Small Satellite Trending & Reliability 2009-2018

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ABSTRACT

This paper quantifies trends in small satellite utilization, reliability, and capability using a database of all small satellites (<500 kg) launched from 2009 through 2018. By analyzing the full small satellite industry over time, this chapter will identify trends in implementation, success rates, and the reasons why some missions have failed. It will also address how to improve future missions to maintain the benefits of the lower cost space element while still achieving complex, multidimensional missions.

This study identified several trends that illustrate the current state of the industry: 87% of small satellites with completed missions launched in the last decade were successful, including 90% of satellites launched in the last three years. 31% are still actively operating within their design life, including 52% launched in the last three years. Launch failures claimed 5% of small satellites. For those satellites that survive launch, roughly 4% fail within the first year. Mission-ending failures are most likely to be attributed to the communication subsystem (26%) or power system (18%). Unattributed failures account for another 23%, with the other subsystems accounting for the remainder. The 6U form factor saw three-fold growth in launch numbers in 2018 over all previous years combined.

INTRODUCTION

Once a niche application or a novelty, small satellites ("SmallSats") are becoming increasingly ubiquitous contributors to the civil, military, and commercial space communities. Each new generation of SmallSats have more capable payloads and bus technologies, demonstrating increasingly sophisticated platforms to collect data from space or provide services to terrestrial users. Small satellites have demonstrated miniaturization of existing components as well as improving reliability of previous generations of flight hardware and software. Widespread demand for highly reliable CubeSat-compatible components has allowed operational users to turn to inexpensive SmallSats to perform missions that historically would have required larger satellites and higher costs, while allowing for new missions that previously wouldn't have been possible if the business case didn't close.

Small satellites are breaking the traditional space paradigm that says that only large, complex, costly satellites can perform useful missions. Data analytics companies are increasingly relying on small satellites as a primary source of unfiltered data that help them understand the world. Research & development SmallSats can demonstrate new technologies or concepts of operations (CONOPS) using inexpensive platforms that minimize the cost of a potential failure. In the first decade following the definition of the CubeSat standard in 1999, most CubeSats were built as Class C/D spacecraft,[1] adhering to a set of design and development principles consistent with a relatively high-risk tolerance. The development and widespread adoption of the CubeSat standard has opened the market up to new entrants, further reducing the cost of space access and fostering competition for high-reliability, low-cost, CubeSat-compatible components. This open marketplace enables substantial 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.

A study was initiated in 2014 by the authors 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 public vs. private sector small satellites?
- Are CubeSats riskier than traditional SmallSats?
- What is the impact of developer experience on the probability of mission success?
- How has the success rate of small satellites changed over time?

– Are there common causes of mission failure in small satellites?

To begin to answer these questions, The Aerospace Corporation compiled a database of 1452 small satellites that were launched over the decade between 2009 and 2018. 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, schedule). Measures of success post launch and root failure causes were also captured. All data were captured from public sources such as websites, conference presentations, journal papers, and even articles in the popular press. The data were used to characterize small satellite activities during this timeframe, and to identify trends that can illustrate how these satellites will be used in the future.

BACKGROUND

The number of small satellites launched per year is anticipated to increase substantially, and is accelerating from previous estimates. Euroconsult predicts that "*about 7,000 SmallSats will be launched over the next decade*[1]*: 580/year in 2022, and growing to 820/year by 2027. This 10-year forecast increased by 13% over a similar prediction made [by Euroconsult] in 2014.*[2] There is no debate that small satellites are establishing their place in the $124 billion space segment of the satellite industry.[3] As the data-driven trending predicted in 2014, small satellites are becoming more useful for missions outside of technology demonstration and education.[4]

The Institute for Defense Analysis (IDA) recently published their "*Global Trends in Small Satellites"* report which determined that there's a high likelihood that two or more "mega constellations" consisting of more than 100 small satellites each would provide affordable global broadband. They also predict that SmallSats will reach near-parity with larger satellites in remote sensing as users begin to prioritize reduced latency and more frequent revisit over higher resolution that can only come from larger satellites.[5]

IDA's analysis on market demand highlighted the benefits to the industry from low-cost approaches to manufacturing and assembly, easier and cheaper access to space, competition driven by the availability of multiple alternative platforms, and government policies designed to reduce barriers to entry.[5]

[1] "The next decade" refers to a time period of 2018-2028.

Nomenclature

The term "small satellite" could mean different things to a university developing its first CubeSat, a traditional satellite builder with product lines in LEO and GEO, or a government agency like NASA. This study used mass as the defining characteristic based on a series of widely available publications.[6,7,8] The definitions for categories used in this study are listed in Table 0-1. Mass Categories.

Table 0-1. Mass Categories

Category	Mass Range
PicoSat	(>= 1 kg)
NanoSat	(1-10 kg)
MicroSat	(10 - 100 kg)
ESPA Class	(100 - 220 kg)
ESPA Heavy Class	(220 - 322 kg)
SmallSat	(322 - 500 kg)

The Cubesat Form Factor

CubeSats are a well-established subcategory of small satellites that conform to a standardized form factor (1U = 10 x 10 x 10 cm). For missions with larger payloads or more complex requirements, the CubeSat 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 in 1999 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 to provide hands-on experience in the field of spacecraft design to students,[9] though the impacts on the spaceflight industry are becoming significantly more widespread as CubeSat development evolves.[10] One of the goals of this study is to investigate trends associated with the CubesSat form factor, or the NanoSat category listed in Table 0-1. Mass Categories. The NanoSats category was split into a 1-5 kg segment and another 5-10 kg segment to better address the correlation with CubeSat bus sizes within the database.

Launch Options

Traditional large satellites have launched to space as the primary payload on a dedicated rocket. As the popularity of SmallSats has increased,[11] 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) or other "POD" from a launch vehicle's upper stage, from the International Space Station (ISS), or from other secondary carrier and ejection systems like the EELV Secondary Adaptor (ESPA Ring) that can carry

SmallSats up to 180 kg to orbit. [10,12]. Several companies have recognized the growth in the SmallSat industry, and are developing low-cost launch vehicles capable of placing SmallSats into LEO[13, 14].

Trending and Characterization

There have been a number previous efforts to characterize small satellite trends, including surveys through 2010, 2012, and 2014.[15,16,17] Several university papers and industry reports have examined different subsets of these data with similar results.[2,6,18] There are also reports looking at economic trends and profiles of significant and emerging players.[18]

Mission Reliability

Mission reliability has always been a top priority, even despite a higher risk tolerance in small satellites. With a higher risk tolerance and less stringent reliability requirements, small satellites can benefit from rapid development times due to reduced levels of required reliably, oversight, and testing.[19] Innovators are consistently looking for new ways to "tailor" mission assurance practices learned on larger programs, and the industry is just now reaching a point where enough data has accumulated to learn from statistics and not just anecdotal information. We see trends of more missions becoming more successful, so the industry is maturing and learning from the mistakes of others.

For the larger satellite industry, the ground equipment market is nearly equal in economic value to the satellite services market ($120 to $125 billion US).[3] Within the small satellite industry, ground services tend to be considered later in development, often triggering integration and communications issues for the mission. In an "Improving Mission Success" workshop, one of the most valuable mission assurance tests was found to be communications link testing with the ground station, in addition to Day-in-the-life testing, power system/discharge, and thermal-vacuum testing.[20]

Of those surveyed in a 2017 paper in improving mission success, 40% of all mission failures could have been avoided with more ground testing, 40% were attributable to the design, and 9% were attributed to the use of COTS parts.[20].

To improve mission success, the developers should address eight different themes: 1) Setting the Purpose and Vision of the Mission, 2) Establishing the Program Structure, 3) The Risk Process, Design and Analysis, 4) The Importance of Testing, 5) Common CubeSat Failures (Communications, 6) Ground Segment, Power, Deployment), 7) Parts Quality, Availability, and 8) Documentation and Launch as Significant Driver.[20]

A study looking at data through a launch date of 2014 stated that failures could be attributed primarily to the power system (36%), compared to 29% for communications, 21% for on-board computing (OBC), and 14% for unknown causes.[21] Comparative and updated results can be found in Section 0.

Publication Background

The Aerospace Corporation initiated a study of small satellite trends in summer 2014 based on a customer request for an understanding of the status and future trends of SmallSats and CubeSats. This chapter continues to build upon the 2014 publication "Small Satellite Trending 2009-2013".[4] For purposes of comparing trends, references to that publication will occasionally be relisted here for illustration of changes over time. Modifications, updates, and corrections to the database will also be noted. The dataset used in this publication is significantly more robust, taking into account additional datasets from across the industry. The primary changes include expanding the database to include satellites up to 500 kg to cover the ESPA-heavy class, and above, recording malfunctions and event times, and reclassification and clarification of some data to better suit the changing industry as cited in the respective sections below.

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

METHODOLOGY

The Aerospace Corporation compiled data on 1452 small satellites over a ten-year period between January 2009 and December of 2018. 1364 of these satellites launched successfully while the remainder were lost in launch failures.

This dataset is not considered fully populated, containing only the information that was publicly available or available from commercial databases. [22,23,24,25] Aerospace 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 satellite's physical characteristics (e.g. mass, size, power) and programmatics, (e.g. cost, schedule, funding source). 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 satellite on orbit. Developer experience was based on an examination of historical launches by the same company, university, or government agency. Operational success is described in more detail below. Overall, these data enabled a comparison across mission types, development agencies, satellite form factors, and other characteristics.

The updated version of this study also sought to include failure and reliability data to a higher level of fidelity. Additionally, mass categories were adjusted to compensate for new industry guidelines, primarily new ESPA-class and ESPA-Heavy-class interface control requirements released in 2018.[7] Mission categories were updated to closer match the trending of current missions, and the data set was also updated to include information on nascent constellations instead of just individual satellites.

The information collected for each mission is as follows:

- Launch, Launch Date, Launch Result (Success, Failure)
- Spacecraft Status (Active, Launch Failure, Retired, Retired due to Malfunction)
- Mission Type (Communications, Earth Observation, Science/ Technology/Test, Other Mission) & Mission Description
- Funding Agency, Category (Academic, Commercial, Civil, Military), and Country
- Developer Type (Academic, Commercial, Civil, Military), and Country
- Physical Characteristics
    - Launch Mass (kg)
    - Launch Mass Category
    - Orbit Average Power (W)
    - Bus Dimensions (m)
    - #U (if CubeSat)
- Programmatics:
    - Design Life (years)
    - Development Cost (Real Year $Millions, USD RY$M)[2]
    - Development Time (months)
    - Developer Experience (# Satellites)
- Constellation Number
- Malfunction event, category and spacecraft age
- Mission Success (Full/Partial/None)

[2] Deemed unreliable from public source data

The data were compiled and analyzed to find relationships between variables, such as satellite mass and size, mission type, funding type, developer category, developer experience, development time, and mission success.

RESULTS

Satellite Mass & Size

The initial publication considered just the 244 satellites launched between 2009 and 2013. In the subsequent five years, another 1208 satellites were launched, a six-fold increase that highlights the dramatic growth in the small satellite industry in a short period of time.

Overall there has been a significant rise in launches in recent years, which was anticipated, predicted, and then confirmed by previous studies.[4,6,17] However, there has not been the exponential growth that was anticipated in 2013 and 2014, which was likely due to a series of launch failures, including Orbital ATK's Antares and SpaceX's Falcon 9 launch vehicles in October 2014 and June 2015. The loss of 51 small satellites on these failed launch vehicles alone, coupled with a reduced launch rate while Orbital ATK and SpaceX undertook rigorous fault identification and recovery actions, meant that significantly fewer SmallSats launched to orbit in 2015-2016. While there has been some recovery in 2017-2018, the overall rate is lower than optimists (including the authors) predicted in 2014.

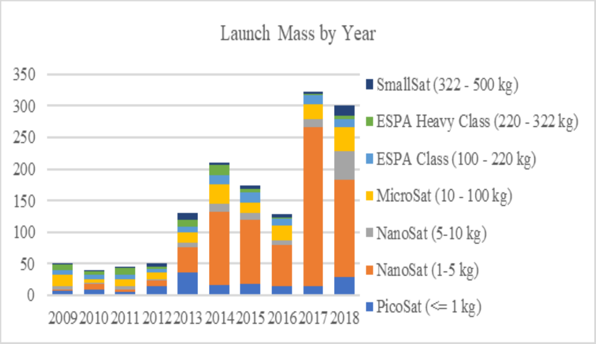

Fig. 0-1. Launch Mass Category by Year (2009-2018)

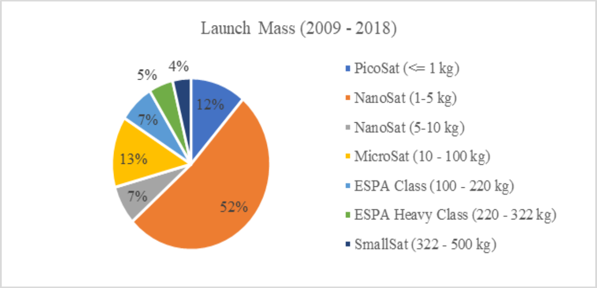

Fig. 0-2. Launch Mass Category Summary (2009-1018)

Fig. 0-2 shows the distribution of satellite mass, which – as expected- correlates well with satellite size shown in Fig. 0-3. Most of the satellites are contained within in the 1 – 5 kg range, which encompasses the 3U CubeSat. Within this dataset, only 9% of the satellites were in the top half of the mass range of this study (220 - 500 kg).

The CubeSat Standard

Of the 1364 small satellites successfully launched between 2009 and 2018, 67% of these missions had a CubeSat form factor. This is 12% higher than the trend from 2009 – 2013, implying the overall usage of the CubeSat standard is on the rise. The "other CubeSat" category included non-standard sizes like 0.25U, 0.5U, 5U, 3.5U and 12U satellites. As illustrated in Fig. 0-3, the dominating form factor is now 3U CubeSats – a change from the 1U CubeSats in the dataset published in 2014.

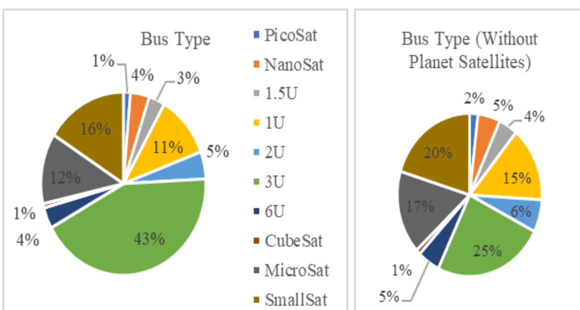

Fig. 0-3. Bus Type Summary (2009-2018)

Planet is the single entity responsible for launching the most satellites, with 335 successful launches out of 369 hosted on launch vehicles. To illustrate the impact of this one corporation on the industry, Fig. 0-3 also shows the resultant data if Planet's satellites are removed from the dataset.

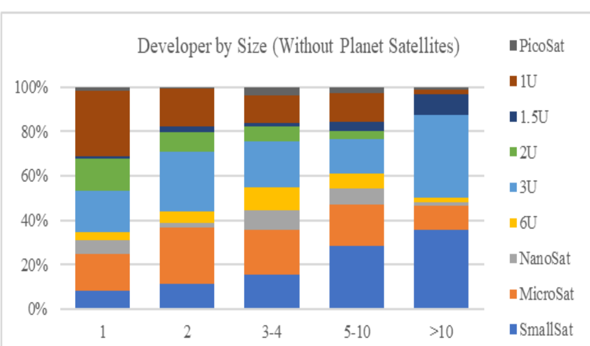

Fig. 0-4. Developer Experience by Bus Type (2009-2018)

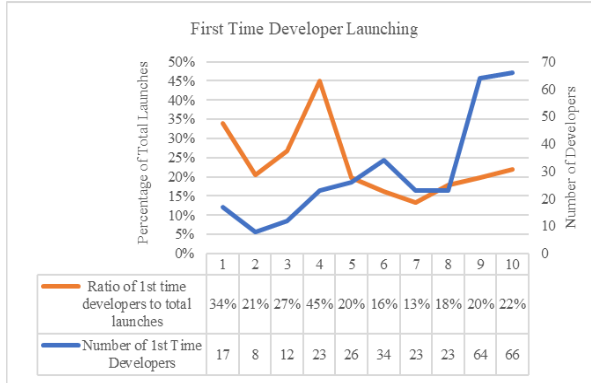

Fig. 0-5. New Developers on the Market

There is also a rise in the number first time developers, that stays on par with launch rates, and they're starting out with primarily 1U and 3U CubeSats (Fig. 0-4). These developers are having a significant impact on the industry as well – take Planet for example, who launched their first technology demonstration satellite in 2013, and now maintains nearly a quarter of all small satellites under 500kg. The average number of developers breaking into the market with their first launch was 21 from 2009-2016, that number rises to an average of 65 boasting first time launches in 2017-2018 (Fig. 0-5). This indicates a healthy market in which new entrants are continuing to develop and launch their first smallsat.

Mission Type

Categories of missions were defined that help differentiate between different types of applications. Updates to these categories have been made to better align with emerging industry trending (i.e. imaging has become "Earth Observation"). Missions were categorized as follows:

- **Communications –** Communications missions provide communications services, such as real-time connectivity, data storing and forwarding, radio frequency communications or system identification.
- **Earth Observation** – Earth Observation (EO) missions provide imagery coverage and data products relating to terrestrial activity.
- **Science –** Science missions gather data about the Earth's surface, weather, the atmosphere, or free space outside the atmosphere. While some Science missions are similar to Earth Observations missions in that they use visual imagery or data products, EO missions focus on human activity while Science missions look at natural phenomena.

– **Technology/Test** – Technology Demonstrations are missions whose purpose is to demonstrate new payloads, components, or subsystems, such as a new reaction wheel or propulsion system that lacked space flight heritage.[3] Technology missions also include pathfinders demonstrating new mission operations paradigms, such as proximity operations or cluster flight.

– **Other** – Other includes new emerging missions including early warning, on orbit servicing, signals intelligence or cargo missions.

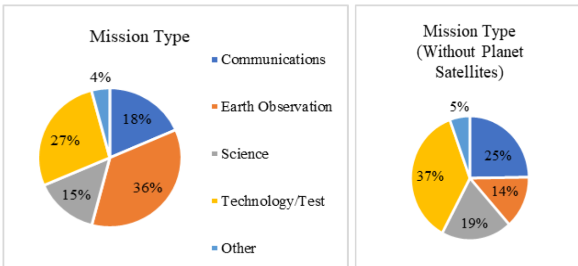

Fig. 0-6. Mission Category Summary (2009-2018)

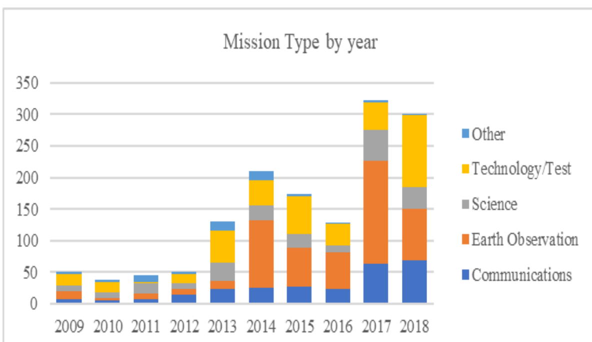

Fig. 0-7. Mission Category by Year (2009-2018)

A note on constellations: A significant player in the last five years has been Planet, resulting in significant increase in Earth observation data. Planet's constellation alone represents 79% of all Earth observation satellites, with 145 launched in 2017 alone. While this chapter treats a constellation of N satellites as if they were N independent satellites, the authors are evaluating methods of aggregating data that limits the skewing effect of large constellations on the dataset.

CubeSat Mission Category

One of the first questions that this dataset was used to address involved the distribution of mission types between SmallSats and CubeSats. As shown in Fig. 0-8, CubeSats are now dominating their share of the mission sets, taking on more than 50% of all mission categories except "other."

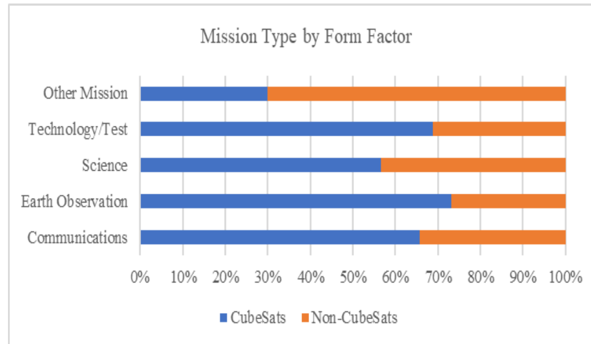

Fig. 0-8. Mission Category by Form Factor

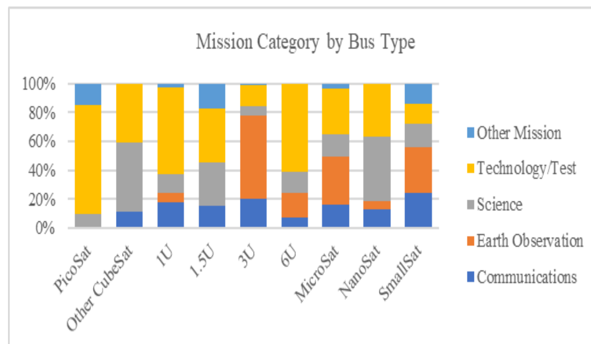

Fig. 0-9. Mission Category by Bus Type

After assessing the breakout of mission type, this study evaluated how SmallSats and CubeSats of different sizes were used, as shown in Fig. 0-9. Consistent with previous analysis, a majority of 1U CubeSats were used for technology demonstration. In contrast, 3U satellites and larger begin to show significantly more usage as science, EO, and Comm. missions. This trend was predicted by the authors' 2014 study[4], and confirmed by recent data. One interesting exception to this trend is in the 6U form factor, which shows usage rates more similar to the 1U form factor than to 3U, NanoSat, MicroSat, or SmallSat classes.

It's possible that because 6U spacecraft are relatively new (in comparison to the more mature 3U spacecraft), the only organizations that launch 6U are those that have new payloads or sufficiently higher power needs that exceed the capability of 3U satellites, and thus tend to be technology demos. The 6U form factor first launched in 2014 with the technology demonstration mission of maritime awareness of PERSEUS M1 and M2. 2018 saw an overwhelming growth in the 6U form factor going from 8 launched between 2014 – 2017 to 31launched in 2018 alone. 2018 has also begun to see

[3] Missions previously categorized as "educational" ("beepsats" intended for teaching purposes alone) are now included in this category due to the difficulty in differentiating between the two categories.

more active missions in the communication, earth observation and science realm for the bus.

Table 0-1. Number of Missions for each Mission Category for a 6U CubeSat

6U Mission Type	2014	2015	2016	2017	2018
Communications		1			3
Earth Observation				1	7
Science			1	2	4
Technology/Test	2	1	1	2	17

2016 also saw the first launch of a 12U form factor with AOXIANG ZHIXING, an academic technology demonstration mission. This was followed by Capella Spaces' CAPELLA-01 (DENALI) launched in 2018, an active technology demonstration looking at Commercial SAR capabilities.

Funding Agency & Developers

The funding agency is the organization that paid for and owns 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.

Public Sector:

- **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.
- **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.

Private Sector:

- **Commercial** includes for-profit commercial entities, such as Planet, ComDev, or Orbcomm.
- **Academic** (previously "university") includes universities and the increasing number of high school and K-12 organizations launching small satellites. Military based academies such as the Naval Postgraduate School and West Point were assigned to this classification as well.

Funding Source

In recent years, we see a growing trend of commercial and academic organizations funding their own small satellites rather than relying on government awards. This shift from the public sector to the private sector is an indicator of a maturing commercial industry with a solid business case, and an indicator that costs to academic institutions are low enough to self-fund SmallSat development projects. During the years 2014-8, 56% of all small satellites were funded by commercial sources, up from 13% over the 2009-2013 timeframe.

Planet is categorized as commercial for this study, but was separated out to highlight the industry impact of the company.

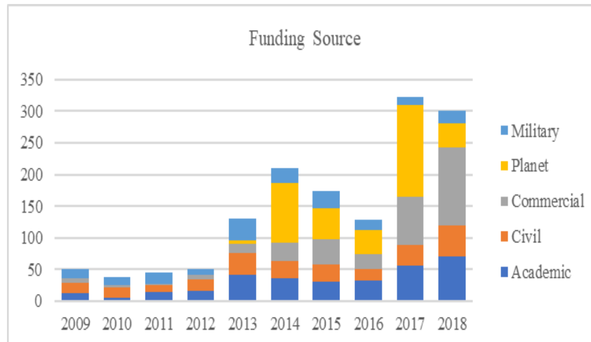

Fig. 0-10. Funding Source by Year

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.

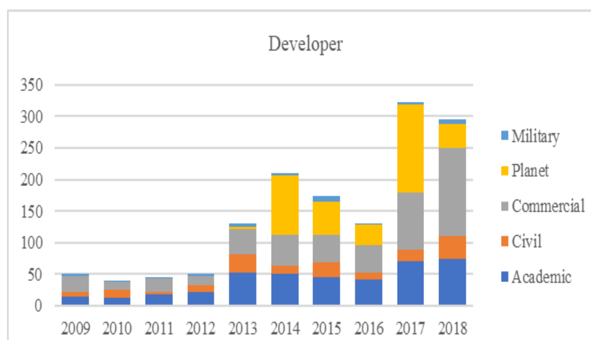

Fig. 0-11. Developer by Year

A consistent trend of the industry has been that commercial developers have dominated the industry, building 51% of all satellites over the last ten years. Academia comes in next with 31% of development

(Ref. Fig. 0-11 and

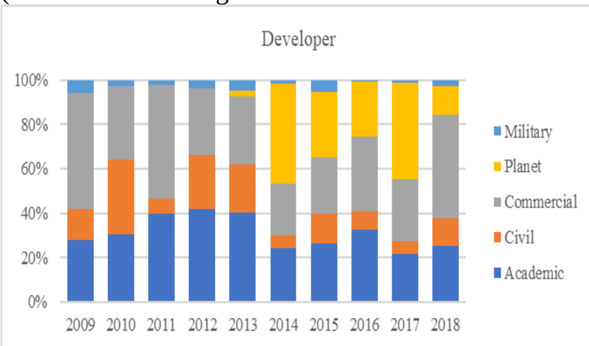

Fig. 0-12.)

The leading developers with over 15 satellite launches are listed in Table 0-2.

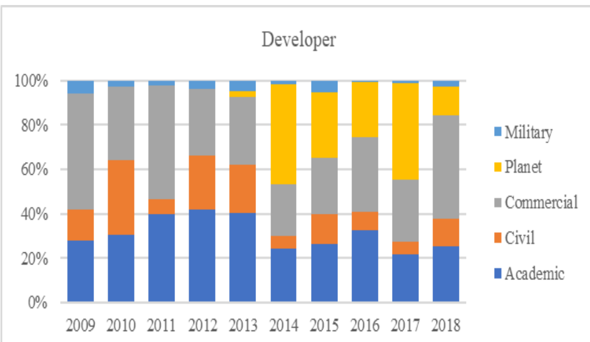

Fig. 0-12. Developer by Year

Table 0-2. Leading Small Satellite Developers (2009-2018)

Developer	Industry Share
Planet	24.3%
Spire Global Inc	6.5%
ISS Reshetnev	2.3%
The Aerospace Corporation	1.4%
SNC Spacecraft Systems	1.4%
CAST - Chinese Academy of Space Technology	1.2%
DongFangHong (DFH) Satellite Company	1.2%
Surrey Satellite Technology Limited (SSTL)	1.2%
Los Alamos National Laboratory	1.1%
Skybox Imaging	1.1%
Tyvak Nano-Satellite Systems Inc	1.0%
UTIAS Space Flight Laboratory	1.0%

To better understand the relationship of funding source and developers, we compared the cross-sectional relationship of the two entities. Fig. 0-13 shows that Academic and Commercial entities will often produce satellites in house, where public sector entities – civil and military will just as often contract out as they build internally.

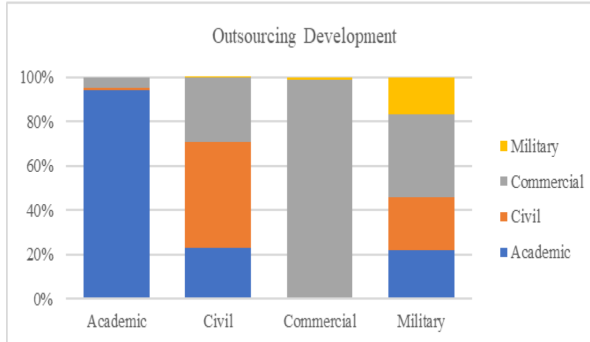

Fig. 0-13. Funding Entities vs. Developer Entities

The authors' 2014 paper stated,

> *"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, 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."*[4]

These predictions and assumptions are continuing to play out in the market as time moves forward.

International Considerations

By separating missions funded by US organizations vs. non-US organizations, the study identified that the United States was responsible for 57% of all satellites in the past decade, up from 49% of all SmallSats launched between 2009 and 2013. Table 0-3 shows the distribution of satellites based on country.

Table 0-3. International Development

Developer	Government Share
United States	57%
China	10%
Japan	5%
Russia	5%
Germany	2%
Canada	2%
India	2%
France	1%
Other (countries with <20 spacecraft)	15%

Again, comparing countries that outsource development internationally, this study found that 94.8% of the 1452 satellites were built by a developer in the home country of the funding organization.

Development Time

The study compiled the development times for each mission, subject to the availability of data in public locations. The development time is calculated as the time between the date the satellite was placed on order and the date of successful launch. The original publication found that the average development time for commercial and military institutions between 2009-2013 was under two years (1.7, and 1.6 years, respectively) and that universities took on average 3.8 years.[4] The overall average development time was 2.6 years. Small fluctuations have occurred in average development times from year to year, without a notable trend in either direction. See Table 0-4.

Table 0-4. Development Times by Year

Year	2009	2010	2011	2012	2013
Development Time (years)	2.6	2.5	2.8	3.0	2.5

Year	2014	2015	2016	2017	2018
Development Time (years)	2.2	2.4	2.8	2.8	2.5

Over time, we've seen development averages begin to level out and become more standard across mission sizes and developers (Table 0-5), with small satellites still holding development times of nearly twice as long as PicoSats.[4] PicoSats maintain the lowest development time (1.8 years), likely due to their inherently lower complexity. 3U CubeSats offer the second-shortest development time (2.2 years), which can likely be attributed to standardization of the form factor and the influence of Planet's constellations. In general, larger and heavier satellites take longer to develop than smaller and lighter satellites, as shown by the comparison between NanoSat, MicroSat, and SmallSat categories. This trend doesn't necessarily apply to the CubeSat form factor due to the proliferation of widely-available commercial parts and the standardization of secondary launch opportunities.

Table 0-5. Development Timelines by Bus and Developer

Bus Category	Time (Years)	Developer	Time (Years)
PicoSat	1.8	Academic	2.7
Other CubeSat	2.8	Civil	2.9
1U	2.4	Commercial	2.4
1.5U	2.2	Military	2.3
2U	2.8		
3U	2.2		
6U	2.5		
NanoSat	2.4		
MicroSat	2.7		
SmallSat	3.5		

Mission Success

In all spaceflight projects, mission success remains the primary goal. A successful effort 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, or provide a commercial service that was not available. For technology demonstration missions, success is indicated by the experimental component or subsystem's ability to successfully operate in the space environment. For science missions, payload data provides its users sufficient data to support or refute their hypotheses (and publish papers). For commercial missions, the satellite must provide services long enough to allow its users to return a profit.

Missions that do not return all the desired data may not be complete failures. There is value to spacecraft

[4] One possible influence of this change should be noted that Military Academies used to be categorized under "military" and are now categorized under "academia" which could have equalized the development times relative to the previous publication.

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.

This study categorized satellite mission success into the following categories:

- Full Success (Green): achieved desired mission performance over its intended design life
- Partial Success (Yellow): achieved desired level of 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 (Grey): rocket did not successfully place the satellite into orbit

This data was collected entirely from public sources, and the Seradata Spacetrack subscription database[25] and not from interviews with developers, operators, or users. Operational status is one of the most difficult data points to collect, since it requires articles or papers to be written months or years after launch. It's possible that some developers and operators may not wish to widely publicize a failure, so this data may trend towards the optimistic. However, it represents the best understanding available in the public domain.

With respect to mission success, the assumption was made that if a satellite is still active and outlived its design life, it is considered successful. However, design life data was only available on 86% of satellites. In the data set, 31% of satellites are still operating in their design life. The data sets below disregard those that are still in mission, or those without a design life (except in the case of failure to operate) – containing only 56% of the data. See Table 0-6.

Table 0-6. Mission Success Parameters

Data Consideration	Status	Number	Percentage
Successful	Active & Exceeding Design Life	356	24%
Successful	Inactive - Re-entered	201	14%
Successful	Inactive – Retired	94	7%
Partial Success	Inactive - Retired due to failure	69	5%
Spacecraft Failure	Inactive - Failed to operate	27	2%
Launch Vehicle Failure	Inactive - Failed to Reach Orbit	70	5%
Not Considered	Active and In Mission	448	31%
Not Considered	No Design Life	195	13%

Success Rates

Overall, small satellites continue to be impressively reliable given the difficulty and complexity of development and the relative inexperience of some of the developers. As the industry matures, success rates are rising. Fig. 0-14 shows a rise in successful missions from 76% to 87% overall. The industry continues to learn and mature, resulting in higher mission success rates. Failures as a result of the launch vehicle are not included in this data set, but discussed further in the following section.

When broken out by year, the rise in success rates is clear, the industry is becoming more successful over time, as shown in Fig. 0-15. Success Rates by Year. Note that the lower bound in this figure is 75% to highlight the variation.

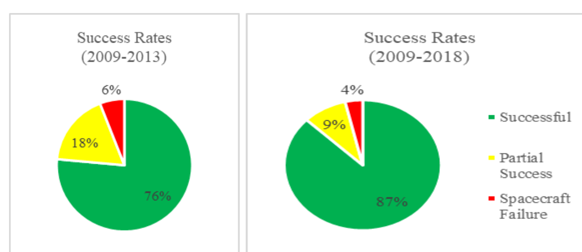

Fig. 0-14. Success Rates Overall, 2009-2013 vs. 2009-2018

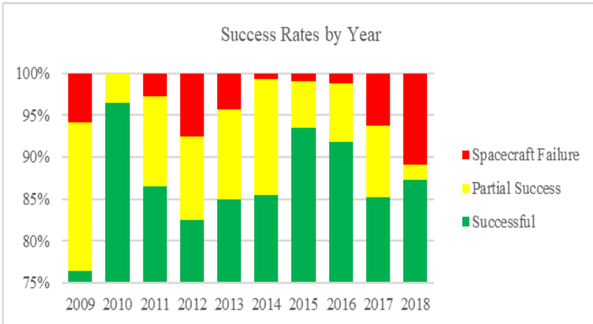

Fig. 0-15. Success Rates by Year

Recall that Fig 1-5 highlighted that small satellites are regularly used for more operational missions with lower tolerances for risk. It's not clear whether the increasing use of small satellites for EO, Comm, and Science missions is driving a demand for higher reliability which is reflected in the industry supply, or whether the improvements in reliability that naturally occur as the industry continues to mature is what drives policymakers to select small satellites. The causality is unclear, but these two factors are clearly interrelated.

The next step was to look at success rate by mass category

(

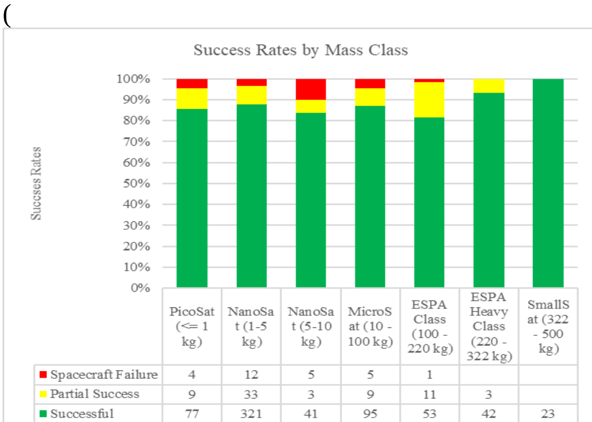

Fig. 0-16. Success Rates by Mass Category

). The fundamental assumption is that larger satellites would offer a higher success rate due to the lower risk posture of the developer, funding agency, and/or users. The data supports this assessment.

Mission Reliability

The authors' previous publication chose to focus on success rates of developers based on levels of experience, showing a data-driven trend of the impact of flight heritage. It showed that as developers gained more experience launching small satellites, they tended to build larger satellites, with higher levels of mission success. It showed that for developers building their first satellite launched between 2009 and 2013, only 64% were fully successful, and another 19% experienced some level of partial success.

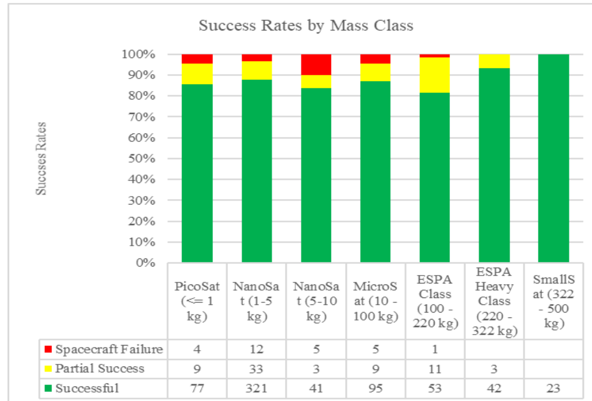

Fig. 0-16. Success Rates by Mass Category[5]

Counting a partial success as half a full success, this results in a "success metric" of 74% for first-time developers. 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 satellite or more[4]. For this phase of the study, the focus was placed on understanding failures – whether it be due to an error in the launch vehicle or a subsystem of the satellite.

Launch Failures

Four events – failures of Orbital ATK's Antares in 2014, SpaceX's Falcon 9 in 2015, Sandia's National Laboratories' Super Strypi in 2015, and the Russian Soyuz in 2017 – were the largest contributors to the overall launch failures over the last ten years. These failures resulted in a combined loss of 5% of the satellites manifested for launch. Table 0-7 breaks down the percentage of small satellites lost to launch failures, illustrating that 2014 and 2015 were particularly bad years for the small satellite industry.

Table 0-7. Launch Failures by Year

Year	2009	2010	2011	2012	2013
% of Launch Failures	4%	2%	4%	4%	0%

[5] As discussed in Table 0-6, only 814 of 1452 total satellites (56%) are represented in this dataset due to those missions which are still "in mission" or in which data was unavailable to make a trusted assessment.

Year	2014	2015	2016	2017	2018
% of Launch Failures	13%	10%	0%	6%	0%

Infant Mortality Rates

Once a satellite has made it past the launch gate, it must start up, establish communications with the ground, and survive on-orbit checkout. Infant mortality rates are identified in Fig. 0-17 below. This chart is based on the time of the malfunction event that put the satellite out of service. Those occurring in the first month of life includes immediate separation or communications events that prevent the ground from contacting the satellite, but do not include failures of the launch vehicle outside of the separation system. Those which occur in later months tend to be subsystem related, and will be addressed in Section 0 below. It is important to note that the design life is considered in this data; if a satellite designed to operate for six months was retired due to a malfunction at nine months, then the mission is considered a success and not listed as a failure in Figure 1-14. Overall, only 63 of the small satellites did not meet design life, failing in the first year, roughly 4.3%.

Of those that failed, 27 failed to operate completely. Of those failing due to malfunction after communicating with the ground, 35 satellites were designed for > 1 year of operations, and 14 failed in less than one year (40%). Meanwhile, 18 satellites were designed for 1 year of operation or less; of these, 11 failed before their design life (62%).

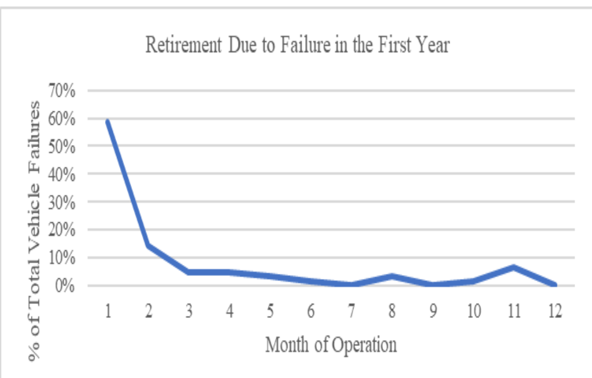

Fig. 0-17. Infant Mortality

Failure Due to Satellite Malfunction

Of the 1452 launches, 70 (or 4.8%) failed due to a launch vehicle failure. 27 (2%) never closed the initial communications link (considered Dead-On-Arrival, or DOA), and 90 (6.2%) were retired early due to satellite malfunctions of spacecraft subsystems. 23% of these causes are unknown, or were unpublished. One quarter of all failures were due to communications issues, and the remaining half were due to various subsystems failures ranging from power collection and distribution issues to loss of structural integrity of the satellite. The full results are listed below in Fig. 0-18. Again, it is important to note that these data come from primarily public sources, and in-depth studies with developers have been performed on a more limited dataset[20].

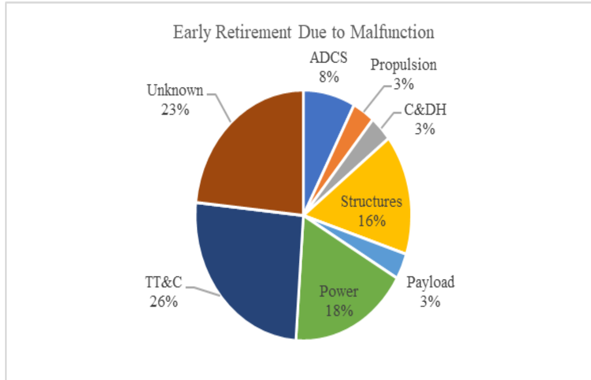

Fig. 0-18. Retirement Due to Subsystem Malfunction

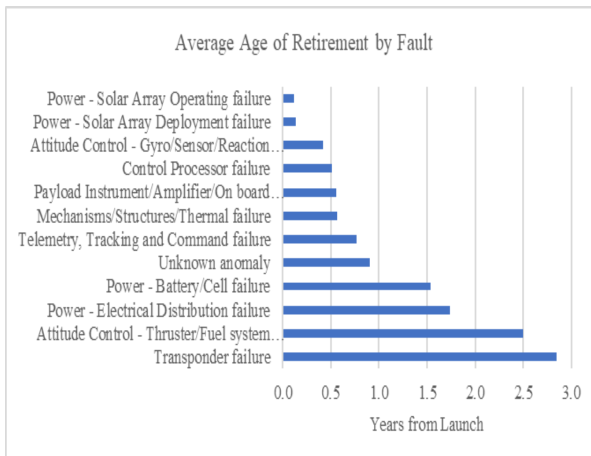

Fig. 0-19. Age of Retirement Due to Subsystem Malfunction

Additionally, the study looked the average age of events of malfunctions that caused satellite retirement (Fig. 0-19). As expected, solar array malfunctions ended missions very early, whereas fuel system and transponder failure issues tended to end missions later in the satellites lifetime.

CONCLUSIONS

This chapter set out with the objective of re-validating the findings of the 2014 study on Small Satellite Trending[4], as well as updating findings to cover the last 5 years. By doing so, we could again provide data-driven answers to key questions about the capability, usage and success rates of Small Satellites and CubeSats.

Overall, many of the trends and predictions stated previously still hold true. Though a series of launch vehicle failures have significantly reduced the number of small satellites that were launched over the anticipated amounts, strong growth has been seen, with three times more satellites being launched in the latter half of the previous decade than the first.

There's been a significant rise in the usage of the 3U CubeSats to perform missions with real utility, and we anticipate significant growth of the 6U form factor in the coming years.

New developers are coming onto the market at a substantially increased rate, and they're starting out with primarily 1U and 3U CubeSats. These developers are having a significant impact on the industry as well – take Planet for example, who launched their first technology demonstration satellite in 2013, and now maintains nearly a quarter of all small satellites under 500kg.

31% of satellites launched in the last decade are still operating within their design life. Of the roughly half of missions where a confident mission outcome could be determined, 87% of missions continued useful operations past their design life.

Launch failures claimed 5% of small satellites. For those satellites that survive launch, roughly 4% fail within the first year. Mission-ending failures are most likely to be attributed to the communication subsystem (26%) or power system (18%). Unattributed failures account for another 23%, with the other subsystems accounting for the remainder.

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 continues to update this database with launches to identify how these trends are changing over time.

Acknowledgements

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