Twenty (plus) Years of University-Class Spacecraft:
A Review of What Was,
An Understanding of What Is,
And a Look at What Should Be Next

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Abstract. The past twenty years have seen the launch of more than 60 "university-class" spacecraft (i.e., spacecraft whose mission in part is to train students in spacecraft engineering), with perhaps 25 more to launch in the second half of this calendar year. And of those 25, twenty are CubeSats, with that trend on the increase.

The on-orbit success and on-orbit utility of these missions has varied widely; some never made it off the rocket, some were deployed but never turned on, while others have been functional for decades.

This paper will review the past twenty years of student-built small satellites. From that data, we will draw broad conclusions about the typical scope and probability of success of these spacecraft. Also, using this information, and drawing from the author's experience and interviews with small spacecraft builders, we will address three questions for future university-class missions:

1) Are CubeSats the dominant future for ALL university-class missions, or simply a 'phase'?

2) What kinds of missions are well-suited for student-built satellites? Are there enough to go around?

3) Are student-built satellites worth the effort? Are there more cost-effective (and mission-effective) ways to train spacecraft engineers?

INTRODUCTION

In the calendar year ending 31 December, 2006, it is anticipated that at least 27 university-class spacecraft will be put into orbit – which is more than twice as many as any previous year. In fact, more student-built satellites are expected to launch in 2006 than were launched from 1981-1999. And, if only a modest fraction of these spacecraft succeed on-orbit, we can expect to see many more in future years; informal estimates place the number of universities worldwide with pre-flight hardware at greater than 75.

While none can deny that student-built spacecraft are an established fact, there is little discussion in either the education or engineering literature about the merits of this fact. Should universities be in the practice of building and launching their own spacecraft? Given the tremendous costs of building and operating university-class spacecraft – measured in student hours, faculty hours, dollars spent, items donated and, especially, the long times between flight operations – are student-built spacecraft worth the cost?

Before we can proceed with the discussion, we need to clearly define what it is we mean by a university-class satellite project.

Definition: "University-Class" Satellite

We prefer the term "university-class satellite" over "student satellite", because the latter has exceedingly broad usage; multimillion-dollar NASA science missions and 3-kg Sputnik re-creations both have been called "student" spacecraft. For the purposes of this discussion, a *university-class satellite* has these features:

1. It is a functional spacecraft, rather than a payload instrument or component. To fit the definition, the device must operate in space with its own independent means of communications and command. However, self-contained objects that are attached to other vehicles are allowed under this definition (e.g. PCSat-2).

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, a university-class satellite is defined by programmatic constraints and is distinct from a space mission with strong university participation. 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; it simply indicates that other factors were more important than student education (e.g., schedule or on-orbit performance).

Finally, it should also be noted that NASA's University Explorer (UNEX) program sometimes calls its spacecraft "university-class missions", although the university participation to date has been concentrated on the instruments and overall mission responsibility; professional contractors have built the spacecraft. None of the UNEX missions to date fit our definition of university-class (though they are not categorically excluded).

Paper Overview

We return to the question: are university-class spacecraft the best use of university resources? In order to answer this question, we will first review the history of university-class spacecraft, from 1981 through mid-June 2006. From that review, we will make general observations about the types of missions pursued, the types of universities participating, and prospects for success or failure on-orbit. Given those observations, we will attempt to address that question, as well as a number of others about subsystem reliability, mission design and proper scoping of projects.

However, we do not claim to have the final authoritative word on the matter. Rather, we hope that this paper continues a meaningful conversation on the proper role for university-class missions.

Disclaimers

This information was compiled from online sources, past conference proceedings and author interviews with students and faculty at many universities, as noted in the references. The opinions expressed in this paper are just that, opinions, reflecting the author's experience as both student project manager and faculty advisor to university-class projects. The author accepts sole responsibility for any factual (or interpretative) errors found in this paper and welcomes any corrections.

Finally, we must admit unfortunate timing: two weeks after this paper is due, a Dnepr rocket is scheduled to launch 14 CubeSats and two other university-class spacecraft. The success or failure of those 16 spacecraft will have a large impact on the results presented below. We will revise our paper and the conference presentation based on whatever data is available by August 2006.

A SMALL HISTORY OF UNIVERSITY-CLASS SATELLITES

A list of university-class spacecraft launched from 1981 until the writing of this paper (12 June 2006) 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 (however low) was assembled from launch logs, the author's knowledge and several satellite databases.[1-4] Because of the difficulty in compiling and verifying information about spacecraft that were not completed, we have only included projects with a verifiable launch date. Furthermore, 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%. Similarly, values in the Mission Duration column are approximate; in the course of our research, we found

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

Launch	Spacecraft	Primary School(s)	Nation	Mass (kg)	Mission Duration (months)	Primary Mission Type	Ref
1981	UoSAT-1 (UO-9)	University of Surrey (UK)	UK	52	98	Science	13
1984	UoSAT-2 (UO-11)	University of Surrey (UK)	UK	60	271	Comm	14
1985	NUSAT	Weber State, Utah State University	USA	52	20	Tech	15
1990	WeberSAT (WO-18)	Weber State	USA	16	97	Comm	16
1991	TUBSAT-A	Technical University of Berlin	Germany	35	181	Comm	6
1992	KITSAT-1 (KO-23)	Korean Advanced Institute of Science and Technology	Korea	49	78	Tech	12, 25
1993	ARSENE	CNES Amateurs	France	154	4	Comm	22
1993	KITSAT-2 (KO-25)	Korean Advanced Institute of Science and Technology	Korea	48	98	Comm	12, 54
1994	TUBSAT-B	Technical University of Berlin	Germany	40	1	Tech?	6
1994	BremSat	University of Bremen	Germany	63	12	Science	
1996	UNAMSAT-B (MO-30	National University of Mexico	Mexico	10	0.0	Comm	
1997	Falcon Gold	US Air Force Academy	USA	18	1	Tech	
1997	RS-17	Russian high school students	Russia	3	2	Edu	5
1998	TUBSAT-N	Technical University of Berlin	Germany	9	46	Tech	6
1998	TUBSAT-N1	Technical University of Berlin	Germany	3	20	Tech	6
1998	Techsat 1-B (GO-32)	Technion Institute of Technology	Israel	70	52	Science	61
1998	PANSAT (PO-34)	Naval Postgraduate School	USA	70	68?	Comm	46
1998	SEDSAT (SO-33)	University of Alabama, Huntsville	USA	41	12?	Tech	7
1999	Sunsat (SO-35)	University of Stellenbosch	South Africa	64	23	Comm	23
1999	KITSAT-3	Korean Advanced Institute of Science and Technology	Korea	110	55	Tech	12, 24
1999	DLR-TUBSAT	Technical University of Berlin	Germany	45	86	Science	6, 21, 48
2000	JAWSAT (WO-39)	Weber State, USAFA	USA	191	1?	Tech	20, 35
2000	Falconsat 1	US Air Force Academy	USA	52	1	Edu	36
2000	Opal (OO-38)	Stanford University	USA	23	29	Tech	38
2000	ASUsat 1 (AO-37)	Arizona State University	USA	6	0.0	Edu	8, 19, 37
2000	JAK	Santa Clara University	USA	0.2	0	Edu	39
2000	Louise	Santa Clara University	USA	0.5	0	Science	39
2000	Thelma	Santa Clara University	USA	0.5	0	Science	39
2000	Tsinghua-1	Tsinghua University	China	50	48?	Edu	
2000	TiungSAT-1 (MO-46)	ATSB	Malaysia	50	40	Edu/Sci	
2000	UNISAT 1	University of Rome "La Sapienza"	Italy	12	??	Edu	10, 49-53
2000	SO-41 Saudisat 1A	King Abdulaziz City for Science & Technology	Saudi Arabi	10	40?	Comm	
2000	SO-42 Saudisat 1B	King Abdulaziz City for Science & Technology	Saudi Arabi	10	40?	Comm	
2000	Munin	Umeå University / Luleå University of Technology	Sweden	6	3	Science	8
2001	Sapphire (NO-45)	Stanford, USNA, Washington University	USA	20	37	Edu	41
2001	PCSat 1 (NO-44)	US Naval Academy	USA	12	57	Comm	40, 45
2001	Maroc-TUBSAT	Technical University of Berlin	Germany	47	57	Science	47
2002	Kolibri-2000	Space Research Institute	Russia	21	2	Edu	9
2002	UNISAT 2	University of Rome "La Sapienza"	Italy	17	18?	Edu	10
2002	Saudisat 1C (SO-50)	King Abdulaziz City for Science & Technology	Saudi Arabi	10	42	Comm	
2003	MOST	University of Toronto	Canada	60	36	Science	11, 63
2003	QuakeSat	Stanford University	USA	3	36	Science	33
2003	AAU Cubesat	University of Aalborg	Denmark	1	0	Edu	
2003	CanX-1	University of Toronto	Canada	1	0	Edu	62
2003	CUTE-1 (CO-55)	Tokyo Institute of Technology	Japan	1	36	Edu	
2003	DTUsat	Technical University of Denmark	Denmark	1	0	Edu	
2003	XI-IV (CO-57)	University of Tokyo	Japan	1	36	Edu	
2003	Mozhayets 4 (RS-22)	Mozhaisky military academy	Russia	64?	33	Comm	
2003	STSAT-1	Korean Advanced Institute of Science and Technology	Korea	100	33	Tech	
2004	Naxing-1 (NS-1)	Tsinghua University	China	25	26	Tech?	
2004	SaudiSat 2	King Abdulaziz City for Science & Technology	Saudi Arabi	15?	24	Comm?	
2004	UNISAT 3	University of Rome "La Sapienza"	Italy	12	24	Tech	10
2004	3CS: Ralphie	ASU/NMSU/CU Boulder	USA	16	0	Edu	34
2004	3CS: Sparky	ASU/NMSU/CU Boulder	USA	16	0	Edu	34
2005	PCSat 2	US Naval Academy	USA	12?	10	Comm/Tech	
2005	Mozhayets 5	Mozhaisky military academy	Russia	64	0	Edu/Tech	
2005	SSETI Express (XO-5	European Universities	Europe	62	0	Comm?	
2005	Ncube II	Norwegian Universities	Norway	1	0	Edu	
2005	XI-V (CO-58)	University of Tokyo	Japan	1	8	Edu	
2005	UWE-1	University of Würzburg	Germany	1	8	Edu	
2006	CUTE-1.7 (CO-56)	Tokyo Institute of Technology	Japan	2	4	Comm/Tech	
2006	Falconsat 2	US Air Force Academy	USA	20	0	Science	

🟩	Still operational
🟨	Semioperational
⬜	Nonoperational
🟧	Premature loss of operations (or severely degraded operations)
🟦	Launch failure

some spacecraft that were known to have lost most or all of the primary payloads and communications equipment and yet were still listed as "operational"! In other cases, spacecraft that have greatly exceeded their planned mission lifetime may be left idle or even abandoned by their primary operators, and thus the failure date of the vehicle is unknown.

1981-1990: A New Hope?

Our history begins in 1981 with the launch of Surrey's UoSAT-1,[13] followed by UoSAT-2 in 1984,[14] and then two Utah-built spacecraft: NUSAT[15] in 1985 and WO-18 (Webersat) in 1990.[16] These first four are unusual compared to recent university-class missions in three respects: they are relatively large (Webersat was by far the smallest at 16 kg, while the rest average more than 50 kg), they all had "real" missions (UoSAT-1 had electromagnetic science instruments, NUSAT demonstrated radar calibration for the FAA, and all but NUSAT were OSCAR-designated spacecraft in the Amateur Radio service), and they all functioned for an extremely long time (NUSAT de-orbited after 20 months, and the others operated for more than 8 years – more than 20 for UoSAT-2).

Before continuing, we must digress for a special explanation 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. Most of their missions would appear to fit the university-class definition. 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, we only consider the first two UoSATs to be university-class, plus KITSAT-1 (1992) and Tsinghua-1 (2000).

The other point to note from this first decade is how few university-class launched. This is as much a reflection of the state of the engineering world before the electronics revolution of the late '80s as it is an indication of how long it takes student programs to launch their first spacecraft. A number of universities will start spacecraft engineering programs by the end of this decade, but no others will launch, yet.

1991-2000: The Phantom Menace

Within a few years, university-class spacecraft programs became active at Stanford University[17], Arizona State University,[18, 19] Weber State University, and the U.S. service academies,[20] among others – with an equal number at schools in Europe,[21, 22] Africa,[23] and Asia.[24, 25] And, especially in the latter half of this decade, those programs start finding their way into orbit – a whopping 30 spacecraft in all, including 13 in the banner year of 2000. In fact, the Class of 2000 requires a section unto itself (see below).

Overall, the university-class spacecraft in this decade are starting to become smaller, although there are still as many over 40 kg as there are under 10 kg. Also, the overwhelming majority of these spacecraft have a real mission, be it Amateur Radio service, technology demonstrations, or science.

Unfortunately, this decade sees the first mission failures. There is also a noticeable bifurcation in the mission lifetimes: university-class spacecraft either fail within the first few days of operation or operate for several years. Still, with the exception of the ill-fated JAWSAT multi-spacecraft launch (see below), success rates are surprisingly good: only 4 of 23 failed to meet their baseline mission objectives.

For U.S. universities, two watershed events took place in this time period. The second (CubeSats) will be discussed in the report on the Class of 2000, below. The first is the formation of the AFRL/NASA/AIAA University Nanosat Program;[26] this design competition serves to motivate and educate engineering students in spacecraft design, with the winning school getting a Space Test Program-sponsored launch of its 30-kg-class satellite. By the time this paper is written, almost every U.S. university known to be building a spacecraft bigger than 10 kg is an active or past participant in the University Nanosat Competition.

Finally, it should also be noted that the number of active university-class projects in this decade far exceeds the number on the launch manifest. Some of these schools make the list in the next decade, while a significant number either never complete their spacecraft or never find a launch. For the sake of illustration, we point out that student papers presented at this Conference from 1993-2000 included missions in development at Iowa State,[27] Brigham Young, San Jose State,[28] University of Arizona,[29] University of Central Florida,[30] University of Washington,[31] Virginia Tech,[31] and UC Boulder.[32]

We do not include these references to belittle the activities of these programs, rather, we include them to illustrate that the odds are stacked against a university even completing its spacecraft, much less launching it and having it operate successfully. As a further example, of the 10 schools to participate in the inaugural University Nanosat competition, only 1 school has subsequently put hardware in space (Stanford, and it was a CubeSat[33]); three other Nanosat schools lost their 2-spacecraft project (3CornerSat) on the first flight of the Delta IV Heavy.[34]

The Class of 2000: Murphy Strikes Back

There are two reasons why the year 2000 deserves special consideration. First, this year must be viewed as both the low- and high-water marks for university-class spacecraft (although 2006 may exceed it, in more ways than one). Second, the CubeSat specification traces its heritage to a spacecraft launched in 2000.

As noted above, twelve university-class spacecraft were launched in 2000, the most ever in any year (the previous high was five, although, admittedly, this record will be shattered by the next Dnepr CubeSat launch). In fact, seven of the twelve were on the same rocket: the 26 January 2000 first-flight of the Minotaur carried the Air Force Academy/Weber State JAWSAT spacecraft,[35] which in turn hosted FalconSat-1,[36] ASUSat-1,[37] and Opal,[38] plus a DoD optical calibration sphere; in turn, Opal carried three spacecraft built by Santa Clara University[39] and one more amateur-built and two more professional spacecraft.

Not only were the numbers higher than ever before, but the year 2000 began with the highest level of enthusiasm for university-class spacecraft. At the time, JAWSAT and similar international multi-spacecraft university missions were viewed as the first of many secondary launch opportunities for the growing stable of completed or soon-to-be-completed student-built spacecraft, including all 10 of the University Nanosat teams. Then, unfortunately, three things happened: in January, 6 of the 7 university-class spacecraft on JAWSAT failed; in March, the "dot com" bubble burst (the NASDAQ index losing more than 70% of its value by year's end), and Iridium filed for bankruptcy protection in November. The latter two events caused a severe contraction in the launch industry – all but eliminating the secondary launch market for universities; the first event may have had an even more profound impact.

While we cannot point to a specific reference or interview, we believe that the aerospace industry takes a rather dim view of the performance and reliability of university-class spacecraft. While we do not disagree with their opinion on performance (which we will discuss, below), the data does not seem to support the belief that student-built spacecraft are unreliable. Setting aside the JAWSAT launch for the moment, only 10 of 55 university-class spacecraft (18%) have failed on-orbit. Even including JAWSAT, that numbers grows to a not-terrible-for-students 16 of 62 (26%, especially considering that Opal's three "failed" university-class picosatellites were sub-500-gram, battery-powered devices; it would have been more surprisingly had they all operated successfully!). Finally, it should be noted that after JAWSAT, only 6 of 34 have failed (18%, again, and 4 of them CubeSats).

Based on the data, we can only conclude that the JAWSAT mission has had disproportionate influence on professional opinion. Although this is hardly surprising: JAWSAT was an extremely visible DoD-sponsored mission, and only 5 U.S.-built university-class spacecraft had flown in the previous 15 years. This mission was the first time that many industry professionals had worked with university projects. And, since JAWSAT, only five U.S.-built spacecraft bigger than 12 kg have been launched (PCSat-1,[40] PCSat-2, Sapphire,[41] and 3CS[34]) – and even though the three that reached orbit all were successful, we believe that the shadow of JAWSAT still hangs over American university-class missions.

Still, the JAWSAT launch did nothing to kill the interest or enthusiasm of university projects. In fact, the Opal mission (Figure 1) marks the second watershed event of this decade. The primary mission of Stanford's Orbiting Picosatellite Automated Launcher (OPAL, or, as commonly used, Opal) was to demonstrate deployable spacecraft technologies: six hockey-puck sized "picosatellites" were deployed from Opal several days after launch (Aerospace Corp.'s PICOSAT 1 & 2, the Amateur payload StenSat, and three from Santa Clara University: Thelma, Louise, and JAK).

Figure 1. Opal [courtesy Stanford SSDL].

While the picosats themselves had mixed results (only the two PICOSATs were ever heard from), the picosat launcher itself was extremely successful. In fact, Opal is the direct predecessor to the CubeSat standard and P-POD developed by Stanford and Cal Poly.[42] According to Stanford's Robert Twiggs, the idea for the 10 cm cube, 1-kg specification sprung from the success of Opal's launcher, the request by picosat providers for a little bit more volume, and the tremendous discrepancy

between the time it took for Opal to be designed, built and launched (5 years) and the period of the picosats (less than 18 months, and some less than 6 months). It was believed that shrinking the spacecraft to these dimensions would both cut development time and increase the number and frequency of secondary launch opportunities.

In terms of sheer numbers, by the middle of the next decade, CubeSats will become the dominant university-class project worldwide, with as many as 70 documented CubeSat projects in development, and possibly 31 CubeSat-class spacecraft launched from 2003-2006 (including those released from the analogous Japanese-built launcher and the DoD-equivalent MEPSI launcher, but not counting more than a dozen more industry and amateur-built CubeSat-sized spacecraft).

2001-2006: Attack of the BeepSats

The first six years of this decade have seen a steady rise in the number of international launches and the beginning in 2003 of what is becoming a flood of CubeSats. Not surprisingly, the average mass of university-class spacecraft is down dramatically, with

only 6 of the 28 spacecraft launched since 2001 having a mass over 40 kg.

The shift towards CubeSats has also brought about two more trends: a sharp reduction in the number of "real-world" missions (e.g. communications or technology development) and a sharp increase in the failure rates (due to a failure rate among CubeSats of 40%).

2006-2010: A New, New Hope?

Predicting future launches of university-class spacecraft is a futile exercise; not only are university program managers endlessly optimistic about when their spacecraft will be finished, but their dependence on secondary launches means they can be delayed for any number of reasons. For example, the late June 2006 Dnepr launch carrying the CubeSat portfolio was once scheduled for August 2004.

Still, for the purposes of illustration, we list in Table 2 those missions which have a confirmed, manifested launch date. Other spacecraft are nearing completion (such as the University of Texas' FASTRAC[43] and Berlin's LAPAN-TUBSAT[44]) and will be added to the list when their manifests are announced.

Table 2. Manifested University-Class Launches, second half of 2006.

Spacecraft	Primary School(s)	Nation	Mass (kg)	Launcher
ION	University of Illinois	USA	2	Dnepr
SACRED	University of Arizona	USA	1	Dnepr
Rincon	University of Arizona	USA	1	Dnepr
ICE CUBE1	Cornell University	USA	1	Dnepr
KUTESat	University of Kansas	USA	1	Dnepr
Ncube	Norwegian Universites	Norway	1	Dnepr
HAUSAT-1	Hankuk Aviation University	S. Korea	1	Dnepr
SEEDS	Nihon University	Japan	1	Dnepr
MEROPE	Montana State University	USA	1	Dnepr
CP2	Cal Poly San Luis Obispo	USA	1	Dnepr
CP1	Cal Poly San Luis Obispo	USA	1	Dnepr
ICE CUBE2	Cornell University	USA	1	Dnepr
Mea Huaka'i	University of Hawaii	USA	1	Dnepr
ALMASat	University of Bologna	Italy	25	Dnepr
Baumanets 1	Bauman Moscow State Technical University	Russia	100?	Dnepr
RAFT-1	US Naval Academy	USA	1	STS-116
MARScom	US Naval Academy	USA	1	STS-116
CP4	Cal Poly San Luis Obispo	USA	1	Dnepr
CAPE-1	University of Louisiana	USA	1	Dnepr
CP3	Cal Poly San Luis Obispo	USA	1	Dnepr
Libertad-1	University of Sergio Arboleda	Columbia	1	Dnepr
MAST	Stanford	USA	3	Dnepr
Falconsat 3	US Air Force Academy	USA	50	Atlas 5
NPSAT1	Naval Postgraduate School	USA	80	Atlas 5
MidSTAR-1	US Naval Academy	USA	120	Atlas 5

Even without the almost-ready-but-not-firm launches, the manifest for the last 6 months of 2006 is staggering: twenty-five spacecraft (including 20 CubeSats). That is more than the previous four years combined (which were pretty good years for university-class spacecraft launches), and twice as many as were launched in the previous banner year of 2000.

What is the implication of 25 new university-class spacecraft? Well, if the statistics hold, it means that 1 of the 5 larger spacecraft will fail, and at least 8 of the 20 CubeSats will fail. If the real numbers are worse than average, than 2006 may eclipse 2000 in terms of the professional opinion of student-built satellites (and, especially in the U.S. the ability of university projects to get sponsorship and launches). On the other hand, a success rate equal to or better than average may make 2006 the most important year (so far) in the history of university-class spacecraft.

In fact, regardless of the outcome, 2006 is shaping up to be the most important year in the history of university-class spacecraft.

OBSERVATIONS

By considering the missions in Tables 1 & 2 as a whole, several observations become apparent:

Types of Universities

Universities involved in spacecraft-building can be split into two relevant categories: flagship universities, and everyone else. By "flagship" university, we mean a school that has been designated by the government as a lead center for spacecraft engineering research and development. While the amounts vary, flagship universities by definition enjoy significant government sponsorship, including financial support, industry mentoring and launches. Examples of flagship universities are the U.S. Naval and Air Force Academies,[36, 40, 45] and Naval Postgraduate School,[46] Germany's Technical University of Berlin,[21, 44, 47, 48] Italy's University of Rome *La Sapienza*,[49-53] the Korean Advanced Institute of Science and Technology,[24, 25, 54-60] Israel's Technion Institute,[61] Saudi Arabia's King Abdulaziz City for Science and Technology, China's Tsinghua University, Japan's University of Tokyo and Tokyo Institute of Technology, and Canada's University of Toronto.[62, 63]

Non-flagship universities must find other means of support, such as internal funding, research sponsorship, or more general space education funds such as NASA Space Grant. Not surprisingly, there have been fewer non-flagship launches than flagship launches

Types of Spacecraft

As outlined above, university-class spacecraft have split into two distinct activities: the 30-kg-class University Nanosat Program sponsored by AIAA, NASA and AFRL (with equivalent-scale, government-sponsored programs in other countries[64-67]); and the 1-kg-class CubeSat program jointly developed by Stanford and Cal Poly San Luis Obispo and adopted by dozens of schools. Several schools are pursuing both CubeSat-class and Nanosat-class missions, but most have focused on one or the other.

Also, increasingly, university-class spacecraft lack a true payload: either the spacecraft's mission is only to return its own telemetry, or the instrument package has been selected simply for the sake of having an instrument package (e.g., Sapphire[41]).

And, while it is not a perfect predictor, it should be noted that most of the flagship universities provide "real" payloads, while many of the non-flagship do not (especially in the last ten years).

Types of Launches

With the exception of the dedicated JAWSAT launch, every university-class spacecraft has flown as either a secondary or part of a large group of secondaries (sometimes without an established primary). The latter option is becoming increasingly common, led by the Russian launch systems such as the Dnepr; it is no longer strange to see 5 or more spacecraft manifested on the same platform. This is a positive trend for universities, especially for the non-flagship, because it opens up the opportunity to share the launch costs among many programs. It also provides automatic teaming and mentoring arrangements between co-manifested missions.

However, for U.S. universities, the fact that most multi-manifest launches are coming out of Russia means that ITAR restrictions must be managed. Several schools, including Cal Poly and the University of Toronto, have taken on the specialized role of international launch broker for university-class missions.

Repeat Business

To date, 35 universities (or university teams) have built 62 spacecraft. Of those 35, only 16 universities have participated in more than one mission. Of those 16, one was Surrey (who "graduated" to SSTL) and only 3 others are not flagships (Stanford, Arizona State and Weber State – and Weber State stopped with JAWSAT). By the end of 2006, we anticipate there will be 14 first-time schools added to the list. There will also be two new multi-mission schools (Naval Postgraduate School and Cal Poly – only the 4th non-flagship school) and three schools adding to their lists.

In other words, 19 non-flagship universities flew spacecraft on only one mission, and of that set, only 6 are known to be building a second. For whatever reason, the faculty, student, administrative and financial resources that were assembled for the first spacecraft have not been available for a second; it is very difficult for universities without strong, consistent support from a government or industry sponsor to stay in the small satellite game. It will be very interesting to see how many of the 14 first-times in 2006 stay around for a second.

What Breaks First?

Whether out of embarrassment, proprietary concerns, or simply a lack of interest, university-class missions are notoriously bad about publishing (or perhaps writing?) failure reports. The following information is the author's best guess based on news articles and the few published failure reports.

Of the 16 spacecraft we have identified as failing prematurely, the failures can be attributed to (or guessed to be) the following:

- **Radiation:** 1 (TUBSAT-B). Killed by the Van Allen Belts due to its 1250 km orbit altitude.
- **Launch interface:** 1 (Mozhayets 5). Failed to separate from the launch vehicle; not clear whether it was a launcher, launch interface or spacecraft problem.
- **Thermal:** 1 (UNAMSAT-B); UNAMSAT's uplink oscillator was too cold before launch and the spacecraft could not be contacted in time to change the battery charging parameters for the cold conditions, and the system failed.
- **Communications:** 2½ (Arsene, SEDsat [partial], JAWSAT). These three spacecraft were operational for at least a little bit of time, but lost either their transmitters or receivers (or both) unexpectedly. Bad wiring is suspected in some.
- **Power:** 3½ (SEDSat [partial], ASUSat-1, FalconSAT-1, SSETI-Express). The reasons vary, but all of these vehicles had problems, typically with the connection between batteries and solar arrays.
- **Unknown:** 7 (JAK, Louise, Thelma, AAU Cubesat, CanX-1, DTUsat, NCube II). These seven spacecraft were confirmed to have released, but contact was never made. Either bad communications or bad power is suspected.

Arguably, all of the known failures save TUBSAT-B, and potentially many of the unknown failures, can be attributed to incomplete system-level testing or system-level design. In all those cases, either the spacecraft was in an unexpected operational environment, or a component failure led to an operational mode from

which ground operators could not recover (e.g. loss of uplink or a disconnect between batteries and solar arrays). While we cannot presume to know what was and was not tested, it would appear that rigorous, extensive fully-integrated functional testing might have caught these problems before launch.

What Doesn't Break?

On the other hand, there are some surprising absences from that list. For example, despite a reliance on converted commercial (actually, terrestrial) electronics, the only recorded instance of a university-class spacecraft lost to radiation events is TUBSAT-B, which was sitting in the Van Allen belts. Perhaps COTS electronics in low-Earth orbit are more rugged than we though?

Similarly, neither batteries nor solar arrays were the established root cause any failures. Granted, battery failure is an extremely likely root cause in the loss of the SCU picosats and possible in the other CubeSats. Still, in the author's experience with Sapphire, modestly-performing NiCad batteries are surprisingly forgiving to student operators who mistreat them. (It is arguable that Sapphire's batteries had exceeded their functional lifetime **before** launch, and they still performed well for 30 months on-orbit.)

Also, the relatively benign thermal environment of LEO and the rugged thermal allowances of COTS components (where it is unusual for electronic devices **not** to operate in the full range of -15 C to +80 C) team up for a forgiving thermal design environment. UNAMSAT-B's main thermal problems were driven by launch conditions in Russia, not by orbital conditions.

Finally, with the exception of Mozhayets 5, none of the other 61 university-class spacecraft are known to have experienced structural failures. Part of this is no doubt due to the fact that vibration/static testing is both effective in catching problems before launch and mandated by launch providers. Part of this is probably due to the fact that student spacecraft are rarely mass-optimized, meaning that they opt for manufacturable and/or high-margin structures over mass savings. Finally, this is partly due to the favorable scaling laws for small structures – small structures have inherently lower bending moments and higher natural frequencies, which give student designers additional cushion.

Again, while no one should discount the importance of sound structural & thermal analysis/testing, nor should students ignore the risks of COTS electronics, the launch history suggests that more time needs to be devoted to system-level functional testing.

Why Do Universities Build Spacecraft?

Building, launching and operating spacecraft is a lot of work. Any of the students who have begun the process can attest to that, and many confess that, had they fully understood the amount of effort required, they may not have signed up. And yet, dozens of universities are joining the "space club", and a small-but-growing set are even starting a second (or third) mission. Why?

In reading through dozens of pre- and post-launch university-class mission reports, we have observed three major motivations. In decreasing order of importance, they are:

- **Inspiration.** The idea that a student could put their hands on something that will go into orbit has undeniable cachet. The emotional appeal of space flight is the overwhelming motivation for both students and faculty participants. This emotional aspect also serves as a way to recruit students to consider careers in the space industry.
- **Education.** It is accepted practice that project-based, hands-on activities are excellent tools for teaching both systems-level engineering and specific disciplines. In addition, it has been our experience that employers preferentially select students with project experience. Thus, the spacecraft becomes a tool for preparing students for their professional careers.
- **Research.** At almost every school (especially among the new CubeSat projects), the value of the mission is in the building and launching of the spacecraft, not in what the spacecraft can do. The exception to that rule has been the flagship universities; because of their government sponsorship, these schools not only have incentives to fly "real" payloads, but also access to "real" payload providers through their government.

OPINIONS

To this point in the paper, we have attempted to present the facts of university-class spacecraft and discuss the implications of those facts. Now, we will venture from fact to opinion. We will first address the question of possible missions, then discuss issues of mission scope and component selection, and conclude with three soapbox topics: the differences between Nanosat-class and CubeSat-class spacecraft, the misleading usage of micro/nano/pico designations, and, finally, the existential question of whether university-class missions should even exist.

Issue: What Should these Spacecraft Do?

Broadly speaking, university-class space projects are effective at relevant, practical training for student engineers but, with a few notable exceptions, produce only marginally-capable spacecraft and marginally-relevant missions. Many university-class missions are internally-motivated; participants see spacecraft as an exciting and relevant way to teach engineering. The payload (if there is one) exists to justify the spacecraft, not the other way around.

Those universities attempting to fly "real" payloads face a different problem: after JAWSAT, the developers of real payloads are justifiably hesitant to risk their components on unproven spacecraft, yet without a real payload, the universities cannot gain the flight experience to prove their capabilities. Even with a real payload, universities still have the challenge of finding an affordable launch. Because the cost-per-kilogram of launch is so high, spacecraft must be extremely reliable and have a compelling mission. And, proper development, integration and testing require significant infrastructure. Non-flagship universities with research-driven university-class missions almost never make it to orbit.

Lacking compelling payloads and lacking the resources to attract such payloads, most student projects focus almost entirely on training. Clearly, this is a worthwhile objective; many students (including the authors) have benefited from hands-on engineering experience despite the lack of "real" payload. However, this approach is not sustainable. Reviewing Table 1, most programs with education-only satellites succeed in launching only one spacecraft (if they launch anything at all).

Rather than attempt to mimic professional spacecraft, student projects should play to their strengths: their tolerance for risk and ability to use their space assets to test revolutionary concepts. The reduced capabilities and simple design inherent to student-built spacecraft makes them ideal for short-term/limited demonstrations of new operations concepts and technologies – such as autonomy, inspection, servicing, robotic assembly, or higher-risk methods for navigation and control. Such mission objectives make it easier for projects to attract outside sponsorship, and it provides students with a more compelling goal.

Again looking at Table 1, one cannot help but notice that from 1981-2001, the vast majority of university-class spacecraft had an OSCAR designation; almost all of those spacecraft carried one or more voice or packet data repeaters for use by the Amateur community. Since 2001, few missions have an OSCAR designation and fewer still accommodate Amateur communications as in previous missions.

Anyone who spends any amount of time monitoring the amsat-bb mailing list will note that there is a significant

amount of confusion, skepticism or outright animosity over the coming flood of Amateur-band-using CubeSats; Amateurs are worried that these spacecraft will use the amateur portion of the band without providing services to the broader community.

In the author's opinion, both the universities and broader Amateur community are mission a golden opportunity to collaborate: student education, project mentoring and launch opportunities would improve with a "real" communications payload, and the Amateurs lose new blood and the chance to fly payloads in the gaps between regular AMSAT-sponsored launches.

It appears that each side is waiting for the other to make a move; one hopes that somebody takes it upon themselves to do so, and soon.

Issue: *How Should They Do It?*

As noted above, while 80% of the spacecraft that reach orbit survive, a much larger pool of spacecraft never make it to the launch vehicle. And those non-flagship programs that launch one spacecraft rarely launch a second. The fundamental obstacle to building and launching university-class spacecraft is cost; universities can take years to complete a spacecraft and even have it fail on orbit, and still consider it an educational success; 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 non-flagship universities to participate.

Such reductions have five requirements, outlined below. While each requirement reduces cost while maintaining (or improving) mission risk on its own, these aspects taken together have a mutually-reinforcing effect on university-class missions: they guide students towards modestly-scoped missions that can be accomplished in the near term with existing hardware.

In fact, "modest" is the overall theme of this section. Students (the author included, once) are excessively optimistic (some would say naïve) about their ability to solve complex technical and integration problems. Sometimes, this optimism is essential, for it helps motivate the teams through the tough parts of the project. But in many cases, it causes fledgling spacecraft teams to take on entirely too many missions, attempt too ambitious a technical challenge – and never finish.

From unfortunate experience, the author advises university programs to heed the advice of Gen. George S. Patton, "Better a good plan violently executed today than the perfect plan available next week." Or, in spacecraft terms, "Better a boring spacecraft that gets finished and flies, than an amazing spacecraft that we never complete."

The five design guidelines are:

Small spacecraft. Setting aside for the moment the relationship between spacecraft mass and launch costs, there are other advantages to students building very small satellites. 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 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.

The question of whether these benefits would apply to other aspects of student spacecraft (wiring harness, power systems, data protocols) deserves further study. Based on the common power problems of failed missions, one would expect that a common power subsystem design would be exceedingly useful.

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. In other words, non-flagship universities who want to finish their project within the students' academic lifetime should avoid missions that require state-of-the-art performance.

Note that this is **not** the same as saying that non-flagship schools should avoid challenging missions. But the challenge should come in terms of ground operations, data processing, autonomy, etc. – not in attempting to perform 3-axis, arcminute-level pointing control on a 10 kg spacecraft.

Rigorous functional and environmental testing. In our missions, early vacuum and thermal cycle testing identified discrepancies between manufacturer specifications and actual thermal behavior of key components. More importantly, a functional prototype is essential for success. It is our belief that many student spacecraft fail due to lack of time to correct problems in ground testing, especially in power subsystems. (Note that the simpler the spacecraft – few components, modest power needs, three or fewer operational modes – the easier it is to integrate and thus the more schedule that is available for testing.)

Issue: CubeSat v. (?) Nanosat

At present, approximately twenty U.S. schools have developed or are developing Nanosat-class spacecraft, with a half-dozen launched in the past 6 years. By contrast, more than 90 schools worldwide are developing CubeSat-class spacecraft, 1-kg, 10 cm cubes that fit within a standard deployment mechanism.

CubeSat-class spacecraft have several educational/ programmatic advantages over Nanosat-class systems. The extremely small size of the spacecraft further constrains design scope, improving the ability of a small group of students to fully understand the entire design. CubeSats have been launched as secondaries on Russian rockets for on the order of $100,000 each, with new orders for CubeSat launches announced at $40,000 each. By contrast, Nanosat-class spacecraft cost millions of dollars for a secondary launch. Thus, most U.S. Nanosat-class programs depend on external sponsorship, almost exclusively through the Department of Defense.

However, the sheer size of a CubeSat (or lack thereof) poses a tremendous constraint on power generation, power storage, communications, and electronics design. In some cases, the cost of miniaturizing components to fit a CubeSat may outweigh the economic advantages of launching a CubeSat instead of a Nanosat. The first 10 CubeSats have had an on-orbit failure rate double that of larger spacecraft; perhaps this rate will decline as a set of best practices are developed and adopted. The Japanese flagships, for example are 4 for 4 on CubeSat launches (which, in return, makes the aggregate success rate of the other 6 CubeSats even worse).

CubeSats also suffer from a perceived lack of value: of the 30 CubeSat-class vehicles in orbit or ready for launch in 2006, only 7 have any significant science or technology demonstration element (QuakeSat, ION, ICE CUBE1/2, RAFT, MARScom, Voyager). Only one of those six has flown (QuakeSat), and it had significant industry sponsorship.

Thus, a university should choose a CubeSat-class or Nanosat-class mission based on its educational objectives and student capabilities. CubeSats can be designed and built more rapidly, provided that the program is capable of developing miniature-scale electronic subsystems, defines modest operational capabilities, and perhaps most importantly, has access to an Earth communications station capable of closing the link with a low-power, low-gain, extremely small spacecraft. Nanosat-class spacecraft have sufficient margin to enable students to build less-optimized, less-capable subsystems and still perform compelling missions. Without a compelling mission, a Nanosat-class program will be hard pressed to find launch sponsorship. While the $40,000 price for a CubeSat-class launch is certainly expensive, it does allow for university programs with less-compelling missions to reach orbit.

Micro vs. Nano vs. Pico: Missing the Point

A significant amount of effort seems to be expended coming up with an exact classification of spacecraft size prefixes; as of this writing, the online Wikipedia indicates that the cutoff between designations are at powers of 10: 100 kg for microsats, 10 kg for nanosats, 1 kg for picosats, etc. In the author's opinion, this discussion is, at best, silly and, at worst, misleading. There are two reasons for this opinion: the category divisions are arbitrary and, more importantly, mass is the wrong discriminator.

It is only useful to classify types of spacecraft if there is something fundamentally different about satellites in different categories. In such a case, the designation is useful shorthand for understanding the expected

performance of objects in that category. For example, automobile manufacturers distinguish between sedans, compact cars and sport utility vehicles because each has very different features and price points. In that regard, the 1/10/100 kg breakpoints are particularly misleading. For example, our university is developing a 3 kg deployable inspector spacecraft, with a long-term goal of reducing the vehicle size under 1 kg – in other words, converting it from a "nanosat" to a "picosat". And yet, the only practical difference between these two spacecraft will be that the "picosat" has a more compact structural design and smaller (i.e. more expensive) components. Functionally, they will perform the same tasks with the same level of accuracy. But by calling one a "nanosat" and one a "picosat", we would be implying that there were some fundamental difference between the two.

For university-class spacecraft below about 60 kg, mass is the wrong discriminator. While it is generally true that the lower the spacecraft mass, the lower the cost of the launch, this only applies to orders-of-magnitude changes in launch mass (1000 kg vs. 100 kg vs. 10 kg) and is most relevant 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.

In the author's experience, U.S. launch providers are indifferent to 5 kg or even 10 kg changes to the mass of a university-class payload; while these changes are enormous with respect to the satellite, they are within the noise of the launch vehicle performance. Try to change your spacecraft's footprint or dynamic envelope, however, and it's a different story.

That is why we believe that volume is the true indicator. Volume dictates whether your spacecraft fits on the launch vehicle, how big a solar array can be accommodated, the size of sensor and communications apertures – in short, volume is a strong reflection of the mission and capabilities of a spacecraft.

If volume is not a convenient discriminator, another useful parameter would be launch interface – knowing whether the spacecraft fits in a P-POD/MEPSI or on an ESPA/Lightband-type interface provides a tremendous amount of information about the satellite's expected performance.

Is This the Best Use of Our Time?

The most important question raised by this study is also the hardest to answer: given that the cost of design, fabrication, launch and operations is in the high tens of thousands of dollars for CubeSats and in the millions for larger spacecraft, given that the on-orbit returns are marginal, are university-class spacecraft worth the

investment? If 40 students are involved in the construction of a 1-kg spacecraft, how many of them are receiving the true benefits of hands-on projects (i.e., the painful learning that comes from integration, system failure and redesign?).

The question can be rephrased this way: can the university's education/research objectives be achieved if the spacecraft never flies? If they can, then why devote all the extra resources to the flight? Wouldn't the sponsors and students be better served by UAV, balloon or even ground demonstrations (where flight costs are in the dozens of dollars and re-flight times can be measured in minutes or hours)? And if your educational/research goals absolutely require a launch, how can you reconcile that it can take 3-5 years (or longer) from project inception to launch – even for CubeSats – and, for larger spacecraft, there is an extremely high probability that the spacecraft will not find a launch or, more likely, never be finished?

These questions are raised because of the very real possibility that the number of secondary launch opportunities will not increase at the same rate as the number of new schools wanting to fly spacecraft (if the launch opportunities increase at all). In the University Nanosat Competition, for example, there is a roughly 2 to 1 ratio between applicants and selected participants, and a 10 to 1 ratio between selected participants and sponsored launches. (Recall that 8 of the 10 original Nanosat teams have not had their spacecraft launched.) If it is true that only 1 in 20 Nanosat-class spacecraft will make it to orbit, wow long can students be strung along on the hope of an unlikely launch before they leave the project?

Thus, the success or failure of the CubeSat Class of 2006 becomes even more important. If a significant fraction fail, it may indicate that most universities are not cut out to fly CubeSats and there may be a backlash among the Nanosat-scale vehicles, too. If a significant fraction succeed, then CubeSats may yet

In the author's opinion, the opportunities for systems-level training in spacecraft engineering provided by the University Nanosat Program are worth the long odds against launch. On the other hand, if all 100+ universities worldwide active in spacecraft hardware opted to build Nanosat-class vehicles, the backlog would never clear.

At the very least, it is imperative that university-class mission managers understand the costs, schedule implications and long odds of university-class missions. Missions which have relevant pre-flight demonstrations are superior to those that can only be tested on-orbit, simply because of the opportunities that provides

students for realistic demonstrations during their academic lifetimes.

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.

Review of Key Ideas

In this paper, we accomplished the following:

- Defined "university-class" missions as those student-built satellites where student training plays at least as important a role as the orbiting mission.
- Identified the 62 university-class missions that have launched to date and the 25 manifested for launch by the end of 2006.
- Recognized that the on-orbit success rate is better than expected: only 16 of 62 failed prematurely; which drops to 10 of 55 if one discounts the bad-luck day of the JAWSAT launch.
- Observed that the ill-fated JAWSAT launch has had a disproportionate influence on professional opinion of university-class spacecraft.
- Identified that there are two categories of university-class programs: the government-sponsored flagships and the non-flagships. Mission types, success rates and reflight rates between the two groups are distinctly different.
- Suggested that structural and thermal design of university-class spacecraft has been adequate, but that power and communications need more attention, especially at the level of system integration and functional testing.
- Encouraged schools to attempt "real", relevant payloads, not only from the educational value of the effort but as a way of reversing the negative opinion of university-class missions and, more importantly, to tackle research problems that are not being addressed in industry. Perhaps the most relevant payload that a fledgling space program could adopt would be an Amateur radio repeater.
- Provided five guidelines for effective mission design: small vehicles, common interfaces, short missions, large margins and rigorous testing.
- Sidestepped the "CubeSat v. Nanosat" debate by recognizing that different schools will be better able to accommodate the strengths and weaknesses of each category .

- Asserted that mass is the wrong discriminator for under 60 kg university-class spacecraft. Specifying the volume and/or launch interface provides a richer understanding of the design.
- Opened the door to the idea that maybe, just maybe, schools are throwing their limited resources at satellites when perhaps terrestrial robotic projects would be more cost-effective.

Mission Design and Mission Risk

In choosing payloads, 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.

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 accessible to university projects will carry significant mission risk, 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.

Closing Thoughts

While both the 30 kg Nanosat-class and 1-kg CubeSat-class vehicles fill relevant portions of the trade space for university projects, the existence of these classes and the significant discrepancy in size and expected operational lifetime raise important questions for future work. In particular, while these very small spacecraft are considered to be "better" for hands-on design projects than 100 kg vehicles, is there a bottom limit to size? Would 100 gram spacecraft better lend themselves to student design, integration and launch opportunities, or would the technological complexities and mission limitations eliminate the value of small size? Similarly, while shorter mission lifetimes improve the design and education process, is there a practical limit to mission length? Could a one-day mission be justified in terms of technical relevance as well as the months (or years) of student development leading up to launch? Could all of the fundamental educational objectives be met with significantly-less-expensive suborbital flights lasting a few minutes?

Answering these questions will require a more comprehensive survey of university-class missions, both in the U.S. and abroad.

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, the launch of 25 university-class spacecraft in the second half of 2006 will dramatically change. It is not at all clear whether this will be a change for the better, or for the worse.

ACKNOWLEDGMENTS

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