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The First One Hundred CubeSats: A Statistical Look

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Abstract

The concept of CubeSats was publicly proposed in 2000, with the first CubeSats launched in 2003. By the end of 2012, more than one hundred CubeSats have been launched, and 80 more are manifested for launches in 2013, with at least that many expected in 2014. Ten years ago, CubeSats were routinely dismissed by industry professionals as being too small to be worth flying; now, NASA is the majority launch broker, and a significant share of the manifests are filled by U.S. DoD-sponsored, industry-built CubeSat missions. How did initial perceptions of CubeSats evolve to this state? Are CubeSats toys, tools, or merely another source of orbital debris?

With so many CubeSats now in orbit, it is now possible to make a data-based assessment of these missions. Using data collected from a variety of sources, this study evaluates the on-orbit performance of CubeSats. The history of CubeSat missions is reviewed, with the missions classified according to size, origin, mission life, and on-orbit performance. It is shown that several correctable design/implementation errors plague the university side of CubeSat missions, and that the P-POD launch container, not the CubeSat specification, is the true enabling technology for this class of mission.

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1. Introduction

As has been extensively documented elsewhere, the CubeSat standard was developed by Bob Twiggs and Jordi Puig-Suari in 1999 (Puig-Suari, Turner, and Ahlgren, 2001), (Nason, Puig-Suari, and Twiggs, 2002), (Heidt, Puig-Suari, Moore, Nakasuka, and Twiggs, 2000), (Wenschel, et al., 2006). By the original definition, CubeSat-class spacecraft are compatible with the Poly-Picosatellite Orbital Deployer (P-POD), a standardized launch interface on the order of 13 cm x 16 cm x 40 cm that carries between one and three small spacecraft totaling less than 5 kg and 10 cm x10 cm x 33 cm in size. The unit size for a CubeSat – called 1U – is 10 cm x 10 cm x 11 cm; thus, a standard P-POD carries a total of 3U. While much attention has been devoted to the miniaturization and standardization afforded by CubeSat spacecraft, the true innovation of CubeSats is the P-POD launch interface. To the greatest extent possible, the P-POD decouples development, integration and verification of the spacecraft from the development, integration and verification of the launch vehicle, with attendant benefits in cost and schedule.

The first CubeSats were launched in 2003, and just nine years later, the one hundredth CubeSat has been put in orbit. By the end of 2012, 112 CubeSat-class missions were flown, fielded by nearly 80 organizations from 24 countries on 29 rockets, representing universities, national space and defense agencies, private companies, and amateur organizations. In 2013, a high school will join the ranks, and the pace of launch will increase considerably; to the author's knowledge, ten launches are scheduled to carry 80 CubeSat-class spacecraft by the end of 2013.

Depending on who is queried, one receives a wide range of opinions on CubeSats. Some consider them to be a disruptive technology that will radically change the future of spaceflight. Others consider them a fad, or a "toy" of middling value to universities – but no value to anyone else. While opinions are diverse, data is scarce. Wikipedia-based lists of CubeSats have been compiled, and surveys have been performed for small spacecraft (DePasquale, Charania, Matsuda, and Kanayma, 2010) and for those with masses under 10 kg (Bouwmeester and Guo, 2010), but no comprehensive study of this important new class of spacecraft has been published.

This paper provides a first-ever statistical history of CubeSat-class spacecraft, from a compilation of a comprehensive database of CubeSat-class missions, using a range of sources. Missions have been organized according to familiar categories, such as size, orbit, mission and provider. Using these categories, trends in reliability, mission type, and launch providers are identified. For example, more than 40% of the CubeSat-class missions to reach orbit did not meet their basic mission objectives, although that number is skewed by university-led missions, which fail much more frequently than industry-led missions. This paper shows that there is a split in capabilities and performance between 1U-sized educational CubeSats and 3U-sized technology/science focused industry-built missions, and in a concluding section, provides a tentative forecast for the next two years of CubeSat missions.

1.1 What is a CubeSat?

The formal definition of a CubeSat is a spacecraft that adheres to the CubeSat Design Specification developed by Cal Poly and Stanford (i.e., it fits inside the P-POD and follows the flight safety guidelines). However, there are other P-POD-equivalent interfaces, such as those developed by these organizations:

- JAXA: J-POD and ISS-qualified S-POD
- University of Toronto Space Flight Laboratory (SFL): T-POD and X-POD
- U.S. Department of Defense: Space Shuttle Picosatellite Launcher (SSPL)
- NASA: Nanosatellite Launch Adapter Systems (NLAS)
- Innovative Solutions in Space (ISIS): ISIPOD.

These launch containers vary in their internal dimensions and other constraints placed on the spacecraft they carry; for instance, a "CubeSat" that adheres to the P-POD standard would not fit in an SSPL. There are enough strong similarities across the spacecraft carried by these containers, however, that they are worth studying as one group. Therefore, we will define our own term: a "CubeSat-class" spacecraft is any spacecraft compatible with one of these standardized secondary launch containers/ejectors. In addition to the systems listed above, we also include the picosat ejectors flown inside the Opal spacecraft (Cutler and Hutchins, 2000), as they are the direct precursors and motivators for the CubeSat/P-POD standard (Puig-Suari, Turner, and Ahlgren, 2001), (Heidt, Puig-Suari, Moore, Nakasuka, and Twiggs, 2000). Larger dispensers have been proposed, such as the 6U, but none had flown during the period of this study.

By defining CubeSats in terms of their dispensers, it is further emphasized in this study that the critical feature of the "CubeSat" standard is the container, not the spacecraft.

To the extent that it is possible in spaceflight, the P-POD decouples its CubeSats from the launch vehicle; from the perspective of the launch provider, the P-POD is nearly a "black box," where the contents do not matter. The value this decoupling provides to a launch campaign cannot be underestimated. Major pre-launch analyses such as coupled loads, electrical wiring, and separation sequences are the same, regardless of the characteristics of the CubeSats that will fly. In addition, specialized CubeSat integrators, such as Cal Poly, SFL, and ISIS, provide a single point-of-contact interface between all the CubeSat providers and the launch provider, further decoupling the two. All of these effects have served to drive down costs and integration delays, and keep them down.

Therefore, this paper does not study spacecraft of a given mass, examining instead the impact of standardized, containerized launch vehicle interfaces on the more than 110 space missions that have flown to date.

1.2 The Database

A detailed database of CubeSats manifested from 1999 until the submission of this paper (December 2012) has been compiled from sources including three online references (Krebs, 2012), (Rupprecht, 2012), (Wade, 2012), the proceedings of the AIAA/Utah State University Conference on Small Satellites, the proceedings of the Spring and Summer CubeSat workshops, and various university and program websites. A complete listing of spacecraft is provided in the Appendix. Because the inclusion or omission of a spacecraft from this list may prove to be a contentious issue, especially with regard to this paper's definition of mission failure, the process for creating the database shall be reviewed.

First, using the sources listed above, a list of all CubeSat-class missions was compiled. Only missions with an official manifest are considered; (Krebs, 2012) is used as the first reference for identifying missions that have not yet launched, augmented by other public announcements, such as press releases. Data on these spacecraft was assembled, with information derived from published reports and project websites as indicated. In some cases, a subjective assessment has been added.

Each mission was assigned a single mission class. A T-class (technology-class) mission flight-tests a component or subsystem that is new to the satellite industry (not just new to the mission provider). An S-class (science-class) mission creates science data relevant to that particular field of study (including remote sensing). A C-class (communications-class) mission provides communications services to some part of the world (often in the Amateur radio service). Missions listed as E-class (education-class) lack any of the other payloads and serve mainly to train students/young engineers and improve the satellite-building capabilities of that particular program; typical E-class payloads include COTS imagers (low-resolution Earth imagery), on-board telemetry, and beacon communications. Many CubeSat mission statements claim that the spacecraft will be collecting valuable science or engineering data; however, if the performance of the flight instrument could not be traced back to quantifiable science or technology objectives, the mission was considered to be E-class. Colloquially, E-class spacecraft are sometimes called “BeepSats”, indicating that they serve no on-orbit function other than “beeping” back telemetry.

Missions are labeled as failed if the mission operator has publicly labeled it as such, or if this analysis was unable to uncover evidence that the mission goals were met. Moreover, missions that were operational for fewer than 60 days on-orbit are assumed to have failed, unless counter-evidence was found. Note that E-class missions also must operate for at least 60 days before they can be classified as a success.

1.3 Disclaimers

In the author's estimation, this database has the most complete set of CubeSat-class specifications available. Still, certain elements such as launch mass and mission duration are approximations.

Recognizing the hubris in assigning success or failure to someone else's mission, these assignments have been made to the best of the author's ability given the information available, and discussion on where the line between success and failure should be drawn is welcomed. A student-built mission that fails to operate as intended on-orbit can be a great learning/training experience, but it cannot be called a mission success. Without objective measurements of success and failure, CubeSats will continue to be dismissed by the space industry.

The opinions in this paper reflect the author's experience as both student project manager and faculty advisor to satellite projects. The author accepts sole responsibility for any factual (or interpretative) errors found in this paper and welcomes any corrections.

2. The CubeSat Manifest

The CubeSat-class launch manifest is listed in the Appendix and displayed in Figure 1 by year of launch; the missions listed for 2013 are those with announced launch dates. The year 2005 can be considered as the beginning of the CubeSat-class Era; other than the first launch of P-PODs in 2003, the missions before then are precursors (Opal and PSSC). Beginning in 2005, there is a steady increase in manifested CubeSats, with an astonishing 99 CubeSat-class missions fielded in eight years, and 129 CubeSat-class overall manifested since 2000.

2.1 Why 2013 Data is Ignored

As shown in Figure 1, the estimated manifest for 2013 dwarfs all other launch years. In fact, the manifest for 2013 contains more missions than the previous six years combined; if the ten launches for 2013 are successful, the number of CubeSats placed in orbit will double. However, 75% of the CubeSats manifested in 2013 are to launch in the last two months of the calendar year (after the writing of this paper); these manifests are projected and by no means guaranteed. Therefore, it would be imprudent to include the forecasted 2013 manifest in this analysis, as those missions are subject to significant change. Instead, focus herein is on the missions already launched, with 2013 and 2014 revisited in the conclusion. Where relevant, general facts about the launch class of 2013 will be included.

2.2 Multi-Mission Launches

When the manifest is grouped according to launch vehicle (Figure 2, next page), it is seen that the majority of CubeSats have been launched in groups of five to nine spacecraft, although launches of two to four spacecraft and single CubeSat launches are also common. Note that some CubeSat missions are 3U in size, and thus the single-mission deployments in 2006 and

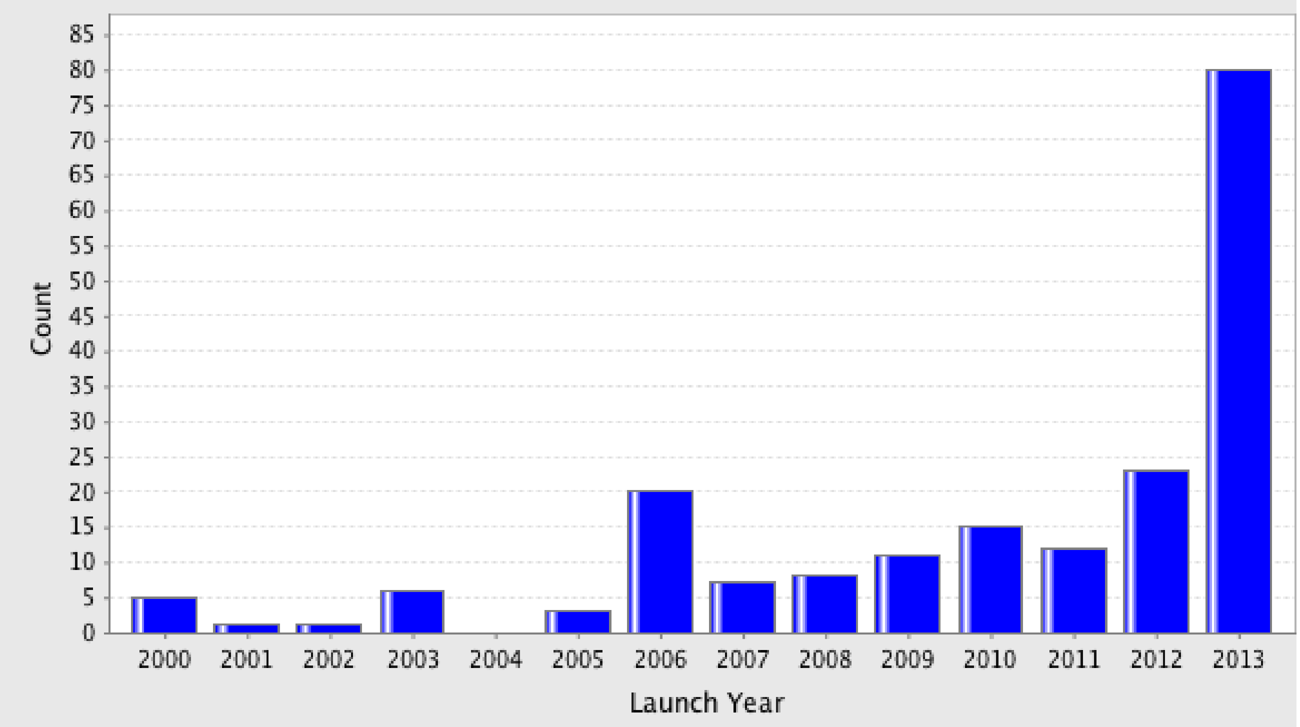

Figure 1. CubeSat-Class Missions Launched Each Year (Including Firm Manifests for 2013)

2009 still involved a complete P-POD. All CubeSats launched to date have been secondary (or tertiary) payloads capitalizing on the excess capacity of a rocket carrying a larger, primary payload. To date, there have only been two "high-capacity" launches of ten or more CubeSats on the same rocket, but three more are scheduled for 2013.

It is predicted by the author that the average number of missions per launch will rise, driven by launch capacity in the U.S. and Russia. Through NASA's Educational Launch of Nanosatellites (ELaNa) program (Skrobot and Coelho, 2012), the U.S. will fly between 3 and 16 P-PODs on most government-procured launches; Russia is similarly stacking many P-PODs on each of their commercial launches, and the 50-CubeSat Qb50 mission is scheduled for 2015 (Muylaert, 2009). It is not the author's belief that small-mission-count launches will cease; rather, there will be many more deployments carrying ten or more missions.

As these high-capacity deployments become more common, the author also expects to see increased scrutiny on radio licensing, orbital debris assessment, and integration. With a dozen or more objects released on a single launch, the process of identifying each mission and avoiding communications conflicts will become more challenging. If failures can be traced back to unexpected cross-coupling between CubeSats (e.g., if RF interference or collision causes one or missions to cease operations), there could result a scenario where the high-capacity launches of 2013 and 2014 are the last of their kind. Regrettably, some sort of incident related these high capacity launches is foreseen, either in terms of operational conflicts or minor collision. Flight results should be monitored very carefully; lessons learned from the management of Qb50 will be of particular interest.

2.3 Ejectors

Viewing the manifest by the ejector used (Figure 3, next page), it is noted that the P-POD standard dominates the manifest, although the variants from the Japanese Space Agency, NASA, and several private vendors are increasing their market share. In the U.S., the SSPL was qualified for Shuttle operations and the International Space Station (ISS); with the phase-out of the Shuttle, the DoD is migrating to the P-POD. The P-POD has been used for international launches (most

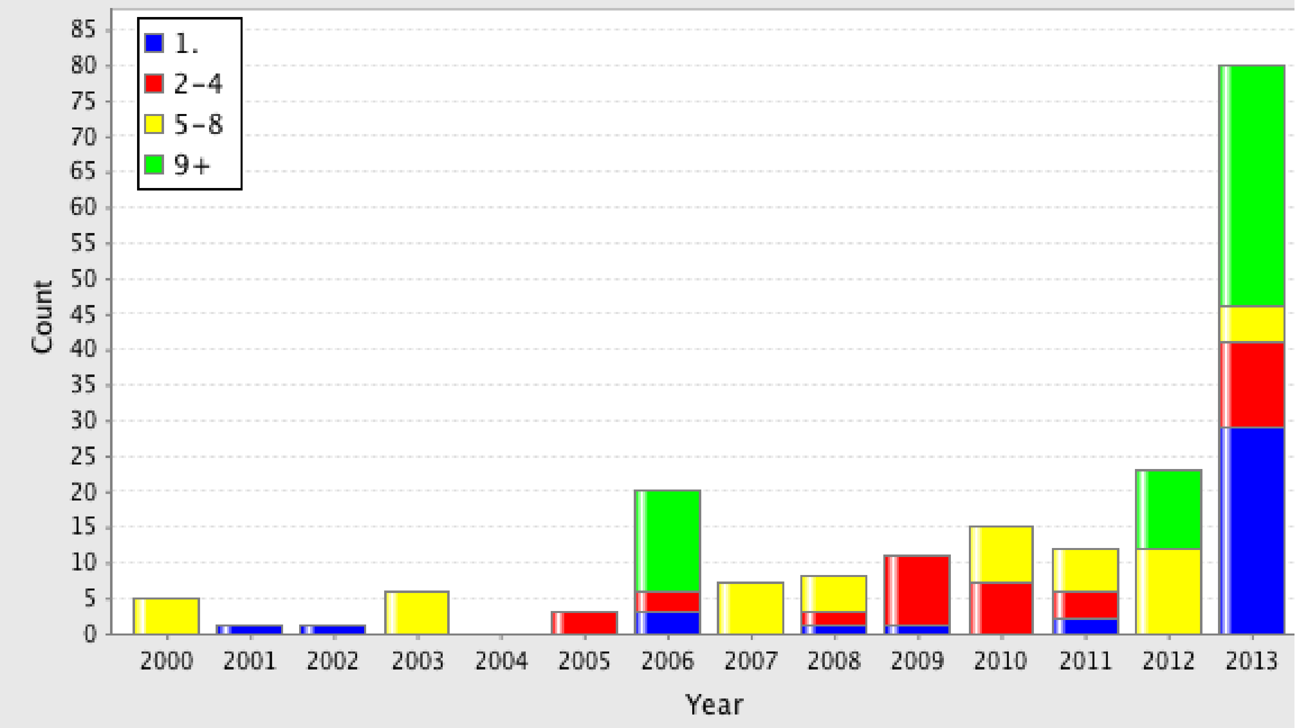

Figure 2. Number of CubeSat Missions per Launch Vehicle

notably ESA's Vega demo flight), but the trend clearly shows that the P-POD is used in the U.S., with international variants used in the rest of the world.

If the manifest is classified by CubeSat size (Figure 4), it is clear that most CubeSat-class missions have been 1Us, with 3U-scale spacecraft becoming more

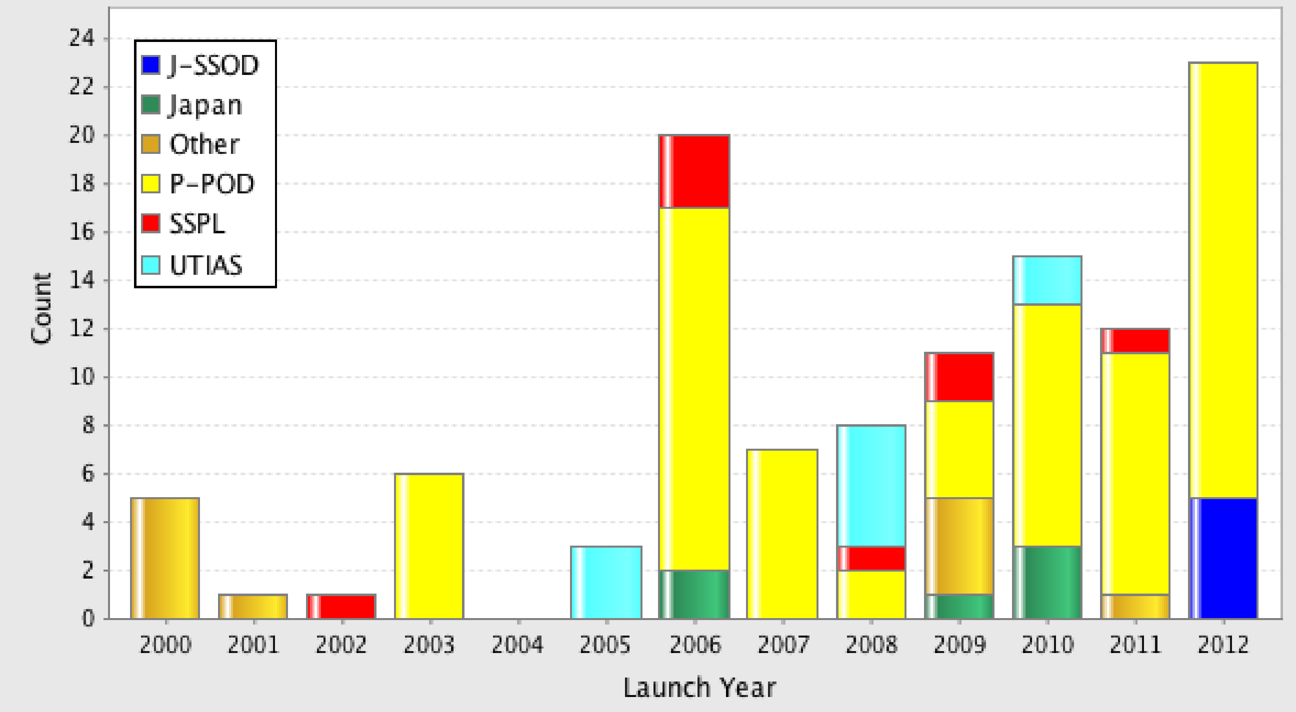

Figure 3. Number of CubeSat Missions Using Each Ejector Type per Year

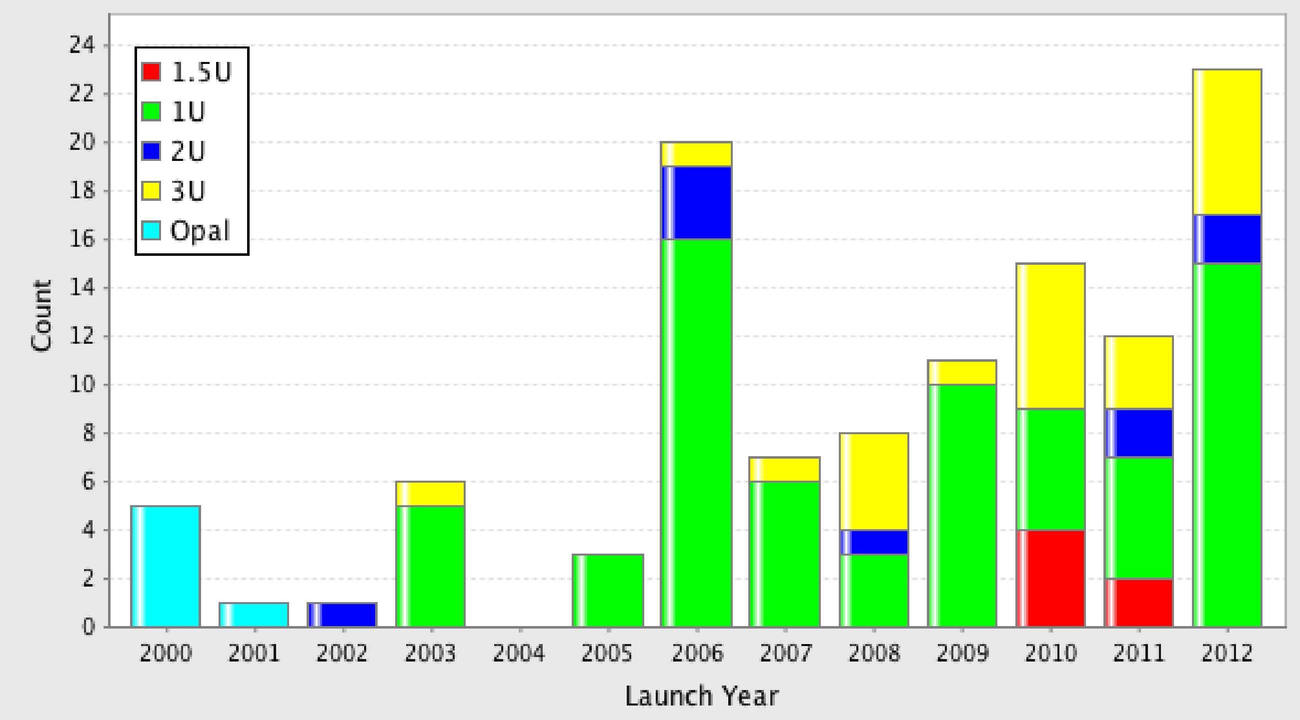

Figure 4. Number of CubeSats Launched of Each Form Factor per Year

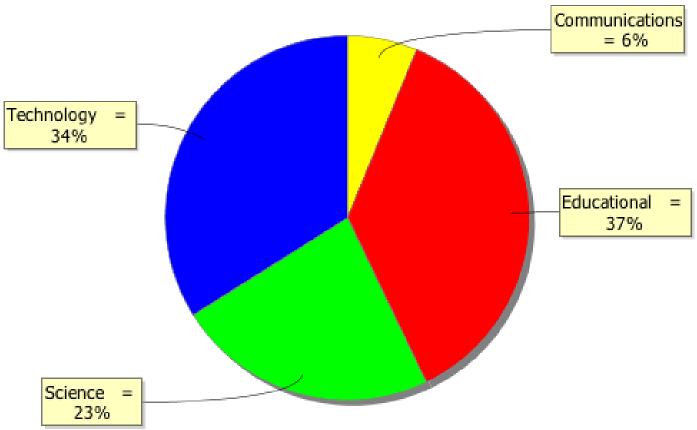

Figure 5. Breakdown of All CubeSat Missions by Mission Category, 2000-2012

popular in recent years; 1.5U and 2U missions are rare. The present paper examines this trend in more detail below, but it is anticipated that more 3U missions will be manifested in the coming years. As noted above, the Opal-launched picosats are included as CubeSat precursors; the Opal designation in Figure 4 is for 10x7.5x2.5 cm, 400-gram spacecraft.

The motivation for moving to 3U-sized spacecraft is a need for more volume and aperture: practically speaking, a 3U spacecraft has more than triple the power, communications and pointing capacity of a 1U spacecraft. 1U spacecraft are volume-constrained more than they are mass-constrained. Because of the scale of standard mechanisms, connectors, etc., a 3U has more useful volume, and more room is available to deploy panels and antennas with better packing factors. It is instructive to note that the very first 3U spacecraft, QuakeSat, was also the first successful S-class CubeSat, and that 28 of 30 3U-class spacecraft have had real missions (compared with 33 of 76 1U missions).

As will be further discussed below, most industry-built CubeSats are 3Us, owing to the enhanced performance available to a 3U. As more universities develop capable missions, they can be expected to follow suit. When the larger dispensers become available (e.g. the 6U dispensers from NASA Ames, NASA Goddard, and/or Planetary Systems), industry-built missions are expected to immediately adopt them in large numbers.

2.4 Mission Relevance

As shown in Figure 6, there has been a significant increase in T-class missions over the last five years, with E-class missions in a close second place (Figure 5); this

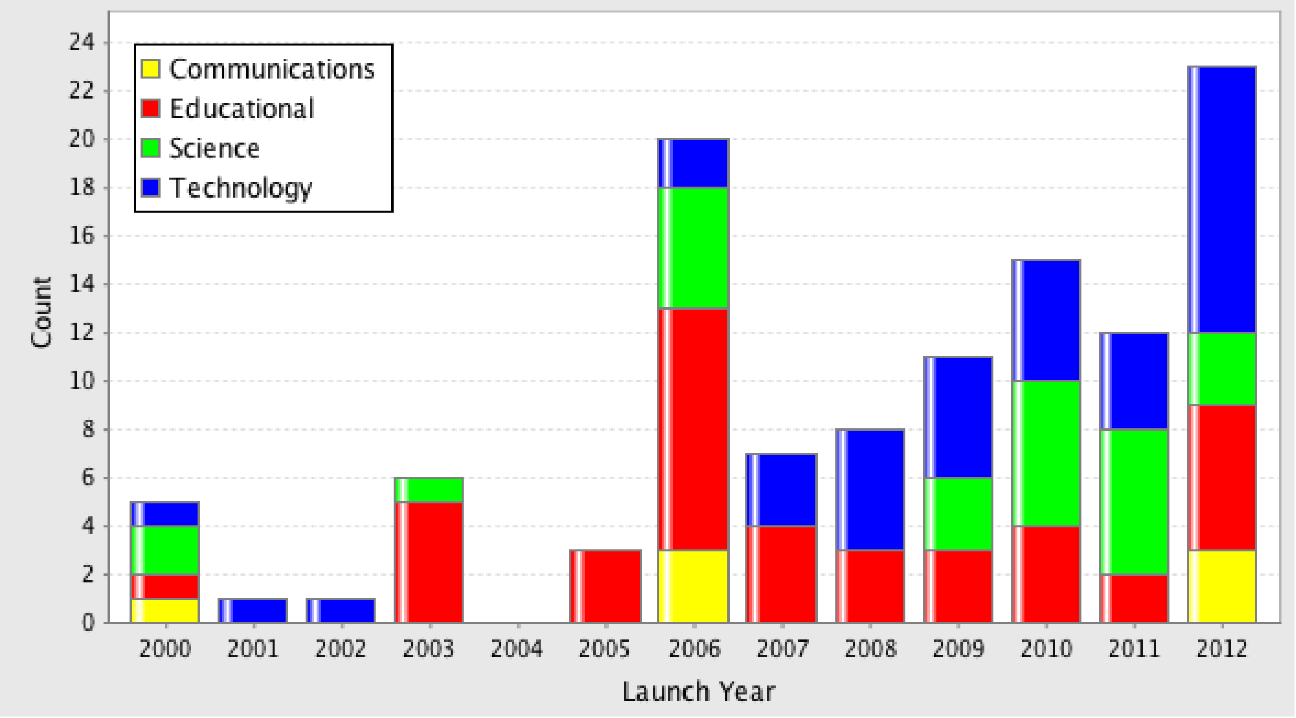

Figure 6. CubeSat Missions Launched by Mission Category

trend in T-class flights is again correlated with the rise in the number of professional CubeSat-class missions. This study also examined the correlation of CubeSat size (Figure 7) with mission utility. Since industry-led missions and 3U-scale missions are strongly correlated, it should not be surprising that larger missions (1.5U and up) are predominantly "real" missions, whereas the 1U missions have a large fraction of BeepSats. In fact, 49 of 54 1Us are university-built, and 49 of 64 university missions are 1U. Similarly, professional programs build bigger spacecraft (1.5U, 2U or 3U); 17 of 27 larger CubeSat-class spacecraft are industry-built (and 17 of the 33 industry-built CubeSat-class missions).

As recently as two years ago, it could be assumed that an industry-built CubeSat would be a T-class 3U, while a student-built CubeSat would be an E-class 1U. While the former assumption is still valid, the 2012 manifest challenges the assumption about universities. S/T/C-class missions comprise nearly half of the university-built 1U missions in 2012 (6 of 14), compared with 28% of the university-class 1U missions launched before 2012 (13 of 45). The author believes this is due to the NASA ELaNa and ESA Vega programs, which select CubeSats based on the relevance of their mission.

This trend is expected to continue. In the U.S., the shortest and least expensive path to launch is through the NASA ELaNa program, which preferentially selects missions with science/engineering return. Thus, increasingly competitive missions in terms of science/engineering return can be expected, regardless of size. This trend bodes well for the future of CubeSats.

2.5 Success and Failure

Examining spacecraft status by launch year (Figure 8, next page), two issues are apparent. First, it is somewhat miraculous that there have been 100 CubeSat missions, when 9 of the first 13 failed to achieve their mission, and only 8 of the first 36 survived launch and operated successfully. In particular, 14 CubeSat-class missions were lost on the Dnepr-1 launch failure of 2006; at the time, it was questioned whether the programs would recover (Swartwout M. , 2006), (Swartwout M. A., 2007). Credit must be given to the perseverance of early adopters and launch providers. Second, it is instructive to note that the number of CubeSat failures each year has not diminished; since 2006, an average of three missions launched each year

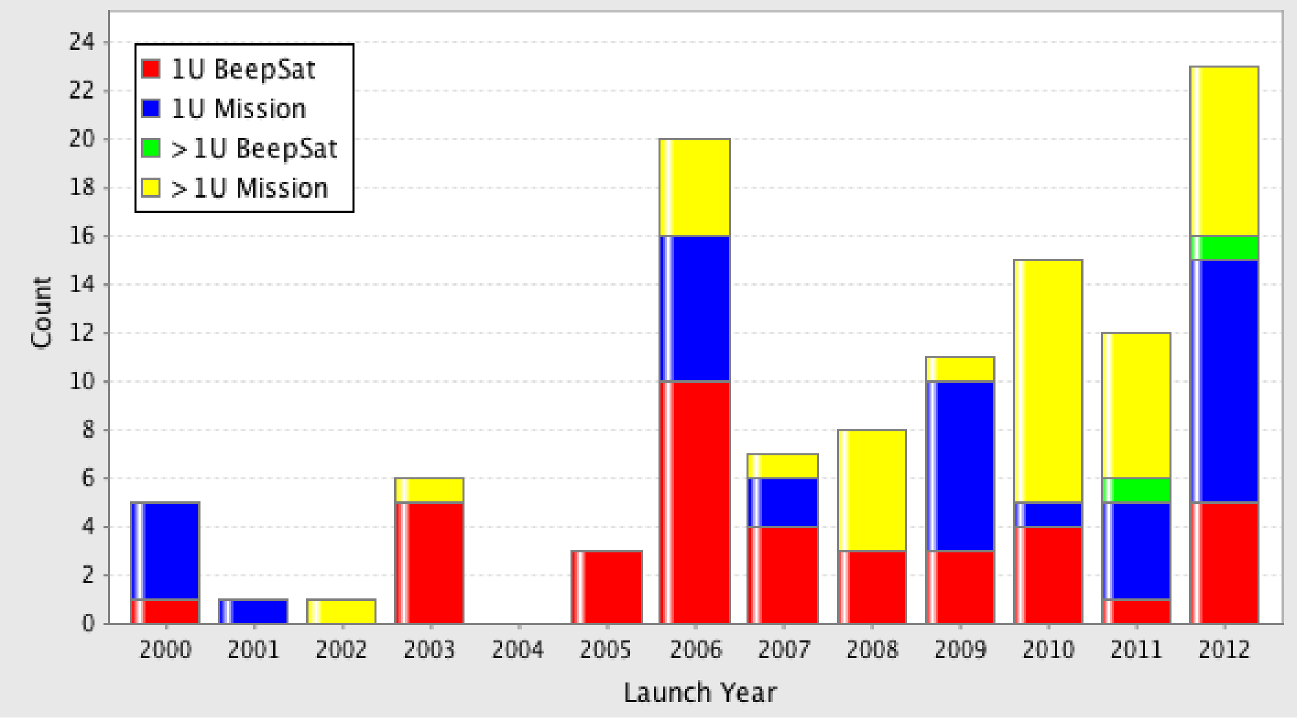

Figure 7. CubeSat Missions by Form Factor and Mission Relevance

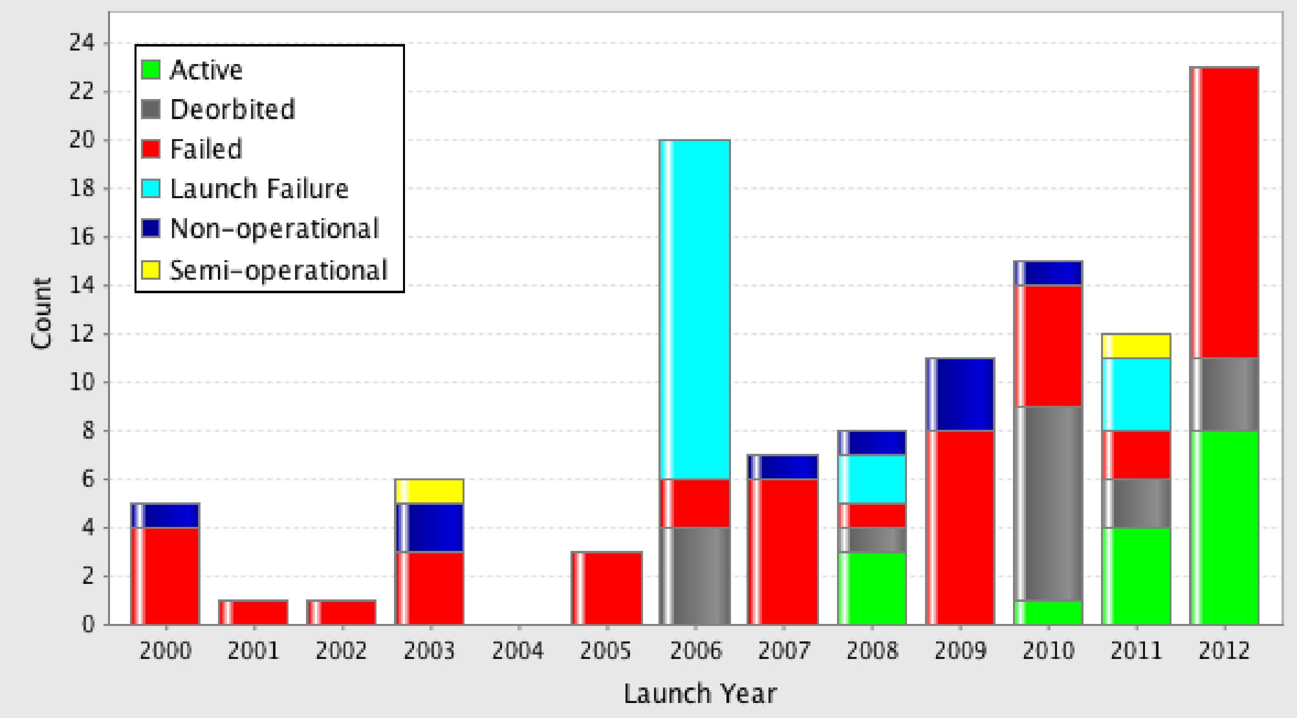

Figure 8. Mission Status by Launch Year

fail to accomplish their objectives. The increase in the number of missions has reduced the impact of failure, but failures are still occurring. The vast majority of the failed CubeSat missions have been university-led projects (27 of 34 failures). It must be noted that industry-led missions are far less forthcoming with mission objectives and performance, and thus it is possible that some failed industry missions have not been identified.

The author again notes with some degree of trepidation the number of high-capacity launches scheduled for 2013; any launch failure will wipe out as many as two dozen missions.

If the causes of mission failure are examined (Figure 9), the striking detail is that a third of all failed missions were never contacted after launch. Such failures could have any number of causes, including power failure, communications failure, software lockup, radiation-induced latchup, or mechanical failure due to launch loads.

Looking at the failure reports more closely, a common thread is discovered, accounting for almost half of all failures: a configuration or interface failure between communications hardware (27%), the power subsystem (14%) and the flight processor (6%). Typical examples of such failures: batteries and/or solar panels not connected properly to the power bus; insufficient power generation to operate the transmitter at a level needed to close the link; and unrecoverable processor errors. These can be classified as failures in functional integration; the spacecraft was not operated in a flight-equivalent state before launch, and thus these easily-caught mistakes were not discovered. Though this allegation obviously cannot be proven, it is strongly believed that a large fraction of the "no contact" failures is due to poor functional integration, and thus as many

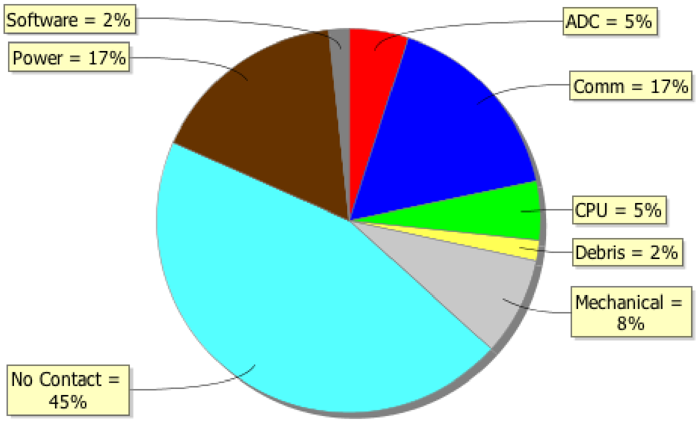

Figure 9. Causes for CubeSat Mission Failure, 2000-2012

as two-thirds of CubeSat mission failures are failures in functional integration.

How could this happen? First, note that 24 of the 30 failures in the no-contact or functional integration categories are university-led missions. Next, based on off-the-record conversations with project managers and lead faculty, two factors appear to be in play:

- Students (and faculty) operate under the misconception that the three biggest obstacles to mission success are system-level design, component-level design, and component-level assembly/test; if these three tasks are performed well, then assembly and checkout of the complete spacecraft will proceed smoothly and in a short amount of time (Cutler and Hutchins, 2000), (Swartwout M. A., 2009), (Swartwout, Kitts, and Cutler, 2006), (Swartwout M. A., et al., 2008). In the experience of the author, system-level integration and test is the schedule driver and the biggest obstacle to mission success University-led projects operate under the faulty assumption that the spacecraft will work as expected the first time it is put together, and thus they do not perform system-level functional tests.
- Even when programs identify system-level functional integration as an area of concern, they lack the schedule margin to give it adequate attention. Obviously, system-level functional testing must come at the end of the development phase, and university programs are usually so squeezed for time that they must immediately move to environmental testing before shipping their CubeSat to the launch site.

Failure rates approaching 50% among university-led missions is distressing, especially since many of the observed failures could be identified and corrected before launch. Recommendations for addressing this shortcoming are offered in the conclusion of this article.

Looking at Figure 9 another way, it is instructive to note that only two of the 112 CubeSat missions have experienced mission failure due to mechanical issues, and at most a handful have failed due to thermal or radiation issues. Granted, revisiting Figure 8 (and, in a moment, Figure 10), it must be admitted that CubeSats do not last very long on orbit (less than 200 days on average). Doubtlessly, inadequate thermal design

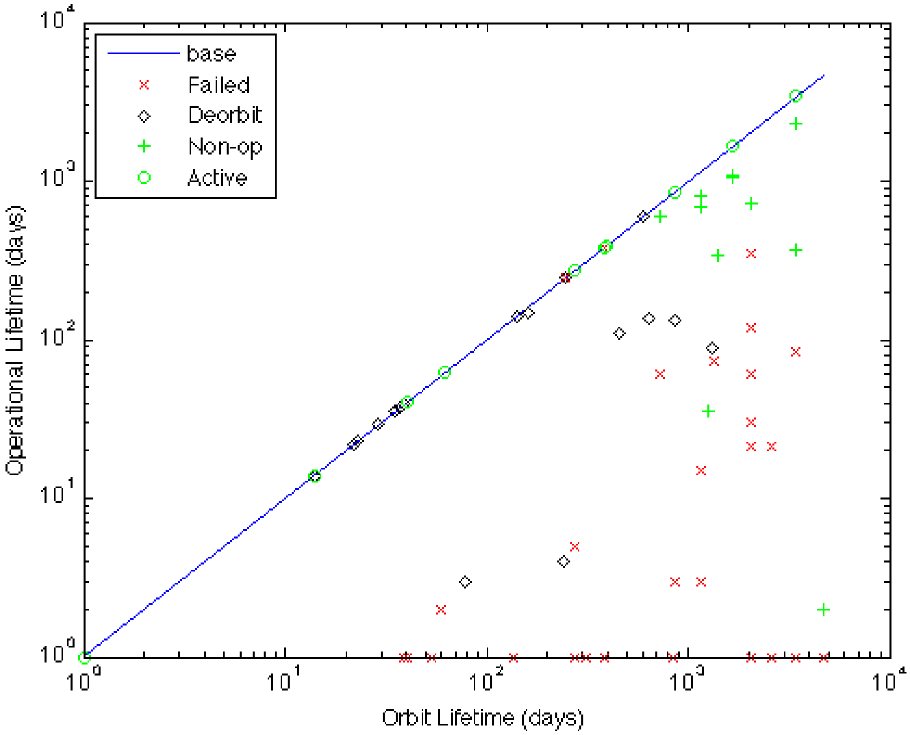

Figure 10. Operational Lifetime vs. Orbit Lifetime, CubeSats Launched from 2000-2012

and inattention to COTS electronics contribute to reduced lifetimes. Again, while no one should discount the importance of sound structural & thermal analysis/testing, nor should programs ignore the risks of COTS electronics, the flight history indicates that more time needs to be devoted to system-level functional testing rather than mechanical, thermal, and radiation issues.

As a final investigation of mission lifetimes, the operational lifetime of each mission is plotted against that mission's orbit lifetime in Figure 10. The blue line is the upper limit of performance; a mission that was operational for its entire orbit lifetime will be on the line. Missions that are decommissioned before orbit decay (either through normal end-of-mission operations or failure) fall below the line. From the plot, it can immediately be seen that many failed missions were operational for some period of time before being declared a mission failure; missions that immediately failed are at the bottom of the plot.

The other observable trend is that more recently launched CubeSats tend to have operational/orbit lifetimes that are short; these missions cluster on the bottom third of the chart and towards the blue line. One of the purported benefits of CubeSats is that their development costs are small enough that it is cost-effective to place them in short-duration orbits (i.e., orbit locations where other missions cannot be placed). One can begin to see missions targeting these regions, starting with the SpaceX F9/Dragon flight of 2010 that carried eight CubeSats with orbit lifetimes of a few weeks. It will be interesting to see if that trend continues, or if only E-Class spacecraft will accept these limited-lifetime orbits.

2.6 University and Industry

If the manifest is examined according to the type of developer (i.e., university, commercial, military or civil government), it is difficult to establish trends (Figure 11). From 2007-2010 it appeared that military and civil government programs would use up all available capacity, leaving no launches available to universities. There was a profound reversal in 2010 and 2011; the number of professional missions increased, but the number of university missions increased at a larger rate. The reason for this shift is apparent if the missions are organized into four categories: 1U-sized built by universities, 1U-sized built by all others, larger-than-

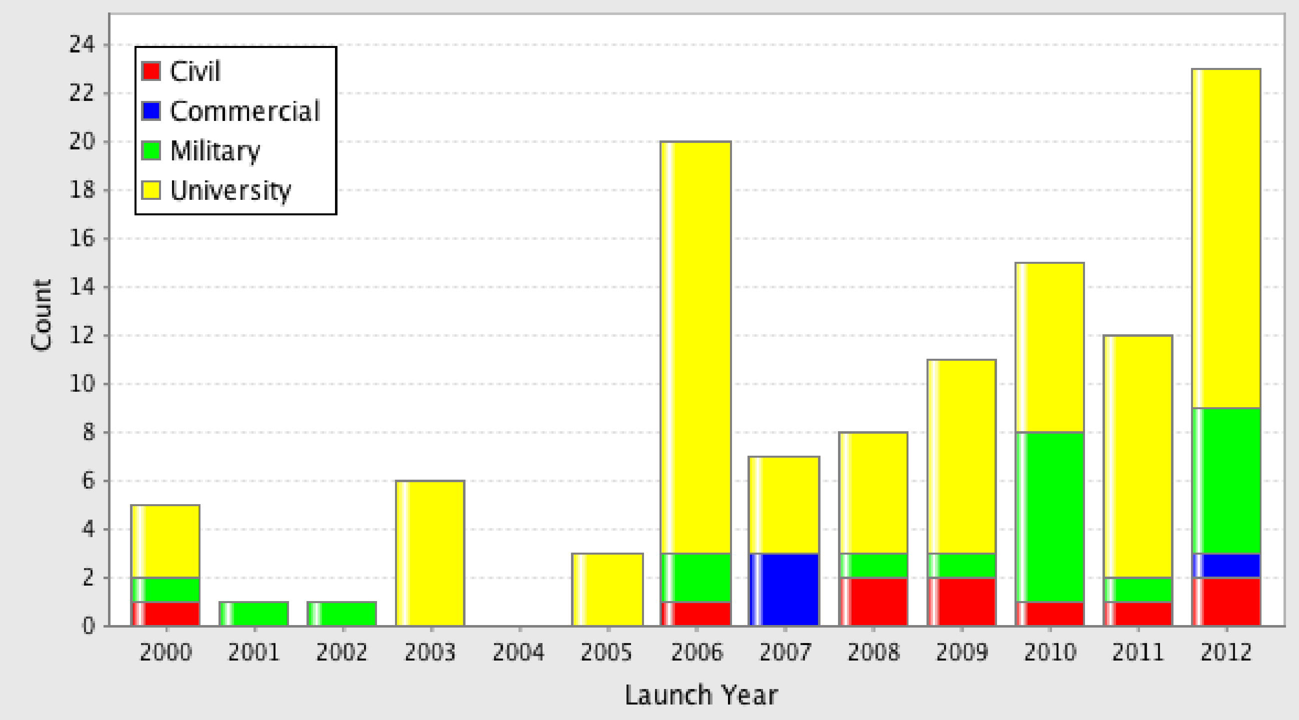

Figure 11. Type of CubeSat Mission Developer by Launch Year

1U missions built by universities, and larger-than-1U missions built by industry. Looking at the data in this way (Figure 12), the increase in 3U-scale missions corresponds to the increase in industry-led 3U-scale missions.

While there are some exceptions, in general, industry-led missions use the 3U form factor to maximize the mass, power, volume – and thus performance – of the CubeSat. It is speculated that the distinction between the two also underscores the different cost structures between industry and university missions: for a professional mission, the costs of launch and of spacecraft hardware are small compared to personnel expenses, whereas for a university, the cost of the launch and spacecraft hardware are the largest components of the mission cost. Thus, the cost of a professional mission is similar whether the spacecraft is 1U or 3U, while a university 3U could cost three times as much as a university 1U.

The recent growth in 3U-sized university-led CubeSat missions (on the order of 5 per year in 2011-2013) and the reverse of the industry-dominating trend of three years ago can be attributed to the following four factors.

1) Various agencies in the Defense Department experienced success with early CubeSats, e.g. the Aerospace Corporation's Aerocube series (Hinkley, 2009), and Boeing's CSTB-1, and decided to adopt the P-POD.
2) The National Science Foundation was also an early adopter, initiating a CubeSat-based Space Weather research grant in 2008 (Moretto T. , 2008), (Moretto T. , 2009).
3) Europe identified the CubeSat as an excellent education and training system, such that they sponsored a competitive program to select university CubeSats to fly on the maiden voyage of the Vega rocket.
4) NASA created the ELaNa program, where nearly every expendable rocket launched by NASA going to LEO will carry P-PODs.

At the risk of overstatement, the value added by P-PODs through decoupling is again emphasized; the speed with which P-PODs have been qualified for nearly every U.S. rocket can be traced back to the simplicity of the design and the ability to accept a wide range of payloads under that single qualification.

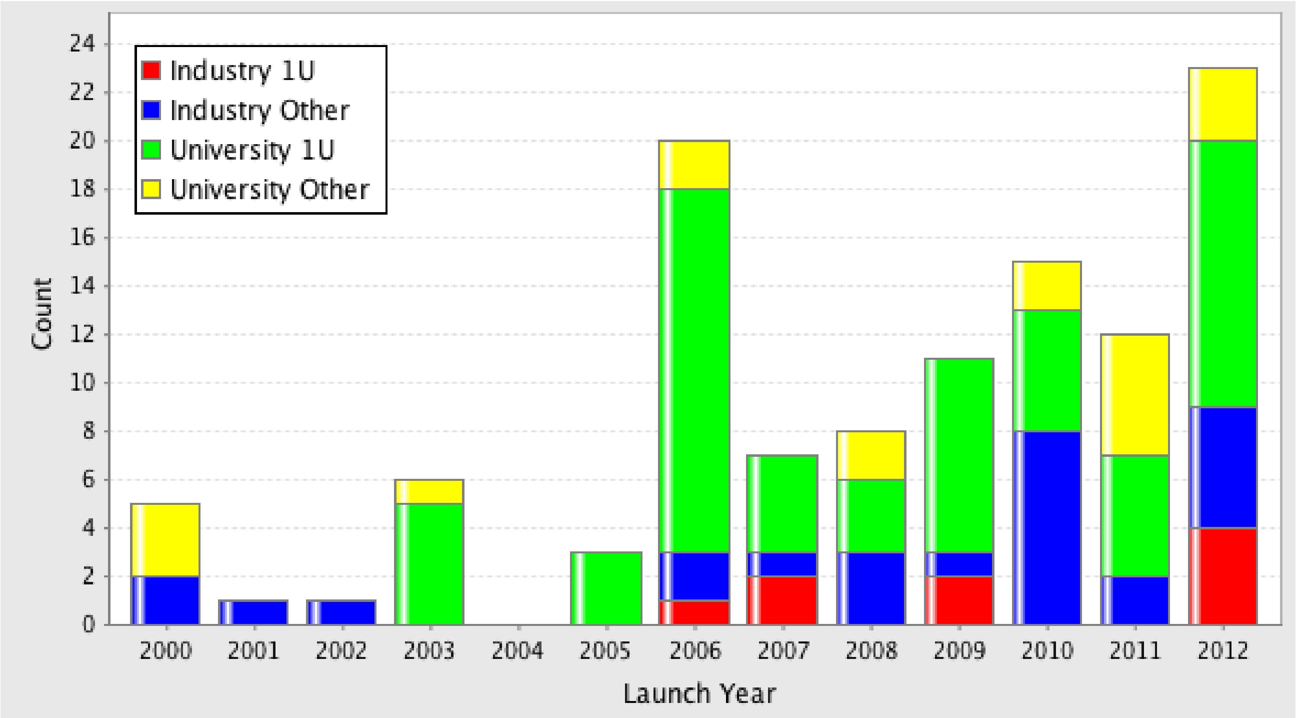

Figure 12. Number CubeSat Missions per Developer Category and CubeSat Size

Therefore, the more recent, larger, university-led missions are sponsored by government agencies such as NSF or DoD, and thus they have a different cost structure (and performance expectation) than university CubeSats launched earlier. This trend is expected by the author to continue: as the number of CubeSats shifts from university E-class missions to industry/university S-class missions, there will be an increase in the number of 3U (and, soon, 6U) CubeSats. As discussed above, this shift indicates that "real" missions will fill the largest volume the P-POD can provide.

Next, if the missions are sorted according to utility (i.e., E-class BeepSats v. "real" missions of the S-, T-, and C-classes) and then categorized by the same university and industry classifications (Figure 15), the expectations are that professionally-led CubeSat missions almost always have real mission value, and that BeepSats are mostly built by universities. However, the recent trend among universities is to fly real missions; in the last four years, real university missions outnumber BeepSats 23-15.

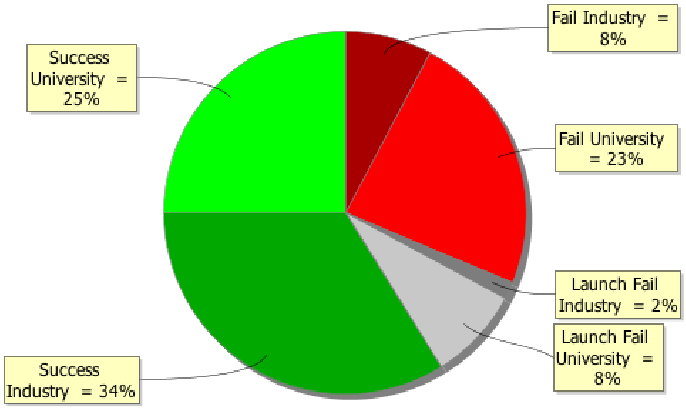

Figure 13. CubeSat Success for University and Industry Missions as Percentage of All Attempted Launches, 2000-2012

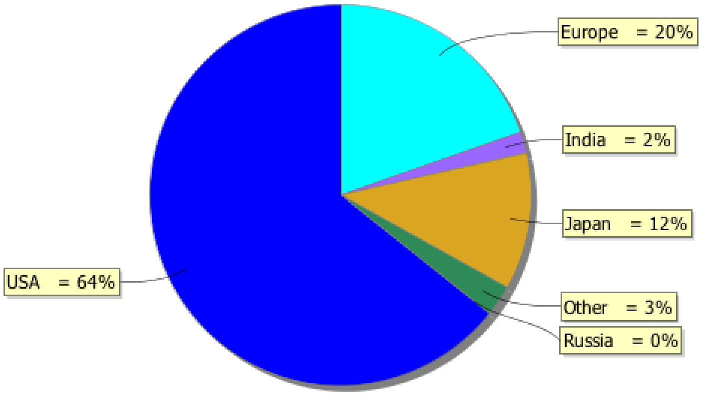

Figure 14. CubeSat Missions Developed by Each Nation, 2000-2012

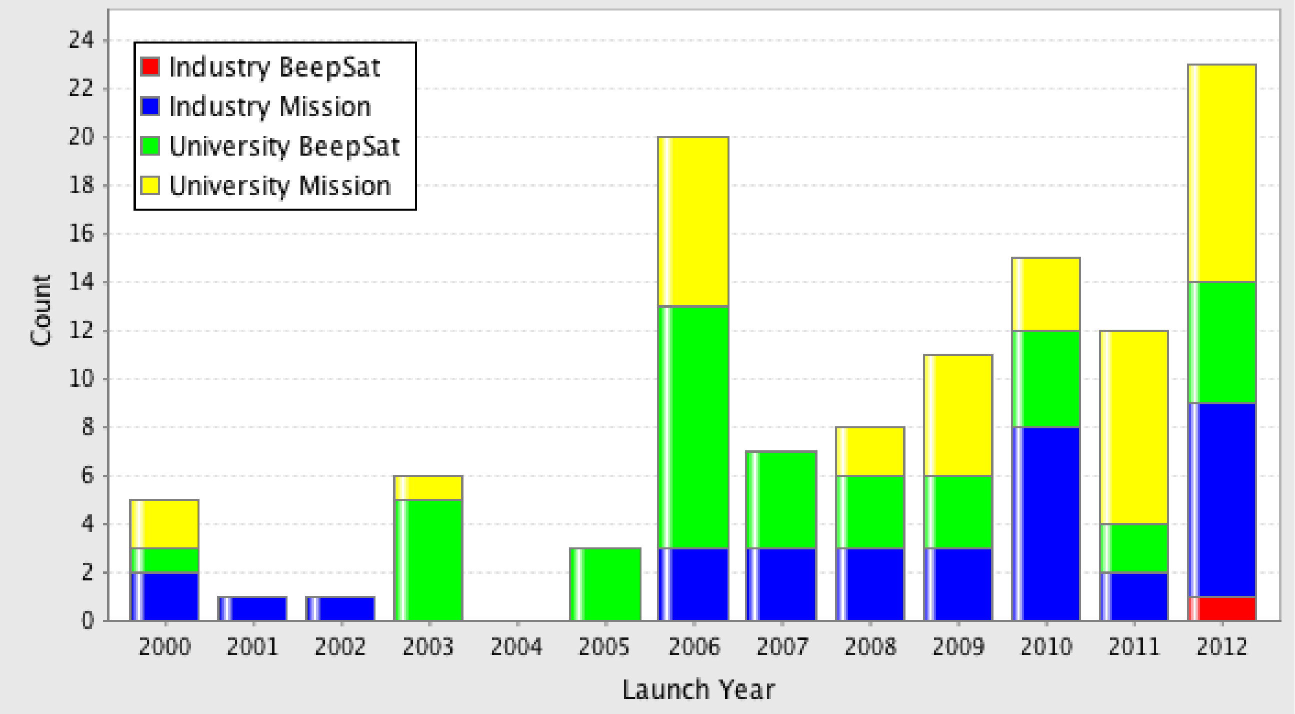

Figure 15. CubeSat Missions by Provider Class and Mission Utility

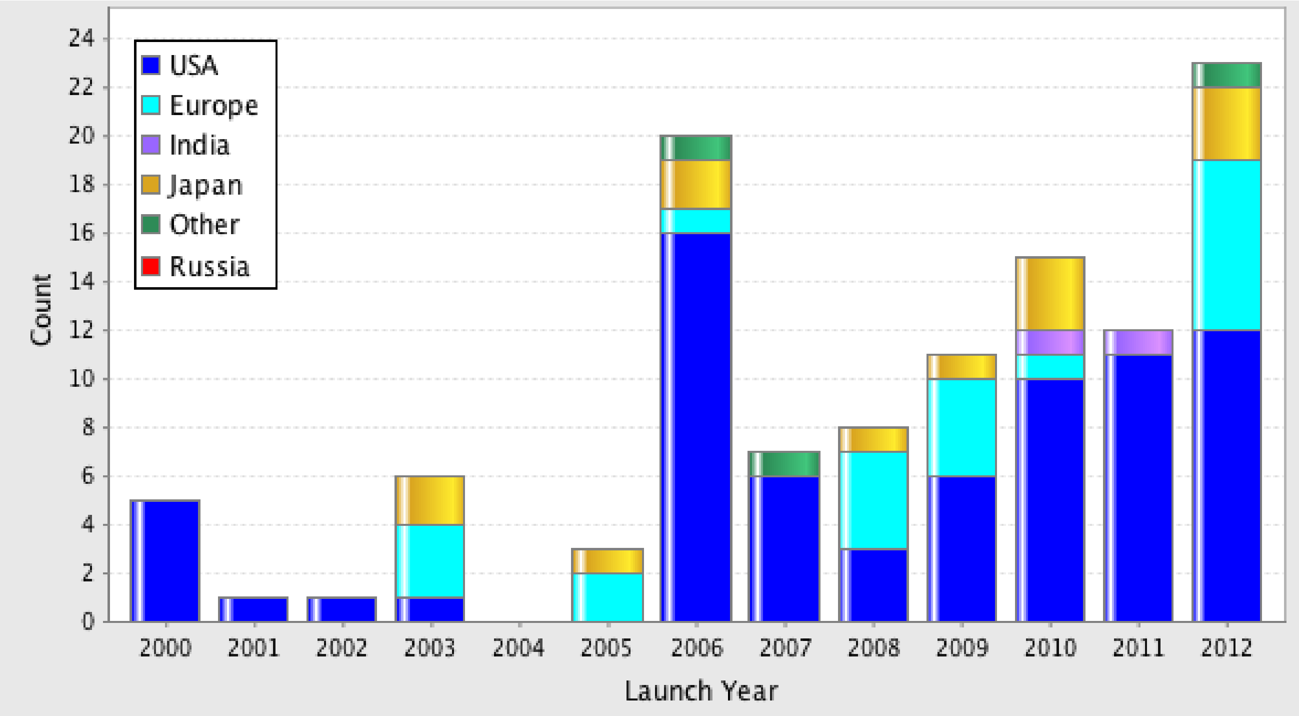

Figure 16. Manifested CubeSat Missions per Nation per Year

Looking through the lens of the industry-university split, issues of mission success and failure can be revisited (Figure 13). One observes that university CubeSats outnumber industry missions by more than a 60-40 split, but that university missions have a disproportionate share of launch failures and mission failures. The universities' share of launch failure is mostly bad luck (most of the university launch failures came on that single Dnepr-1 crash). It should be noted, however, that university-led missions tend to be manifested on maiden launches of new systems, and so the launch risk these schools must carry should not be entirely discounted.

Nearly half of all university-led CubeSat missions that reach orbit fail to achieve mission success, while less than 20% of industry-led CubeSats have mission failure. There is a clear split in capabilities.

2.7 International Trends

The CubeSat and P-POD were conceived and developed by U.S. universities, and with the notable exception of the flights in 2003 and 2005, the first 12 years of CubeSat-class missions were overwhelmingly U.S.-developed (Figure 16 and Figure 14). That changed dramatically in 2012, where the number of non-U.S. CubeSats was on par with the U.S.-made CubeSats. This is largely due to the first Vega flight. This trend is expected to reverse in 2013, as NASA and DoD place P-PODs on almost every Falcon 9, Antares, Minotaur, and Atlas launch on the manifest; well over 75% of the CubeSats listed for launch in 2013 will come from the U.S., in amazing testimony to the speed with which NASA and the U.S. DoD have embraced the P-POD.

If the missions are sorted by the nation from which they launch (Figure 17, next page), similar trends can be observed. The U.S. is steadily-increasing the number of CubeSat missions launched each year, with Europe, Japan, India and Russia periodically flying CubeSats. In the case of Russia and Europe, these flights come in large batches, with eight or more CubeSats on the same launch. The launches credited to the International Space Station (ISS) could be credited to Japan, as the launch came from a Japanese-developed P-POD equivalent (the S-POD) attached to Japan's Kibo module. The separate category for the ISS-ejected CubeSats was created because the means of launch and release is so different than the others in the database, and be-

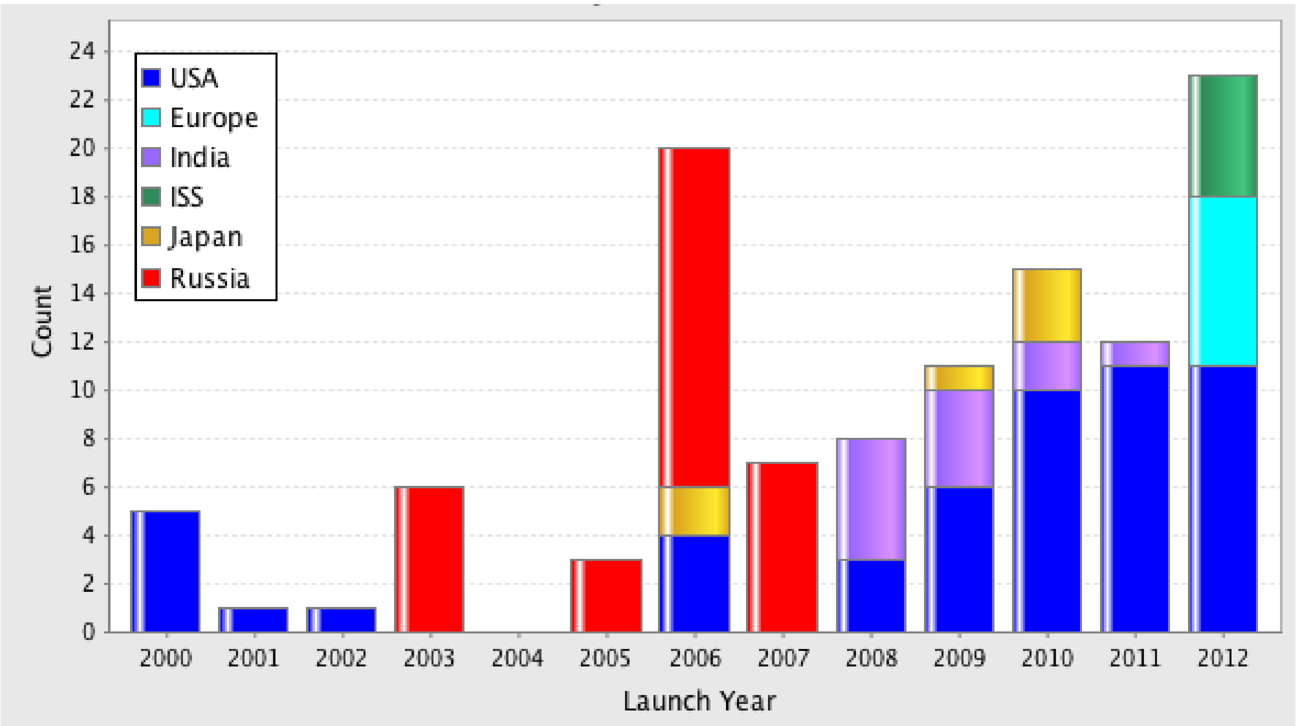

Figure 17. Manifests per Year, Sorted by Launch Vehicle Nationality

cause the U.S. is developing its own ISS ejector.

If Figures 16 and 17 are combined, one can observe which nations are launching which CubeSats, organized by launch nation (Figures 18 and 19). It should not be a surprise that the U.S. only launches U.S.-made CubeSats, although the U.S. is not alone in exhibiting a preference for locally-made spacecraft; only Japanese CubeSats have flown on Japanese rockets (although the Japanese-led ISS launches have been international), only European CubeSats launched on Europe's Vega rocket, and every Indian-built CubeSat has been launched in India. Russia has not built a CubeSat to date, although it is the second most prolific launch provider.

If one is in the market for a CubeSat launch, this figure indicates that India and Russia are the most available. Each has supplied launches for international customers. The United States, by contrast, is showing the effects of its ITAR policy, with no international manifests. Still, the U.S. has launched more CubeSats than anyone, and this lead is expected to widen next year.

Revisiting Figure 2, listing each launch separately, confirms that multiple-CubeSat missions are becoming the norm (Figure 20). All nations participate in launching five or more CubeSat spacecraft on a single launch vehicle, although only the U.S. and Russia are presently involved in the high-capacity launches.

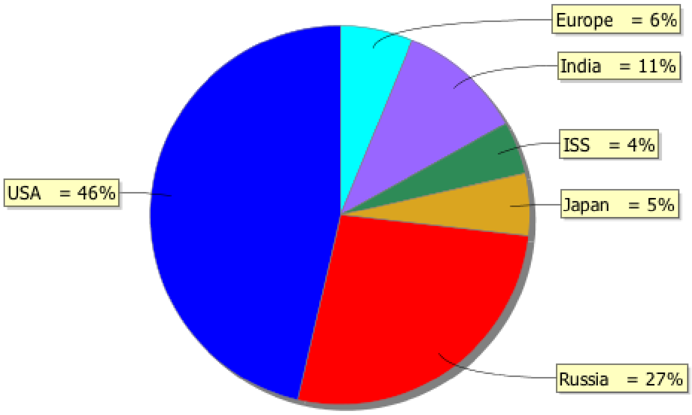

Figure 18. Share of CubeSats Launched by Each Nation, 2000-2012

3. Conclusion

While the continuous improvements in technology and the development of "off-the-shelf" CubeSat com-

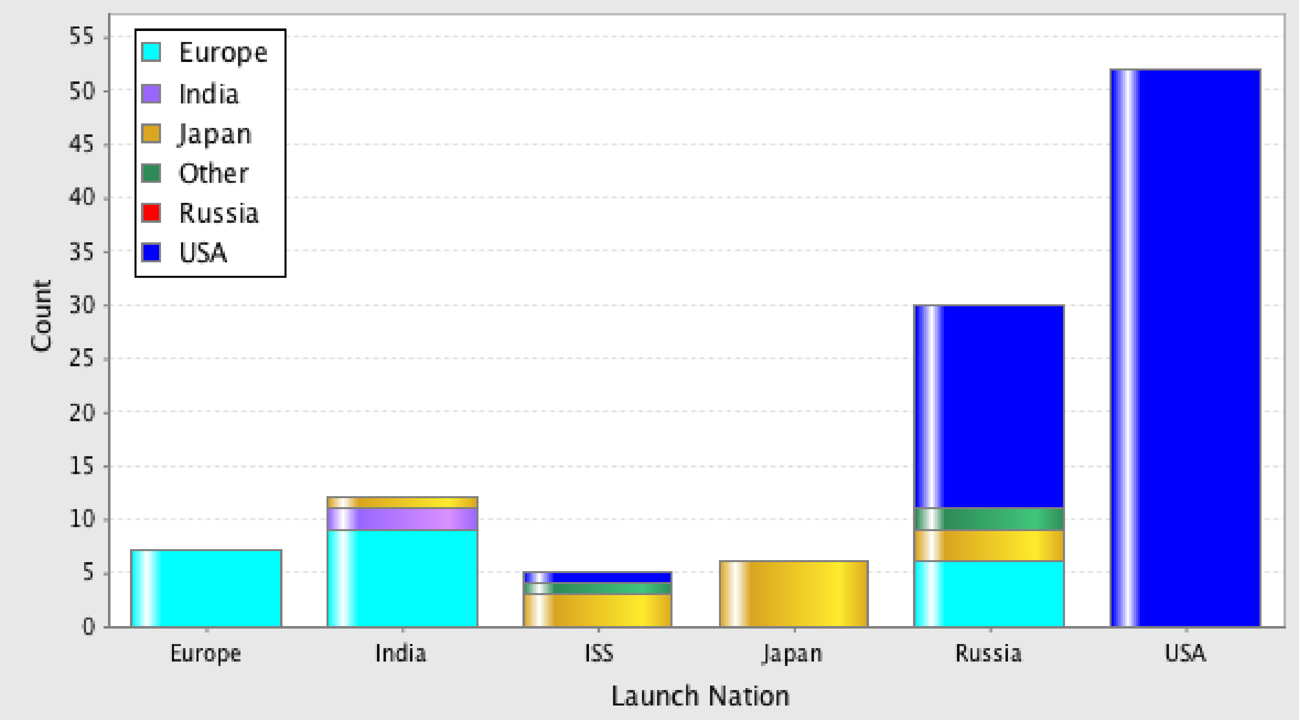

Figure 19. CubeSat Missions Launched from Each Nation, Subdivided by Nation of CubeSat Developer, 2000-2012

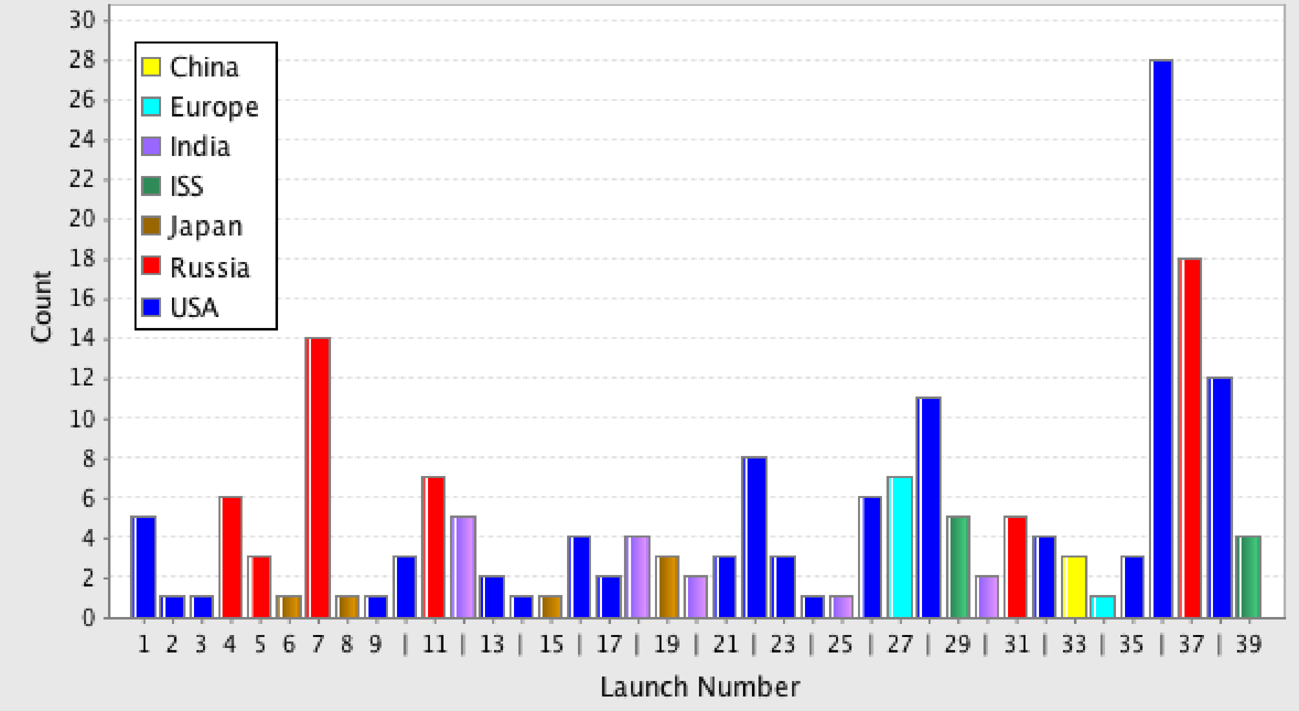

Figure 20. Number of CubeSat Missions Per Launch. (Note: Launches 30-39 were in 2013)

ponents can be credited, the author believes that the growth in university-led missions (and thus CubeSats), paradoxically, is attributable to government agencies (the DoD, ESA, NSF, and NASA). These agencies embraced the CubeSat standard in its early phases; each one made it easier for the next agency to adopt the standard and further bolster its performance. This progress has culminated in the NASA ELaNa program, which will launch several dozen university-class CubeSats in the next 12-18 months; it is particularly interesting that so many ELaNa missions are sharing space on DoD launches in 2013-14 (ORS-3, ORS-4, and NROL-39, to name three). With more than 60 missions selected for launch (Skrobot and Coelho, 2012), and a backlog of some 55 missions, the NASA ELaNa program appears to be ready to fill any excess capacity provided by U.S. launch systems.

Still, the high failure rates among university-led missions are troubling, especially so many from this mission category will launch in 2013. If the nearly 50% mission failure rate persists, then ELaNa alone will have a dozen mission failures in 2013. Will enthusiasm for the program continue if large numbers of CubeSats don't operate properly on-orbit?

As noted above, it is believed that the failure-rate problem is solvable, given that most failures can be traced back to insufficient system-level functional testing on the ground. Furthermore, it is thought that a "day in the life" operational demonstration is just as essential as vibration testing to certify a CubeSat for flight. Operational tests that demonstrate startup sequences, power management and graceful recovery from resets are all necessary. Obviously, it is one thing to identify these tests as essential; it is another to carve out schedule and budget to carry out such tests. The author recommends that university-led missions push their design schedule towards early integration and system-level functional demonstrations in order to give time to identify and correct the typical problems.

3.1 Observations

A significant amount of effort has been expended on the precise nomenclature for spacecraft size, typically using a discriminator of mass: 100 kg for microsats, 10 kg for nanosats, 1 kg for picosats, etc. In the author's opinion, mass is the wrong discriminator for missions whose mass is below 100 kg, including CubeSats. At that size, mass is no longer the driver for launch costs: a 10 kg spacecraft may not cost any less to fly in a secondary opportunity than a 50 kg vehicle, since 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 payloads of this size; while that change is on the order of the spacecraft mass itself, they are within the noise of the launch vehicle performance. On the other hand, any change to the dynamic envelope or interface is strongly resisted. That is why the author believes that volume and launch interfaces are the true indicator. Volume dictates whether the spacecraft can be accommodated in the secondary payload slot, and it indicates the size of solar arrays, sensor apertures, and antenna sizes – in short, volume is a strong predictor of the mission and capabilities of a spacecraft.

More importantly, the picosat/nanosat boundary splits up the CubeSat-class: a 1 kg 1U-scale CubeSat is a "picosat", while a 5-kg 3U-scale CubeSat is a "nanosat" – despite using the same launch interface, submitting to the same qualification requirements, and probably using the same flight components.

Instead, the author proposes that a better classification for small spacecraft is the type of launch adaptor used: knowing whether the spacecraft fits in a P-POD, uses an ESPA/Lightband-class adaptor, or requires its own custom interface provides a tremendous amount of information about the satellite's capabilities. It is for that reason that this paper has avoided using the terms "nanosat" or "picosat."

3.2 Predictions

By the end of 2013, ten launches will have carried 80 CubeSats into orbit: 4 American, 2 Russian, and 1 each from India, China, Europe and Japan (via the ISS). Seven launches have been announced for 2014, carrying more than 60 CubeSats. The university share appears to be increasing, mostly due to the NASA ELaNa program. And while it is anticipated that there will be many more S-class and T-class 3U CubeSats (from both university and industry developers), the author sees no reason to believe that the university-led missions will be any more successful. Therefore, the author must regrettably predict that between 10 and 25 of the missions launched in 2013 will fail to meet their objectives, consistent with historical rates. To be more accurate, it is predicted that the failure rate will be closer to 25 than

10, since with the sheer number of new schools participating in these new high-capacity launches, there is less room for professional oversight to ensure these new missions avoid the common mistakes of the old missions. The author believes that the ELaNa program is robust enough to survive so many failures, but there is still concern about the impression this will make on skeptics in the space industry.

Similarly, the author regrettably predicts that the launch and regulatory systems are not prepared for the onslaught of 150+ new CubeSats launched from 2013 -- 2014. These launches will overwhelm the radio coordination efforts of the IARU and national regulatory agencies such as the U.S. FCC (for radio licensing) and NOAA (for imaging licensing); no one has had to manage so many missions coming online in such short times. Because of this, some issues are expected to slip through the cracks, such as unlicensed RF broadcasts or unexpected interference between ground or space segments. Some small fraction of these missions on high-capacity launches will invariably be adversely affected by the near-simultaneous release of a dozen or more CubeSats – possibly by collisions, but more likely by coordination/tracking issues that prevent timely contact with a spacecraft. In short, this author believes that the larger cohorts of 2013 and 2014 will bring new challenges in the successful launch and operation of many missions.

There are also some bright spots, however. For instance, the author expects continued improvement in the performance of CubeSat-class missions, particularly in terms of pointing control and communications. As pointing control improves, new classes of missions will open up to CubeSats. It is also anticipated that a large number of missions in 2013-2014 will be contributing science and technology demonstration missions, especially as the 6U dispensers are space-qualified.

3.3 Future Work

Any comprehensive study of space missions is only as good as its database. This paper was limited by the census-style nature of the available data: mission names, sizes, launch dates, nationalities, etc. While the failure data is an important contribution, much more can be done to better understand and categorize the sources of failures. In addition, it would be useful to study technological capabilities of CubeSats (power, data rates, pointing control) to look for trends and predictions. Such a study would require better data on specific missions than is currently available.

Finally, as noted above, this entire study should be revisited in late 2014, after the 160 CubeSats of 2013 and 2014 are put in orbit. The number of CubeSats could well triple by the end of 2014, and the performance indices and predictions doubtlessly will be very different then.

Acknowledgements

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Appendix A: Cubesat Manifest

Below is the list of all manifested CubeSat-class missions from 2000-2012.

Name	Launch Date	Class	Size	Mission Type
PICOSAT 1&2 (TETHERED)	2/6/00	mil	Opal	T
PICOSAT 6 (StenSat)	2/10/00	civ	Opal	C
PICOSAT 3 (JAK)	2/10/00	uni	Opal	E
PICOSAT 4 (Thelma)	2/12/00	uni	Opal	S
PICOSAT 5 (Louise)	2/12/00	uni	Opal	S
PICOSAT 7&8 (TETHERED)	9/6/01	mil	Opal	T
MEPSI	12/2/02	mil	2U	T
QUAKESAT 1	6/30/03	com	3U	S

Name	Launch Date	Class	Size	Mission Type
DTUSAT 1	6/30/03	uni	1U	E
CUTE-1 (CO-55)	6/30/03	uni	1U	E
AAU CUBESAT 1	6/30/03	uni	1U	E
CANX-1	6/30/03	uni	1U	E
CUBESAT XI-IV (CO-57)	6/30/03	uni	1U	E
UWE-1	10/27/05	uni	1U	E
CUBESAT XI-V (CO-58)	10/27/05	uni	1U	E
Ncube 2	10/27/05	uni	1U	E
CUTE 1.7	2/21/06	uni	2U	C
AeroCube 1	7/26/06	mil	1U	T
CP 1 (K7RR-Sat)	7/26/06	uni	1U	E
CP 2	7/26/06	uni	1U	E
HAUSAT 1	7/26/06	uni	1U	E
ICECube 1	7/26/06	uni	1U	S
ICECube 2	7/26/06	uni	1U	S
ION	7/26/06	uni	2U	S
KUTESat Pathfinder	7/26/06	uni	1U	E
Mea Huaka'I (Voyager)	7/26/06	uni	1U	E
MEROPE	7/26/06	uni	1U	S
Ncube 1	7/26/06	uni	1U	E
Rincon 1	7/26/06	uni	1U	E
SACRED	7/26/06	uni	1U	E
SEEDS	7/26/06	uni	1U	E
HITSAT (HO-59)	9/22/06	civ	1U	E
GENESAT (GeneSat 1)	12/16/06	civ	3U	S
MEPSI (MEPSI 2A)	12/20/06	mil	2U	T
RAFT (RAFT 1. NO 60. Oscar 60)	12/20/06	mil	1U	C
MARSCOM	12/20/06	mil	1U	C
CSTB 1	4/17/07	com	1U	T
MAST	4/17/07	com	3U	T
AEROCUBE 2	4/17/07	com	1U	T
LIBERTAD 1	4/17/07	uni	1U	E
CP3	4/17/07	uni	1U	E
CAPE 1	4/17/07	uni	1U	E
CP4	4/17/07	uni	1U	E
CANX 2	4/28/08	civ	3U	T
COMPASS 1	4/28/08	uni	1U	E
AAUSAT CUBESAT 2 (AAUSAT 2)	4/28/08	uni	1U	E
DELFI C3 (DO-64)	4/28/08	uni	3U	T
SEEDS 2 (CO-66)	4/28/08	uni	1U	E
PreSat	8/3/08	civ	3U	T
NanoSail D	8/3/08	civ	3U	T
PSSC-Testbed 1	11/15/08	mil	2U	T
KKS-1 (KISEKI)	1/23/09	uni	1U	T
PHARMASAT	5/19/09	civ	3U	S
HAWKSAT 1	5/19/09	civ	1U	S
AEROCUBE 3	5/19/09	mil	1U	T
CP 6	5/19/09	uni	1U	E
DRAGONSAT 2 (AggieSat 2)	7/15/09	uni	1U	T
BEVO 1	7/15/09	uni	1U	T
SWISSCUBE (SwissCube 1)	9/23/09	uni	1U	S
BEESAT	9/23/09	uni	1U	T
UWE-2	9/23/09	uni	1U	E
ITu-pSAT 1	9/23/09	uni	1U	E
HAYATO (K-SAT)	5/20/10	uni	1U	T
WASEDA-SAT2	5/20/10	uni	1U	E
NEGAI (Negai-Star. Negai-Boshi)	5/20/10	uni	1U	E
STUDSAT	7/12/10	uni	1U	E
TISAT 1	7/12/10	uni	1U	E
O/OREOS	11/20/10	civ	3U	S
RAX 1 (USA 218)	11/20/10	uni	3U	S
Mayflower-Caerus	12/8/10	com	3U	T
QBX 2	12/8/10	mil	3U	T
SMDC-ONE 1	12/8/10	mil	3U	T
PERSEUS 003	12/8/10	mil	1.5U	T
PERSEUS 001	12/8/10	mil	1.5U	T
QBX 1	12/8/10	mil	3U	T
PERSEUS 002	12/8/10	mil	1.5U	T
PERSEUS 000	12/8/10	mil	1.5U	T
NANOSAIL-D-002 (NanoSail D2)	1/17/11	civ	3U	T
E1P (Explorer 1 Prime)	3/4/11	uni	1U	S
KySat 1	3/4/11	uni	1U	E
Hermes	3/4/11	uni	1U	T
PSSC-2	7/20/11	mil	2U	T
JUGNU	10/20/11	uni	3U	E

Name	**Launch Date**	**Class**	**Size**	**Mission Type**
DICE 1 (DICE X)	10/28/11	uni	1.5U	S
DICE 2 (DICE Y)	10/28/11	uni	1.5U	S
RAX 2	10/28/11	uni	3U	S
AubieSat1 (AO-71)	10/28/11	uni	1U	S
M-Cubed	10/28/11	uni	2U	T
HRBE	10/28/11	uni	1U	S
e-st@r	2/13/12	uni	1U	T
Goliat	2/13/12	uni	1U	E
MaSat 1 (MO-72)	2/13/12	uni	1U	E
XaTcobeo	2/13/12	uni	1U	E
PW-Sat 1	2/13/12	uni	1U	T
ROBUSTA	2/13/12	uni	1U	T
UniCubeSat-GGs	2/13/12	uni	1U	T
We Wish	10/4/12	com	1U	E
F1	10/4/12	uni	1U	E
TechEdSat	10/4/12	uni	1U	T
FITSAT-1 (NIWAKA)	10/4/12	uni	1U	T
Raiko	10/4/12	uni	2U	E
SMCD ONE 1.1	9/13/12	mil	3U	T
Re (STARE)	9/13/12	civ	3U	T
CINEMA 1	9/13/12	civ	3U	S
Aeneas	9/13/12	mil	3U	T
SMDC ONE 1.2	9/13/12	mil	3U	T
AeroCube 4.0	9/13/12	mil	1U	T
AeroCube 4.5A	9/13/12	mil	1U	T
AeroCube 4.5B	9/13/12	mil	1U	T
CSSWE	9/13/12	uni	3U	S
CXBN	9/13/12	uni	2U	S
CP5	9/13/12	uni	1U	E

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