit inspector, dock and flight electronics are less than 3 kg in mass and requiring less than 2 W of power on average. The system is modular, allowing it to be integrated onto other platforms as flight opportunities arise. Also, the experimental plan is incremental, meaning that the entire flight experiment could be conducted over several missions, if needed.

If successful, the Bandit mission would be disruptive by demonstrating that autonomous, image-navigated spacecraft could be produced at a very low cost. On a larger scale, the Bandit mission (and others like it) are disruptive by demonstrating that real spacecraft engineering research can be performed at universities.

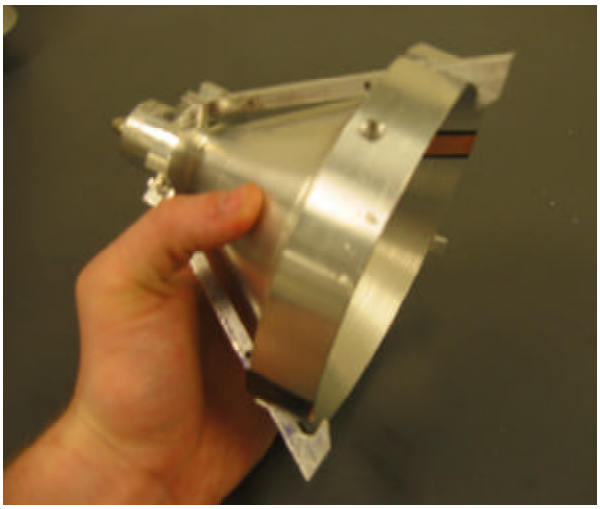

Figure 4. Bandit Dock.

CONCLUSIONS

Universities around the world have discovered that hands-on student satellite projects are an excellent way to educate and motivate students in all aspects of spacecraft engineering. However, the real-world constraints that come with building real-world spacecraft have proven to be very taxing, and only a very few universities have had sustained spacecraft-building activities.

One reason for the lack of sustained programs is the relevance of the spacecraft payload (or lack thereof). Universities can gather the support and resources to sponsor one education-only mission, but can rarely do that for two. The inevitable pressures of cost and schedule and the difficulties in maintaining continuity with regular student turnover are particularly challenging problems for university programs.

The electronics revolution has created new opportunities for university-class spacecraft; reasonably capable spacecraft can be designed and integrated within a student "lifetime" at very low cost (tens of thousands of dollars). The only real cost of the mission is the launch campaign – and these extremely small components lend themselves to extremely small spacecraft, reducing those costs as well.

The advent of extremely small, short-development-cycle, low-cost spacecraft provides an opportunity for universities to apply their unique strengths to spacecraft research: the enthusiasm and novel ideas of students and the freedom to fail. University-class spacecraft are an ideal way to test radically new technologies and architectures, for university-class spacecraft are the most risk-tolerant programs in the space industry.

There is an important difference between mission risk and flight safety risk; for university-class spacecraft to succeed, this difference must be clearly identified by both universities and their launch sponsors. Spacecraft designs or practices that lead to unsafe vehicle behavior during launch or separation poses a threat to the entire launch campaign and should be managed using well-established design, integration and test practices. These practices are completely compatible with disruptive university-class missions.

Mission risk, on the other hand, are those designs or practices that do not pose a flight safety risk but might threaten the on-orbit performance of the vehicle. While mission risk should be minimized, many important demonstrations of new, disruptive technologies will carry significant mission risk (e.g. the Bandit), especially if they are to be attempted within the constraints of a university-class spacecraft. In the author's experience, mission managers and flight safety engineers often do not distinguish between flight risk and mission risk; failing to draw this distinction places additional, unnecessary burdens on the university development team. Much work remains to be done to

convince design reviewers to allow universities to carry their own mission risk.

Perhaps the most interesting development in the history of university-class spacecraft has been the rise of the CubeSat projects; more schools are presently developing CubeSats than the total number of previous university-class spacecraft. As discussed above, it remains to be seen whether this extremely small platform can produce reliable research platforms.

This paper has considered the question of university-class spacecraft as disruptive research platforms without specifying many possible disruptions. The main reason for this is a recognition of the author's inability to predict future events. However, it is interesting to consider that the aspect of the space industry that is most likely to be "disrupted" by university-class spacecraft is the small satellite industry itself; CubeSats and Nanosats, if properly developed, may introduce completely new missions for small spacecraft and completely new ways to design, build and operate these vehicles.

Finally, the work of this paper emphasized the engineering role of universities in developing disruptive technologies. As mentioned in the introduction, the university also plays a significant science/payload development role in all space missions. It would be a worthwhile investigation to learn why university researchers opt for large satellites over small.

ACKNOWLEDGMENTS

The themes of this paper grew out of several years of ongoing discussions with Christopher Kitts, Freddy Pranajaya, Jamie Cutler, Brian Engberg and Keith Bennett. The author would also like to thank all of the university-class spacecraft teams of the past twenty years: the enthusiasm and joy of these students, faculty, industry mentors and sponsors make university spacecraft worth building.

The author accepts sole responsibility for any factual (or interpretative) errors found in this paper and welcomes any corrections.

REFERENCES

Most university-class spacecraft do not publish their work; this is further demonstration of the non-research aspects of their missions. Therefore, most information had to be collected from websites; these sites were current as of this writing (June 2004).

1. Small satellite database managed by Surrey: centaur.sstl.co.uk/SSHP/micro/index.html.
2. Another Surrey database for nanosats: centaur.sstl.co.uk/SSHP/nano/index.html.
3. Satellite and launch database managed by Gunter Krebs: www.skyrocket.de/space/space.html.
4. A Brief History of Amateur Satellites: www.amsat.org/amsat/sats/n7hpr/history.html.
5. Sweeting, M.N., "UoSAT-1: A Review of Orbital Operations and Results," Journal of the Institution of Electronic and Radio Engineers, vol. 57, No. 5, Sep-Oct, 1987.
6. Bonsall, C.A., "The NUSAT I Project--Government, Industry, and Academia Learning Together," IEEE Transactions on Education, vol. 34, No. 1, Feb, 1991.
7. Renner, U., "University Experiments for Small Satellites," European Space Agency (Special Publication), No. 298, May, 1989.
8. Kim, H.S., J.H Park, K.H. Kim, H.K. Lee and S.D. Choi, "On-board Computer System for KITSAT - the First Korean Satellite," AIAA/IEEE Digital Avionics Systems Conference Proceedings, 1994.
9. Yoo, S.K. S.R. Lee, H.J. Kim, H.J. Lim, H.S. Lee, D.K Sung and S.D. Choi, "KITSAT-2 CCD Earth Imaging System Experiment," Proceedings of SPIE - The International Society for Optical Engineering, vol. 2317, 1995.
10. RS-17 (Sputnik 40): web.ccr.jussieu.fr/physio/Satedu/sputnik40.html.
11. TUBSAT-N and N1: www.ilr.tu-berlin.de/RFA.
12. Guelman, M., I. Flohr,; F. Ortenberg, M. Shachar, A. Shiryaev, A. Volfovsky, and R. Waler, "Israeli Microsatellite TECHSAT for Scientific and Technological Research: Development and In-Orbit Testing," Acta Astronautica, vol. 46, No. 2, 2000.
13. Evans, S.W., "Post Deployment Recontact Issues for the SEDS/SEDSAT Mission," Advances in the Astronautical Sciences, vol. 93, No. 2, 1996.
14. Phelps, R.L., "Operational Experiences with the Petite Amateur Navy Satellite – PANSAT", Proceedings of the 15th AIAA/USU Conference on Small Satellites, Logan, UT, 2001.
15. G.W. Milne, A. Schoonwinkel, S. Mostert and J.J. du Plessis, "Educational Aspects of the SUNSAT Microsatellite and its Enabling Role for Other Developments," IEEE AFRICON Conference, vol. 2, 1996.
16. Roemer, S., "Flight experiences with DLR-TUBSAT," Acta Astronautica, vol. 52, No. 9-12, May/June, 2003.
17. Kim, E.E., S. Kim, D.K. Sung, and S.D. Choi, "Development of an Engineering Test Satellite,

KITSAT-3," European Space Agency (Special Publication), No. 430, 1999.
18. Rademacher, J.D., H.L. Reed, and J. Puig-Suari, "ASUSat 1: an example of Low-Cost Nanosatellite Development," Acta Astronautica, vol. 39, No. 1-4, Jul-Aug, 1996.
19. Cutler, J. and G. Hutchins, "OPAL: Smaller, Simpler, and Just Plain Luckier," Proceedings of the 14th AIAA/USU Conference on Small Satellites, Logan, UT, September 2000.
20. Valdez, A., C. Hu, C. Kitts, M. Breiling, A. Slaughterbeck, J. Ota, D. Hadi, T. Kuhlman, and S. Lyons, "Artemis Project: Picosatellites and the Feasibility of the Smaller, Faster, Cheaper Approach," IEEE Aerospace Applications Conference Proceedings, vol. 2, 1999.
21. Graziani, F., G.B. Palmerini, F. Santoni, P. Tortora, and C. Marchiori, "Mechanical Design and Manufacturing of the Microsatellite UNISAT," European Space Agency (Special Publication), No. 468, 2001.
22. Barabash, S, I. Kiryushkin, O. Norberg, M. Ovchinnikov, and V. Penkov, "The Nanosatellite Munin, a Simple Tool for Auroral Research," Advances in Space Research, vol. 31, No. 2, 2003.
23. Kolibri 2000: www.iki.rssi.ru/kollibri/otch_e.htm
24. UNISAT: gauss.ing.uniroma1.it/attivita/unisat/intro.htm
25. Rucinski, S., K. Carroll, R. Kuschnig, J. Matthews, and P. Stibrany, "MOST (Microvariability and Oscillations of Stars) Canadian Astronomical Micro-satellite," Advances in Space Research, vol. 31, No. 2, 2003.
26. STSAT-1: satrec.kaist.ac.kr
27. Twiggs, R.J., "Space System Developments at Stanford University - From Launch Experience of Microsatellites to the Proposed Future Use of Picosatellites," Proceedings of SPIE - The International Society for Optical Engineering, vol. 4136, 2000.
28. Puig-Suari, J., C. Turner and W. Ahlgren, "Development of the Standard CubeSat Deployer and a CubeSat Class Picosatellite," IEEE Aerospace Conference Proceedings, vol. 1, 2001.
29. Kitts, C.A. and M.A. Swartwout, "Beacon Monitoring: Reducing the Cost of Nominal Spacecraft Operations," Journal of Reducing Space Mission Cost, vol. 1, 1998.
30. Swartwout, M., J. Macke, K. Bennett, W.D. Smart, "The Bandit: An Automated Vision-Navigated Inspector Spacecraft," Proceedings of the 17th AIAA/USU Conference on Small Satellites, Logan, Utah, August 2003.