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Small Satellite Trends 2009-2013

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ABSTRACT

Small satellites offer the ability to demonstrate new technologies and missions at significantly lower cost than traditional large satellites. This study aims to provide data-driven answers to key questions about the historical usage of small satellites, such as: What types of missions are typically performed by spacecraft of different sizes? Are mission-focused spacecraft more successful than demonstration satellites? What is the impact of developer experience on mission success?

The Aerospace Corporation used public sources to compile a database of nearly 250 small satellites launched between 2009 and 2013. Fourteen data points were collected for each mission, including physical characteristics and programmatics. These data were used to characterize these missions, and illustrate trends that influence how these vehicles will be used in the future.

This study was able to answer key questions using historical experiences. These data showed that small satellites have become more capable and more successful over time. Science missions become increasingly viable at form factors as small as a 3U CubeSat. Typical development times for non-university CubeSat efforts are 18-24 months, but universities typically take at least twice as long. The probability of mission success is significantly higher for organizations that have previously developed at least two satellites.

INTRODUCTION

Small satellites offer the ability to demonstrate new technologies, payloads, missions, CONOPS, or development processes at costs that are significantly lower than traditional large satellites. The development and widespread adoption of the CubeSat standard has opened the market up to new entrants and further reduced the cost of space access. This provides considerable flexibility for designers of space architectures, who can now consider CubeSat, SmallSat, and large satellite options (both independently and collaboratively) in defining missions to meet today's requirements and tomorrow's goals.

Historically, CubeSats have typically been built as Class C/D spacecraft [1], adhering to a set of design and development principles consistent with a relatively high risk tolerance. For space architects to make informed trades between satellites of different sizes and development processes, they need to better understand the performance, cost, and risk implications of each option in the trade space. This study was initiated to provide data-driven answers to these types of key questions:

- What types of missions are typically performed by spacecraft of different sizes?
- Are "mission-focused" satellites more successful than "demonstration" satellites?
- What is a typical development schedule for commercial vs. university CubeSats?
- Are CubeSats riskier than traditional SmallSats?
- What is the impact of developer experience on the probability of mission success?

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To begin to answer these questions, The Aerospace Corporation used public sources to compile a database of nearly 250 small satellites that were launched between 2009 and 2013. Each entry included details on the physical characteristics of the satellite (e.g. mass, power, size) and programmatics of the mission (e.g. funding agency, spacecraft manufacturer/integrator, cost, schedule). Each targeted mission also included two factors that were not available in other data sets: the experience level of the spacecraft manufacturer (based on the prior number of satellites developed and launched), and a measure of how successful the spacecraft was after reaching orbit. These data were used to characterize small satellite activities during this timeframe, and to illustrate trends that can influence how these vehicles will be used in the future.

BACKGROUND

Table 1 describes typical breakpoints between descriptions of satellites of different classes [2]. Satellites in the low end of this range are historically built to Class C/D [1] standards and thus often carry significantly lower cost than Class A/B missions. With a higher risk tolerance and less stringent requirements, small satellites can benefit from rapid development time due to lower levels of reliably, oversight, and testing [3].

Table 1: Satellite Class vs. Mass [2]

Satellite Class	Wet Mass Range
Femto	10-100 g
Pico	0.1-1 kg
Nano	1-10 kg
Micro	10-100 kg
Small	100-500 kg

CubeSats are a well-established subcategory of small satellites that conform to a standardized form factor (1U = 10 x 10 x 10 cm). If additional space is required, the form factor can be extended in increments of the original volume (e.g. 3U = 30 x 10 x 10 cm). The CubeSat standard was developed and maintained by the California Polytechnic State University's Multidisciplinary Space Technology Laboratory (MSTL) and Stanford University's Space Systems Development Laboratory (SSDL). It was developed initially as a means to provide hands-on experience in the field of spacecraft design to students [4], though the impacts on the spaceflight industry are becoming significantly more widespread as CubeSat development evolves [5]. Figure 1 describes several notable events in the history of CubeSats.

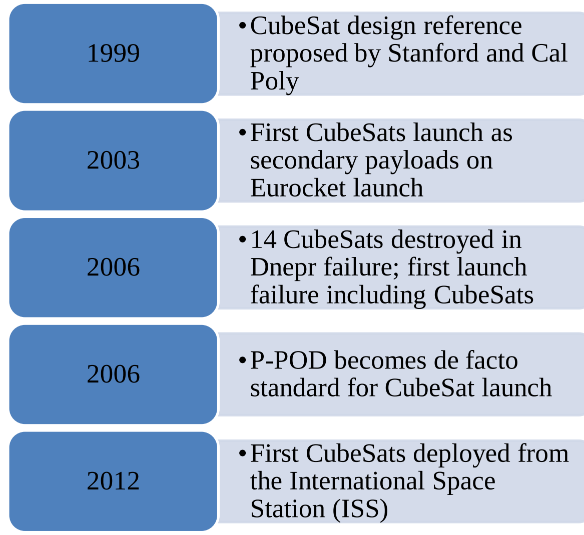

Figure 1: CubeSat Timeline

For the purposes of this study, the term "small satellite" implies any spacecraft below 250 kg launch mass. Any small satellite that conformed to the CubeSat standard was categorized as a CubeSat regardless of its size (e.g. 1U, 3U, 6U, etc.), while SmallSats are defined as small satellites that do not conform to the CubeSat standard.

As the popularity of SmallSats has increased [6], the number of options for launch has expanded in parallel. SmallSats can launch as a primary payload on a small launch vehicle, or they can rideshare as a secondary payload on larger launches. CubeSats can be launched via the Poly Picosat Orbital Deployer (P-POD) from a launch vehicle's upper stage or even from the ISS [5], and SmallSats up to 180 kg can be carried to orbit on an EELV Secondary Adaptor (ESPA Ring) [7].

Previous efforts have been completed to perform characterization of small satellites, including surveys through 2010 [8], and through 2012 [9]. Surveys have also been completed to develop predictions into future industry behavior [2]. While industry surveys have been released for 2014 [10], this paper summarizes work done in summer 2014 for all SmallSats and CubeSats that launched in calendar years 2009-2013. By looking historically at past launches rather than current year launches, a more reliable measure of the on-orbit success of each spacecraft could be collected.

The goals of these collection efforts were to collect and analyze additional data points, and use that the collected information to provide data-driven conclusions to previously documented findings.

METHODOLOGY

The Aerospace Corporation initiated this study in summer 2014 based on a customer request for an understanding of the current status and future trends of SmallSats and CubeSats. The Aerospace Corporation compiled published data for 244 different earth orbiting small satellite missions launched over the five-year period between January 2009 and December 2013. This dataset is not fully populated, containing only the information that was publically available. The Aerospace Corporation did not contact anyone affiliated with the missions for validation or to fill out missing data points. All collected data were self-reported and unverified by secondary sources, introducing the potential for errors and skewed results. Conclusions should be considered general in nature, and are not necessarily predictive.

Data Collected

The survey collected data on each mission's physical characteristics (e.g. mass, size, power) and programmatics, (e.g. cost, schedule, organization). In addition, this study collected two pieces of data that were not easily available elsewhere: the developer experience and a measure of the operational success of the vehicle on orbit. These data enabled a comparison across mission types, development agencies, and satellite form factors, and other characteristics. The information collected for each mission is as follows:

- Launch
  - Launch Date
  - Launch Result (Success, Failure)
- Mission Category
  - Mission Type (Educational, Technology Demonstration, Science, Communications)
  - Funding Agency (Civil, Military, Commercial)
  - Developer Type (University, Commercial, Civil, Military)
- Physical Characteristics
  - Launch Mass (kg)
  - Power (W)
  - #U (if CubeSat)
- Programmatics
  - Design Life (months)
  - Development Cost ($M)
  - Development Time (months)
  - Developer Experience (# Satellites)
- Operations
  - Mission Success (Full/Partial/None)

These data was compiled and analyzed to find relationships between variables, such as vehicle mass and size, mission type, funding type, developer category, developer experience, development time, and mission success, as described below.

RESULTS

Vehicle Mass & Size

Of the 244 small satellites launched between 2009 and 2013, 55% of these missions comply with the CubeSat standard, as shown in Figure 2. More than half of all CubeSats launched in this timeframe fit in the 1U form factor, but 3Us were also very popular.

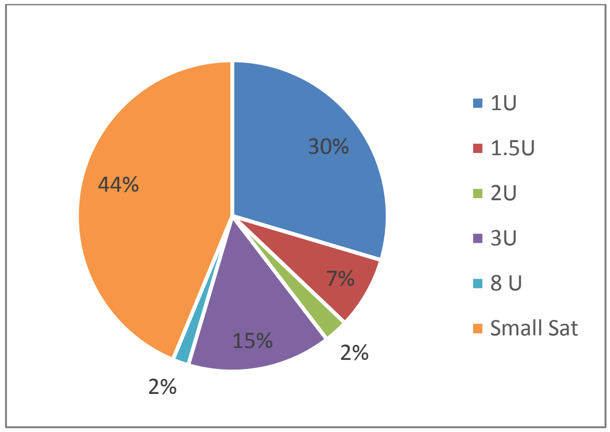

Figure 2: Size

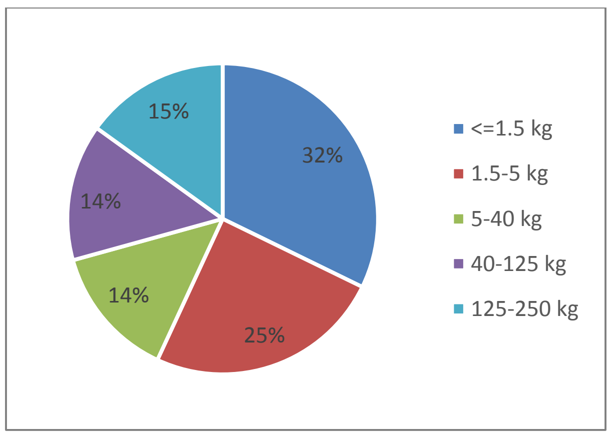

Figure 3: Launch Mass

Figure 3 shows the distribution of vehicle mass, which correlates well with vehicle size shown in Figure 2. In general, heavier and larger spacecraft are more complex, though there are exceptions for simple or passive high-mass vehicles such as calibration targets or ballast payloads. Within this dataset, only 15% of the vehicles were in the top half of the mass range of this study (125-250 kg).

Mission Type

Categories of missions were defined that help differentiate between different types of applications. Missions which were categorized as **Educational** are those with no mission, aside from emitting signals that verify the satellite is operational on orbit. These satellites are colloquially known as "beepsats;" their primary purpose was to teach students and faculty about CubeSat system topics and the systems engineering processes of building and flying hardware. **Technology Demonstration** missions were intended to demonstrate new components or subsystems, such as a new reaction wheel or propulsion system that lacked space flight heritage. **Science** missions performed data gathering missions, such as earth or space environmental monitoring. **Imaging** missions focus on earth observing remote sensing. **Communications** missions provide communications services, such as real-time connectivity, data storing and forwarding, radio frequency communications or system identification.

It is sometimes difficult to differentiate between missions whose primary purpose is Educational vs. Technology Demonstration. Educational missions will often attempt to fly a new component or subsystem in addition to its primary goal as a learning experience for students, while Technology Demonstrations may have a secondary goal of exposing personnel to the challenges encountered throughout the program lifecycle. During this study, the survey relied on public sources to identify whether the program's primary goal was closer to pure education or technology demonstration. In the case of ambiguity, the authors used their engineering experience to evaluate whether a program's objectives would have truly extended the state of the art. If so, the mission was categorized as a Technology Demonstration.

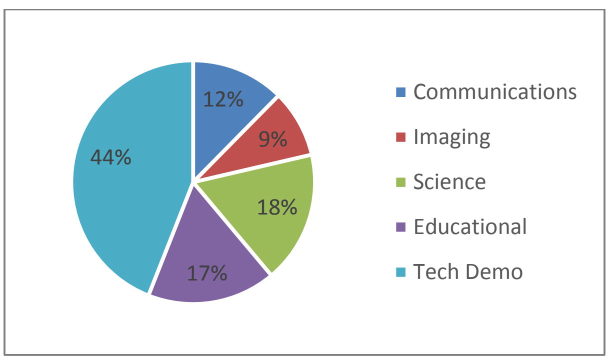

Figure 4: Mission Type

Figure 4 shows that from 2009 to 2013, 61% of all small satellites were demonstration missions (44% Technology Demonstration + 17% Educational), and the remaining 39% performed Science, Imaging and Communications missions.

CubeSat Mission Type

One of the first questions that this dataset was used to address involved the distribution of mission types between SmallSats and CubeSats. Figure 5 shows that CubeSats are more likely to be used for educational and technology demonstration purposes, and only 24% of CubeSats were used for Science and Communications missions.

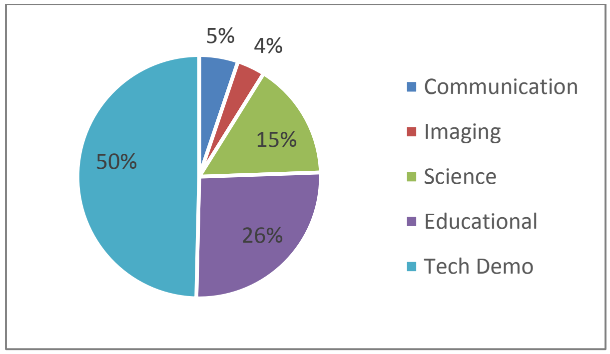

Figure 5: CubeSat Mission Type

Mission Type by Size

After assessing the breakout of mission type, this study evaluated how SmallSats and CubeSats of different sizes were used (see Figure 6). For 1U CubeSats, more than 95% are either educational or technology demo missions, with 50% purely educational missions. In the 1.5-2U category, 79% are educational or Technology Demonstration, but only 8% are purely educational. For 3U CubeSats, this ratio is 45%, nearly identical ratios to the ratios in the non-CubeSat SmallSat category. This implies that mission-focused spacecraft can provide mission utility in a 3U CubeSat form factor.

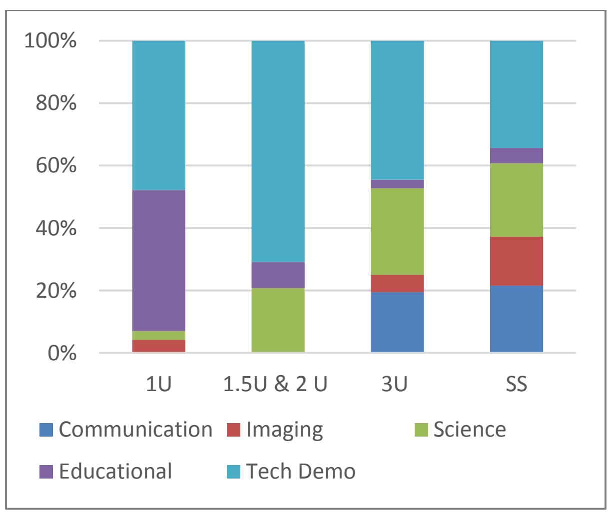

Figure 6: Mission Type vs. Size

Funding Agency

The funding agency is the organization that paid for the mission. In the case of public/private partnerships, missions were categorized according to the primary source of funding. It is important to note that the funding agency is often different than the developer or integrator of the satellite.

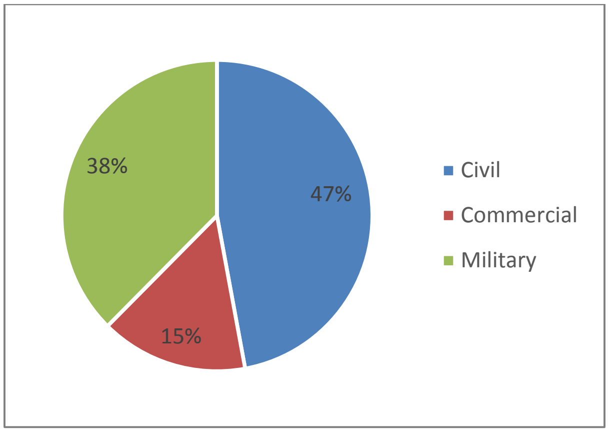

Figure 7: Funding Agency

Figure 7 describes the breakout of organizations. **Civil** includes US and foreign civil organizations such as the United States' NASA and NSF, Germany's DLR, Norwegian Space Centre, and the Indian Space Research Organization. **Commercial** includes for-profit commercial entities, such as Planet Labs, ComDev, or Orbcomm. **Military** organizations include the United States' Army, Air Force, and Navy, as well as military branches in other countries. For some countries, the government space programs are dual-use, performing both civil and military activities that benefit both types of customers.

By separating missions funded by US organizations vs. non-US organizations, the study identified that the United States was responsible for 49% of all SmallSats launched between 2009 and 2013, as shown in Table 2.

Table 2: US vs. Non-US Funding Source

Category	United States	Foreign
Civil	30	59
Commercial	14	15
Military	50	21
Total	**94**	**97**

Developer

Each mission was categorized depending on the organization responsible for spacecraft development. This is often the spacecraft manufacturer, but not always. In the case of partnerships and collaborative efforts, the organization that performed spacecraft integration was used for categorization.

Figure 8 illustrates that 51% of small satellites are developed by Universities, with another 27% developed by Commercial organizations. Only 22% are directly developed by government entities (Military and Civil).

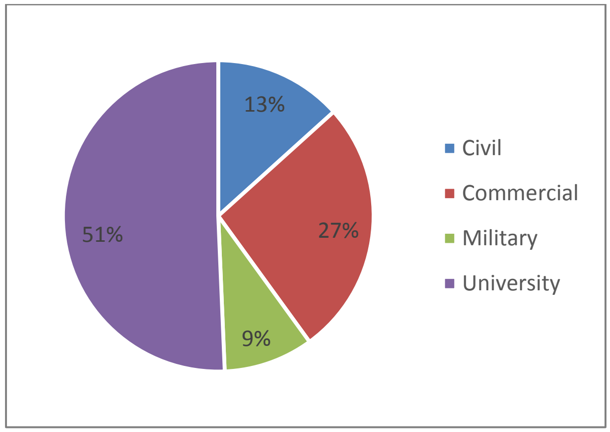

Figure 8: Developers

By combining the data from Figure 7 and Figure 8, it can be seen that most SmallSats are funded by government organizations (civil and military), and built by university and commercial developers.

Developer - CubeSats

The year 2013 represented a watershed moment for the CubeSat community. Overall, more CubeSats launched in 2013 than in all previous years since the development of the CubeSat standard in 1999. As shown in Figure 9, CubeSats are increasingly being used by military, civil, and especially commercial applications. This trend is expected to continue as commercial entities become responsible for the majority of CubeSat launches.

The rapid growth of CubeSats is based on a number of factors that collaboratively make it easier, cheaper, and faster to launch hardware into space. This includes the increased availability of commercial off the shelf (COTS) hardware and software for CubeSats, reduced price points due to miniaturization and standardization across suppliers, and common/standard launch opportunities, such as Nanoracks. Students who build CubeSats at university are bringing these skills into industry and government. The broader space community continues to realize that science and communications missions are possible within the CubeSat form factor, and the burgeoning commercial market reflects this philosophy.

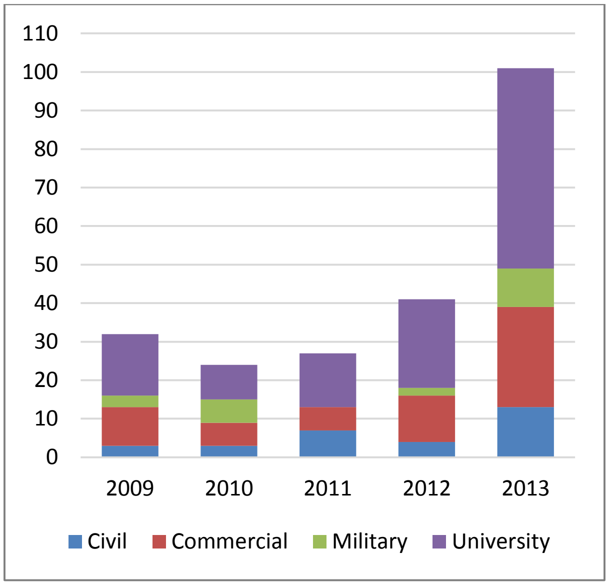

Figure 9: CubeSat Developers

Development Time

The study compiled the development times for each mission, subject to the availability of data in public locations. The average development time of CubeSats built by different types of developers in shown in Table 3.

Table 3: Development Time

Developer	Average CubeSat Development Time (Years)	% of CubeSats Built in Two Years Or Less
Commercial	1.7	100%
Military	1.6	92%
University	3.8	21%

The study found that the average development time of CubeSats built by universities is more than twice as long as the development time for those built by commercial or government entities. In addition, 94% of CubeSats built by commercial and military entities are built within 24 months, but only 21% of CubeSats built by universities are done in the same timeframe.

There are several reasons why university CubeSats may take longer to build. One factor could be the turnover rate of students, or the limited availability of students who are simultaneously attending classes in addition to developing their CubeSats. Civil, commercial and military satellites are built by professional staff with no educational responsibilities, leading to shorter development times (but higher costs due to full cost accounting).

Mission Success

In all spaceflight projects, mission success remains one of the primary goals. A successful mission will collect sufficient mission, spacecraft, or payload data to enable its users and/or operators to understand something that they didn't understand before launch. For technology demonstration missions, this is a measure of a new component or subsystem's ability to operate in the space environment. For science missions, its payload data that provides its users some operational utility. For commercial missions, is the vehicle must provide services long enough to allow its users to return a profit.

Missions that do not return all of the desired data may not be complete failures. There is value to spacecraft designers and operators in understanding the cause of a mission-ending or mission-degrading failure, so spacecraft that fail early can still provide lessons learned that improve the reliability of future satellites. There is also value in providing some payload or mission data, even if not every instrument or sensor is operating. As a result, this study considered two types of partial success, as described in the following categories:

- **Full (Green)**: achieved desired mission performance over its intended design life
- **Partial (Yellow)**: achieved desired mission performance but subsequently suffered an early mission-ending failure, OR achieved some level of degraded (but still useful) performance over its intended design life
- **Spacecraft Failure (Red)**: complete mission failure – no successful contact after deployment
- **Launch Vehicle Failure**: rocket did not successfully place the satellite into orbit

Since this study was conducted in summer 2014 and all vehicles launched no later than December 2013, there was sufficient on-orbit operations experience to evaluate most of the vehicles in the dataset. Of the 244 missions in the database, public sources contained information about the current status of 203 missions. Seven missions were lost due to launch vehicle failures; these were removed from the dataset and analysis to focus on satellite-level operational experience.

Figure 10 shows that 77% of all spacecraft launched in this timeframe achieved full mission success. Only 9% were complete failures, and the other 14% experienced some level of partial success. To compare success rates across different subsets of the data, a single metric of mission success was used. This metric gave full credit for full success, and half credit for partial success. Using this metric, the success rate of all satellites in the database was 84%.

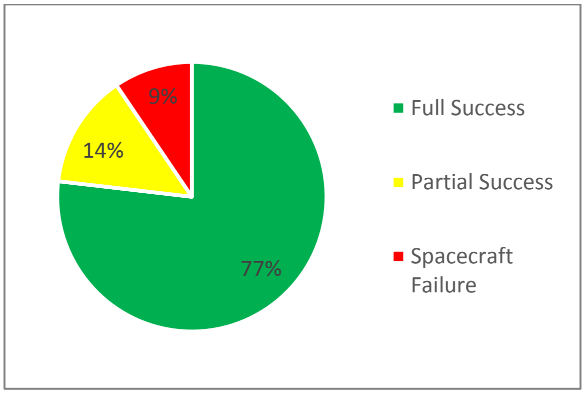

Figure 10: Small Satellite Mission Success Rate

Once this type of data was available, the next logical step was to compare subsets of the data. The first query performed looked at how CubeSats' mission success compared to that of all small satellites. Table 4 shows that the success rates for these different sizes of spacecraft were remarkably similar, providing confidence in the ability of CubeSat developers to produce quality products.

Table 4: Satellite Class vs. Success Rates

Success Criteria	CubeSats	SmallSats
Full Success	76%	78%
Partial Success	12%	16%
Satellite Failure	12%	6%

It is important to note that the majority (54%) of data for CubeSats comes from 2013 alone. To see if the success rates for missions changed over time, the success rate by year is shown in Figure 11. Over the five year period, there did not appear to be any significant trends in success rate over time, and there was no significant difference between the CubeSat and SmallSat curves.

Success vs. Developer & Mission Type

Next, this study looked at different ways of dividing the database to see if there were other relevant trends in the success rate of different types of missions or vehicles.

By evaluating the success rate of small satellites developed by different types of organizations (see Figure 12), the study identified that vehicles developed by government entities (Civil and Military) had the success rates of 94%. Commercial entities achieved 87%, while

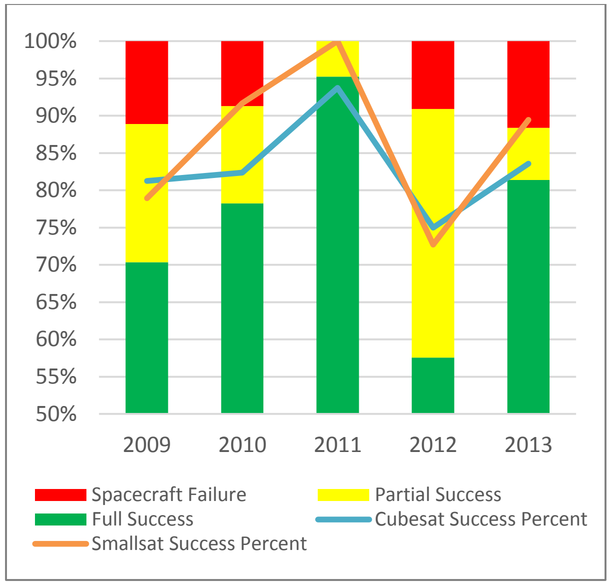

Figure 11: Success Rate by Year ((Does not include Launch Vehicle Failures)

Universities were lower at 78%. It's important to remember that these success rates are also impacted by the type of mission, as shown later in this paper.

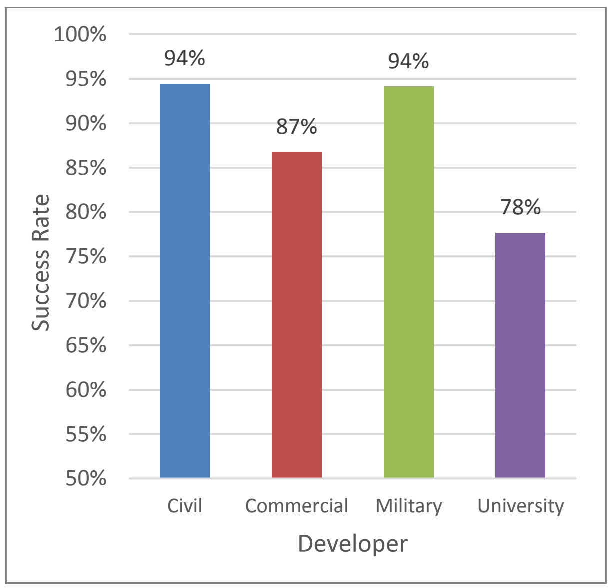

Figure 12: Developer Success Rates

The 78% success rate of universities is an extremely positive indicator in their ability to achieve mission goals despite personnel turnover, simultaneous education and research responsibilities, limited experience with space flight hardware, and often a lack of formal systems engineering processes. Often, university missions prioritize student learning and exposure to the end-to-end development cycle as much as successful on-orbit performance, so even a failed mission can be considered a useful learning experience. That being said, the 22% failure rate of university-developed vehicles is more than three times higher than that of government-developed vehicles (6%). Whether or not this is acceptable depends on the relative cost, development time, mission goals, and risk posture of the selection authority.

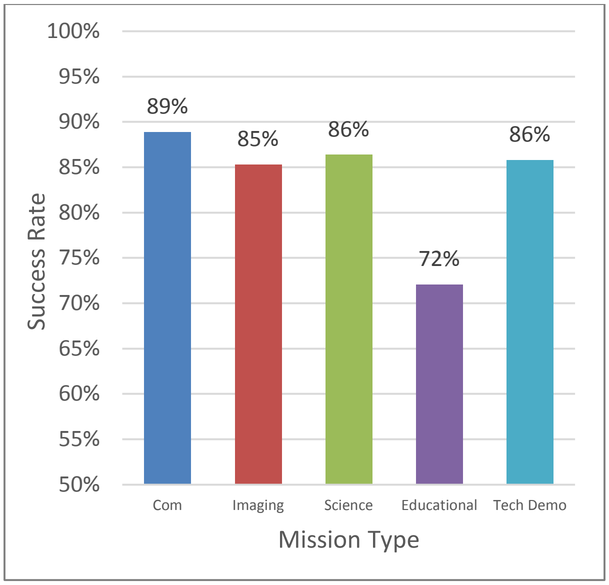

Figure 13: Success Rate vs. Mission Type

By separating data based on the mission type, Figure 13 shows that the success rate of communications, science, and technology demonstration missions is nearly identical at 85-86%. Educational missions are further behind at 72%, which remains impressive for the reasons outlined above.

Success vs. Experience

One of the key goals of this study was to understand the success rate of new entrants, as well as understanding how their success rate changed as they gained on-orbit experience. This would allow a selection authority to evaluate the risk associated with new entrants against potential benefits in cost/schedule or industrial base considerations.

Figure 14 shows the success rate of developers as a function of the number of satellites they have built. For developers building their first satellite, approximately 64% of their missions are fully successful, and another 19% experience some level of partial success. Only 17% of these satellites are complete failures, resulting in a mission success metric of 74%. For their second launch, the success metric increases to 82%. For their third and fourth launches, it jumps to 87%, and reaches 94% for developers building their fifth vehicle or more.

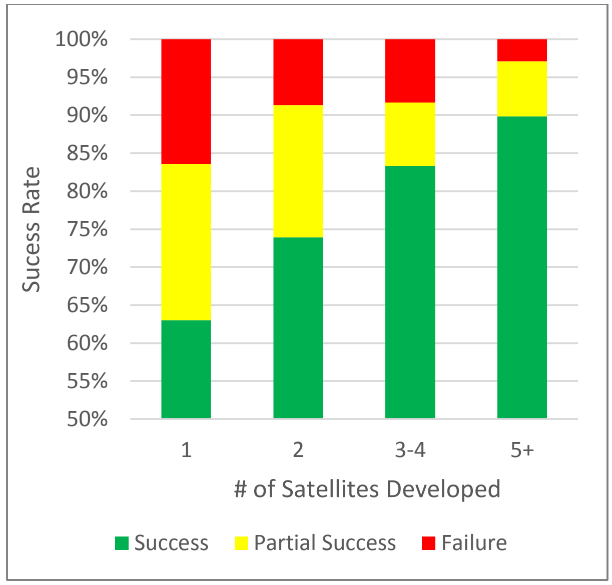

Figure 14: Success Rate vs. Experience

Similar to the discussion of university vs. government processes above, the same optimistic/pessimistic approach can be used when evaluating this data. On one hand, 63% of satellites launched by organizations with no spaceflight experience are fully successful, and another 20% returns some level of useful data. On the other hand, the failure rate of first-time developers is four times higher than those with considerable experience (16% vs. 4%).

As a result of this study, source selection officials who are considering the relative benefits of new entrants and experienced developers now have access to data that helps describe the statistical risk associated with each category. Selecting an experienced organization provides the expectation of high likelihood of mission success, but if a new entrant provides a substantially lower cost, proposes extremely innovative ideas using new technologies, processes, or CONOPS, or fulfills a desire to expand the industrial base, the selection authority can decide whether the expected rate of success justifies the risk.

Size & Mission vs. Experience

With data about the experience level of each developer, it was possible to compare changes in the sizes of satellites and types of missions as developers gain more experience. This is shown in Figure 15 and Figure 16.

Developers building their first satellite choose to build a 1U CubeSat 55% of the time. By the time a developer has 5+ missions of experience, only 4% selected the 1U form factor. While there are always exceptions, in general heavier and larger satellites tend to be more complex than smaller satellites [11]. This implies that developers with more experience are choosing to build more complex, more capable vehicles.

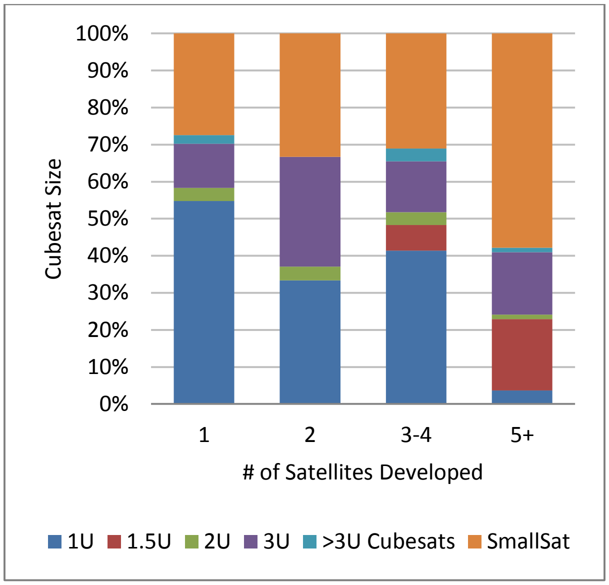

Figure 15: Experience vs. Size

In mission space (Figure 16), 40% of the missions flown by first-time developers are intended as educational missions, and another 42% are technology demonstrations. By the time developers are building their third or fourth unit, the fraction of educational missions drops to 4%, and no developers with 5+ vehicles of experience continued to build educational missions. Nearly half of all missions built by highly experienced developers were more complex missions that performed either science or communications functions.

When taken together, the last three figures (Figure 14, Figure 15, and Figure 16) illustrate a clear trend describing the impact of heritage. As developers gain more experience, they attempt to build larger spacecraft, perform more complex missions, and do so with a higher rate of success. While this matches the space community's intuition, this study provides data to support that conclusion.

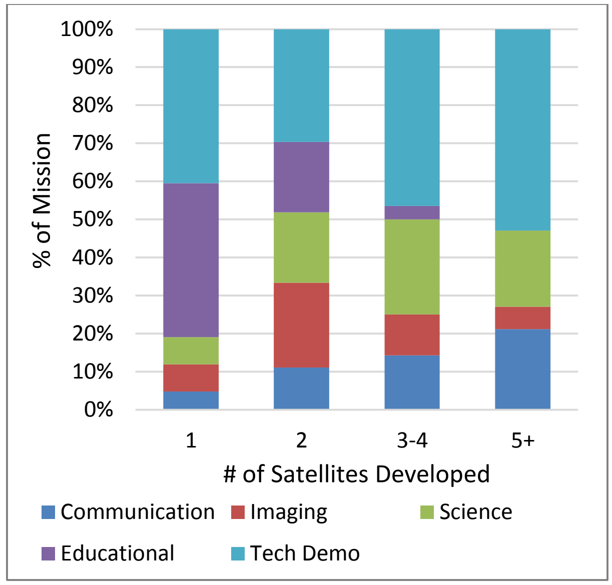

Figure 16: Mission vs. Experience

System Cost

Mission cost was particularly challenging data point to collect from a survey of public information. Most cost values in the database were system-level costs quoted in news stories about the mission. It was impossible to figure out whether each value included costs for the space segment, ground segment, and launch vehicle (or rideshare accommodation). It was not possible to evaluate whether the quoted cost included the entire program lifecycle, including the development, integration, and operation phases. As such, it was important to maintain a healthy dose of skepticism when evaluating any potential conclusions based on cost. The Aerospace Corporation developed best-fit curves of SmallSat and CubeSat cost, but was not able to draw any meaningful conclusions about cost trends of SmallSats or CubeSats over time. There was limited information about the relative costs of CubeSats developed by universities vs. commercial and government entities, but given the noise in the data, additional data will be needed to form useful conclusions. The type of data that would be required is likely to require cooperative collaboration with the mission developers to better normalize and standardize system-level costs.

CONCLUSIONS

This study provided data-driven answers to key questions about the capability, usage, and success rate of SmallSats and CubeSats.

The data showed that science and communications missions become increasingly viable at form factors as small as a 3U CubeSat. Typical development times for non-university CubeSats are 18-24 months, but universities typically take at least twice as long. The probability of mission success is significantly higher for organizations that have previously developed at least two satellites.

Reduced cost and maturing standards offer considerable flexibility for designers of space architectures, who can now consider CubeSats, SmallSats, and large satellite options (both independently and collaboratively) in defining missions to meet today's requirements and tomorrow's goals. The trends identified in this study will help define these future architectures.

Next Steps

The Aerospace Corporation is continuing to update this database with launches from 2014-2015 to identify how these trends are changing over time.

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