Secondary Spacecraft in 2016: Why Some Succeed (And Too Many Do Not)

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Abstract—**This paper updates previous reviews of secondary spacecraft. With the number of new secondary spacecraft exceeding 100 per year, it is necessary to revisit the data, to better understand the trends and make new predictions. While CubeSats are the dominant type of secondary payloads, they are not the sole focus of this work.**

For 2016, we will re-examine our data and previous claims using a new set of classifications. We now believe that secondary-spacecraft developers are best divided into three groups: novices, traditionalists and experimentalists. Each of these groups approaches the development and operation of rideshares in very different ways, and the mission success rates between the three groups diverge.

In this paper, we will review the census data (mass, lifetime, mission category, contributing organizations). examining trends and identifying deviations from (or confirmations of) previous predictions. Our focus will be on mission success and failure. We have accumulated sufficient information to define failure rates based on the type of organization, and to identify most-likely-causes based on the mission and organization type.

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1. Introduction

Rockets are expensive. Published costs begin at $20M for placing hundreds of kilograms to low-Earth orbit, and upwards of $100M for a flight to geostationary orbit. It should not be surprising, then, that someone thought of ***secondary payloads***: adding more spacecraft to the same launch vehicle, making use of the leftover margin not used by the primary payload. The advantage of the secondary payload is the reduced price; the disadvantage is that the secondary has little to no control of the launch vehicle's target orbit or schedule.

While secondary payloads have been flown for more than 50 years, the number of secondaries has drastically increased over the past ten years, and especially over the past three. The standardized launch container (i.e., the CubeSat) has enabled secondaries to be placed on every rocket in the world. More than one-third of the spacecraft placed on orbit in 2015 were secondaries.

There are wide range of opinions on the value and capabilities of CubeSats. In particular, it is claimed/cited that about half of all CubeSats fail to complete their stated missions. The actual rate is closer to 25% - but that is still a very large fraction of missions that are not achieving their objectives. However, as will be shown, there are three distinct types of mission developers, who have very different rates of mission success.

A Very Brief History of Secondaries

The first secondary payload was the 20-kg SOLRAD-1, which accompanied the 100-kg Transit 2A flight in June 1960; both were Navy experiments. The first multi-agency secondary was the University of Iowa's 16-kg Injun-1, launched with Transit 4A and SOLRAD-3 in June 1961. From the 1960s through the early 1980s, secondaries were predominantly US military missions. In 1981, commercial secondary opportunities became common with the advent of the Ariane Structure for Auxiliary Payloads (ASAP) platform; the second flight attempt of the Ariane-1 launch vehicle carried the Radio Amateur Satellite Corporation (AMSAT) Phase-3A spacecraft. Since that time, there have been hundreds of secondary payloads flown and now, since 2012, CubeSat-class adapters have enabled hundreds of secondaries to fly each year [1-5].

A Very Brief History of This Paper

We have discussed secondaries in each of the five previous conferences: beginning in 2011, we presented a statistical look at the more than 300 secondary payloads launched from 1990-2010, examining issues of mass, nations of origin and launch and mission type [1]. Examinations of the data indicated that the broad range of mission types, sizes and participating nations could be classified in several useful ways. For example, we were able to forecast a bifurcation of secondaries into those compatible with CubeSat dispensers and those compatible with the Evolved Expendable Launch Vehicle (EELV) Secondary Payload

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Adapter (ESPA). In 2012, we extended the analysis back to the first secondary payload in 1960 and updated the results to the present date [2]. We were able to confirm that the changes in the numbers and demographics of secondaries were tied to the availability of specific launch vehicles/systems, namely the Ariane, Dnepr, Shuttle and Cal Poly's Poly-Picosatellite Orbital Deployer (P-POD); and that the sharp increase in the number of CubeSat flights represented a significant change in the nature of secondaries. In 2013, we observed that there had been almost twice as many secondaries flown in the four years from 2009-2012 than in the eight years previously (and those eight years had seen the most secondaries flown since the '60s). We examined the implications of having so many secondaries fly, and predicted that we were in the middle of a very significant shift in the number and nature of missions flown [3]. In 2014, we further discussed the shift to having large numbers of secondaries on the same launch, and the regulatory / mission success implications [4]. Finally, in 2015, we extended the analysis to consider mission success rates between universities and professional programs; we identified the significant differences in success rates, but did not have firm conclusions for why there was such a difference [5].

Better Data, Better Papers

We are submitting a sixth consecutive paper for two reasons. First, with more than 100 new CubeSat missions each year, the observations and conclusions of the previous year need to be reviewed. In particular, the CubeSat-class launch adapters have completely changed the playing field for secondary payloads; nobody (the author included) fully understands the long-term implications of this new method for reaching orbit. But it is worth making some educated guesses. Second, as noted above, new data on mission success and failure is available, allowing long-standing questions to be addressed.

Outline

Using launch manifests, catalogs of satellite orbital elements, published information and a commercial database, we have compiled a detailed list of all the secondary payloads since 1960; for the purposes of this paper, we will focus on missions from 2000-2015. We will reassess the claims of previous papers using the new data, and we will extend the previous work with additional data on mission success and failure. Specifically, using a new classification for organization type, we will re-examine the failure rates.

Definition: Secondary Payload

For the purposes of this paper, a "secondary payload" is any self-sustained mission that is not the primary customer/ payload on a launch vehicle. Our definition covers traditional secondary spacecraft mounted separately to the launch vehicle and deployed, strap-on experiments that remain with the last stage, and so-called "tertiary" spacecraft that are carried by/ejected from another spacecraft (the prime payload, or another secondary).

This definition is intended to cover the spectrum of "piggyback" launch opportunities: taking advantage of excess launch capacity to fly a comparatively small/limited mission at a discounted price.

This definition does not cover hosted payloads, where a component or instrument is integrated with another spacecraft, drawing power, data and/or pointing from the main device. Hosted payloads are an important and successful segment of the rideshare industry. However, the metrics for hosted payloads and secondary payloads are sufficiently different that hosted payloads are outside the scope of this study.

To automate the process of sifting through the thousands of missions flown over the past 50 years, we use the following heuristics to identify the secondaries:

- There must be at least two spacecraft on the launch vehicle; the heaviest payload is assumed to be prime, and the rest could be secondaries. The spacecraft's International Designator (aka COSPAR number) is a good indicator; typically, the primary payload is given the "A" designation. Exceptions were made in the case of certain Dnepr launches where there may be as many as 17 payloads, and no one payload dominates the mass budget; all of the payloads are considered to be secondaries.
- The spacecraft is not in geostationary Earth orbit (GEO); to our knowledge, there have not been any GEO "secondaries". When more than one spacecraft are on a GEO launch, they are a cost-share among co-equal spacecraft. Many GEO spacecraft have hosted payloads but, as noted previously, that is beyond the scope of this study.
- The spacecraft must have a launch mass of less than 500 kg. This restriction further enforces the philosophy of secondary launches.
- Missions involving the launch of identical/ complementary spacecraft are not considered to be secondaries. The Iridium, Orbcomm, Globalstar and Glonass constellations often filled one launch envelope with 3-6 spacecraft. These are not secondary payloads, but rather an efficient business decision of a single primary customer. This restriction eliminated more than six hundred Russian surveillance/communication spacecraft, as well as dozens of constellation elements noted above.

2. Presentation of Data

This paper is based on a review of the launch history through 2015. Spacecraft information was collected from several online databases [6-10], double-checked against the Ascend SpaceTrack database, and assembled into one master list of the more than 7600 spacecraft launched through the end of 2015. We include launch failures in this list, since the missions had already committed to the secondary payload.

For the purposes of our study, the launch date of a secondary is not the date that the object lifts off from the surface of the Earth, but rather the date that the object is ejected/activated on-orbit. For example, Planet Labs' 28 Dove spacecraft carried by the Cygnus capsule to the International Space Station (ISS(in December 2013 were assigned launch dates of February 2014, when they were ejected from the ISS. The author admits that both the ISS launches and the Planet Labs Dove constellation pose problems for this database. The ISS does not fit into the convenient launch vehicle / nationality categories. The ISS "problem" is addressed by our taxonomy: we track separately the mission success stages of integration, launch and on-orbit ejection, and can distinguish between the vehicle that carried the secondary to orbit and the vehicle that ejects the spacecraft into free-flying orbit.

The Planet Labs "problem" has two elements: first, the Dove constellation is a single mission, with dozens of distinct secondary spacecraft placed into orbit over the span of years. It is not useful to consider the mission success of a single spacecraft, as the failure of any one spacecraft does not jeopardize the mission. The second problem is that Planet Labs is responsible for half or more of the secondaries flown each year, and thus all the statistics are skewed by its inclusion. For this year, these problems are indirectly addressed by giving Planet Labs its own category.

From the list of all spacecraft launched, the subset of secondaries was identified using the rules defined above. This left 983 secondary payload missions flown in 56 years, an average of 18 per year. As shown in Figure 1, the number of secondaries launched in each of the last 15 years matches or exceeds that average. In fact, the years 2009-2012 were unprecedented in terms of the number of secondaries launched, and at the time, we though that 40 launches a year was not sustainable [2]. And then those "unsustainable" numbers were greatly exceeded from 2013-2015. We conclude that we do not know what the "sustainable" number of CubeSats is.

For the first 53 years of secondary payloads (1960-2012), secondaries comprised only 7.5% of the spacecraft flown. In 2012, 30% of the missions flown were secondaries, and in 2013, they were 53% (115 of 217). The year 2015 continues that trend. This change is worth examining. The number of launches (and thus primaries) is not decreasing; over the last 5 years, between 75 and 85 launches are attempted each year. Instead, many more secondaries are being place on the same launch. The manifests of 2013-2015 have a few large-capacity launches responsible for the bulk of the secondaries. In 2013, these flights carried 33 secondaries (Dnepr), 28 (ORS-3) and 15 (Falcon-9 Flight 8); in 2014 another Dnepr launch set a new record with 38 secondary spacecraft. The ISS is releasing dozens of missions each year. Each of these flights carry more missions than the average number of missions flown in any calendar year, and the Dnepr flights had more secondary payloads than were flown in any year prior to 2009!

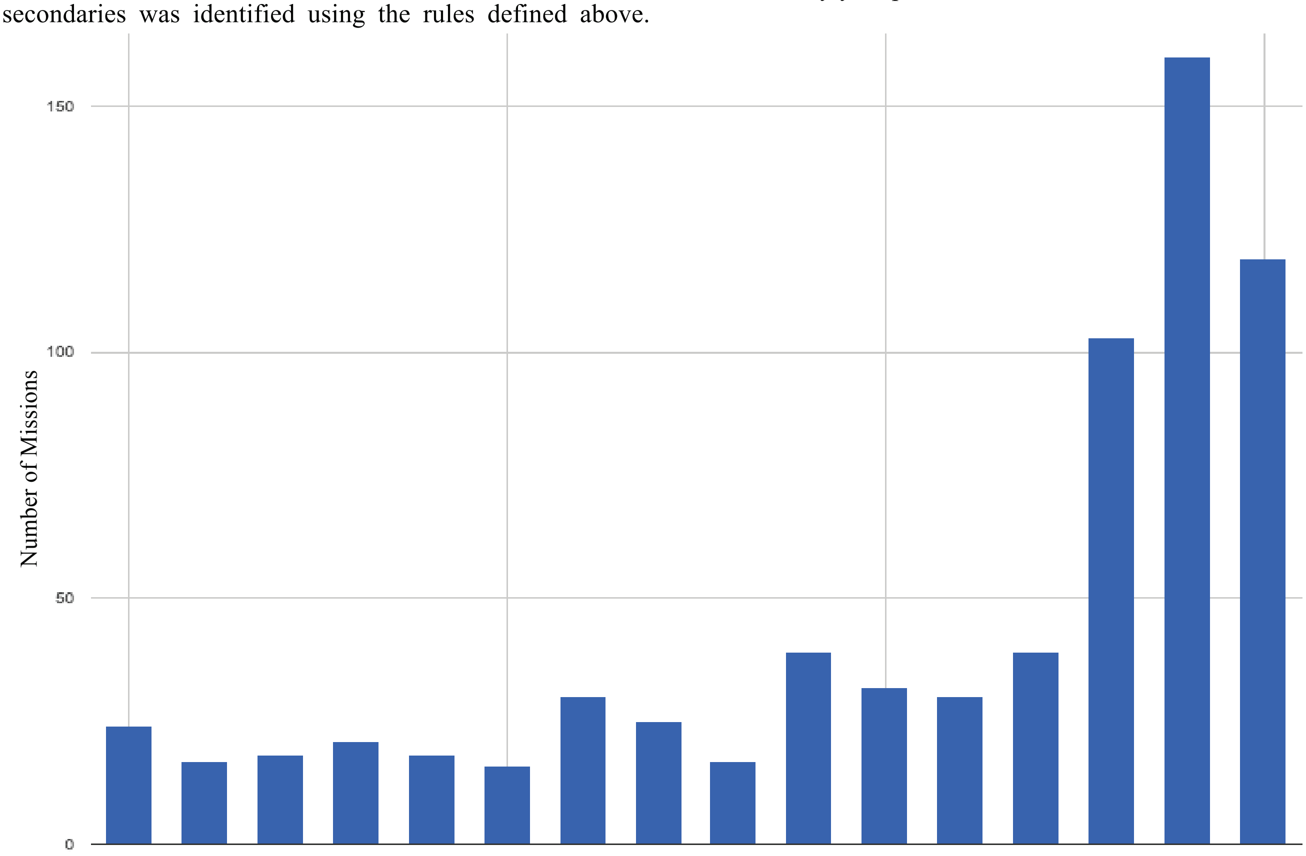

Figure 1. Secondary Missions Launched Per Year, 2000-2015

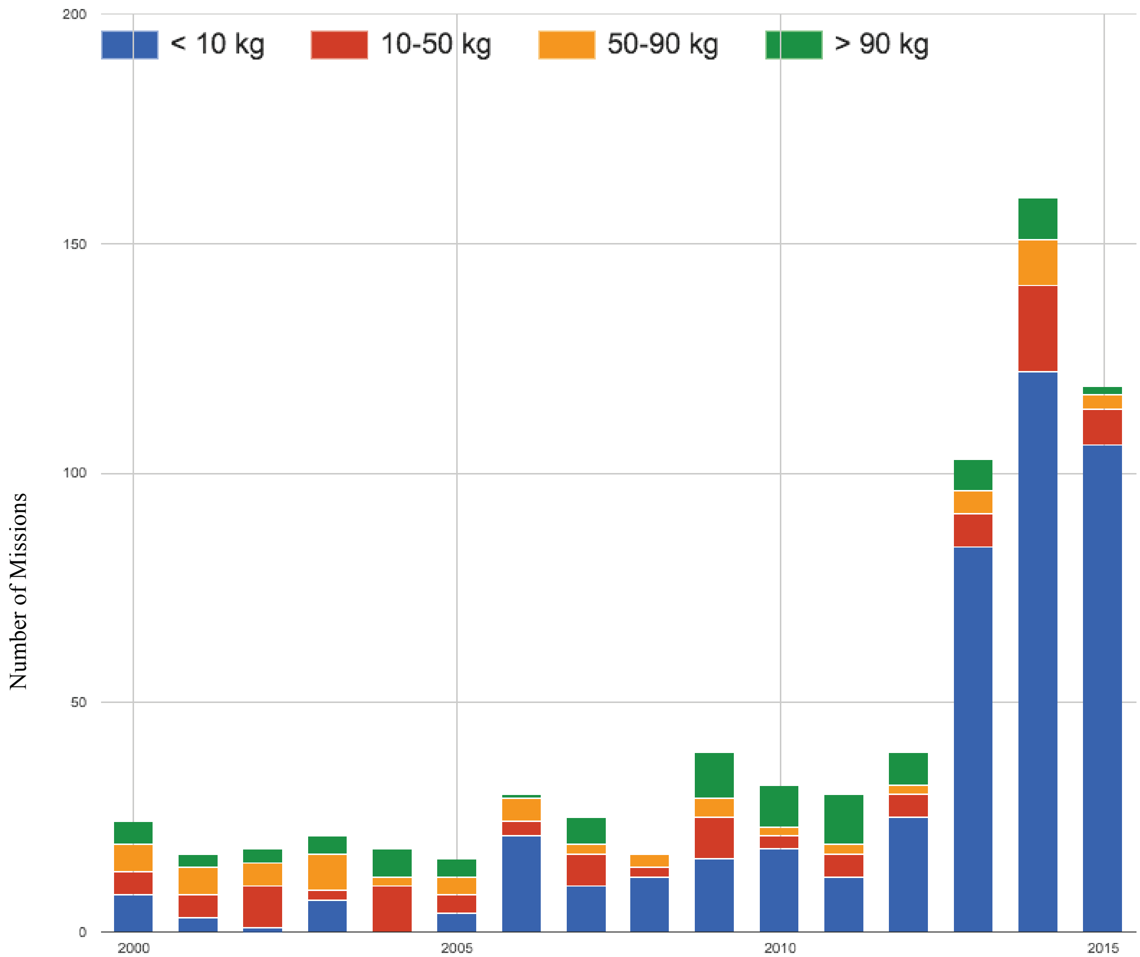

Figure 2. Secondary Missions by Launch Mass, 2000-2015

We believe that these "mega-launches" carrying 10 or more secondary payloads will become increasingly common, and thus the total number of secondaries flown will exceed 100 per year for the near future.

What has changed, such that these mega-launches are now common, and the total number of secondaries has increased so dramatically? We identify three related trends: the space industry has finally caught up with the microelectronics revolution of the 1990s, Russia and India have developed the infrastructure to support commercial mega-launches, and both spacefaring branches of the US government have embraced the CubeSat standard. We also note that China conducted two launches within a span of a few weeks in October 2015, with more than 28 secondaries flown. We will be watching to see if this capacity will be used for domestic-only missions (as is common with Japan), or whether they will follow the route of Russia and India.

CubeSats

As shown in Figure 2, the total number of secondaries launched each year with mass greater than 10 kg has been roughly constant since 2000, averaging about 15 per year. The sharp increase in the number of secondaries can be attributed to the CubeSat class (which was introduced in prototype form in 2000, although the first secondaries called CubeSats were launched in 2003). As shown in Figure 3, most but not all spacecraft under 10 kg are CubeSats. CubeSats comprised 75% of the secondaries flown in 2013 and nearly the same ratio in 2014-2015. There is every indication that this trend will continue.

Larger spacecraft are still launched, but their numbers are overshadowed by the number of CubeSats. If the CubeSat-class missions were removed from Figure 2, the launch numbers would be consistent with the years 1985-2000, with 5-10 launched per year, and a few boom years of 20+.

Not all secondaries can (or should) be CubeSats; there are instruments and spacecraft capabilities that don't work in a CubeSat (e.g., power draws above 50 W, precision pointing, and/or very high data-rate communications). Thus, there continues to be a need for larger secondary spacecraft, and launch providers have adapted. The Russian and Indian programs accommodate large numbers of larger secondary missions, with many on a single flight. If and when the US ever fields a standard ESPA platform on its EELVs, we might see a significant growth of secondaries in the 100-200 kg class. (We have been writing that in every paper for six years, so we are not holding our breath.)

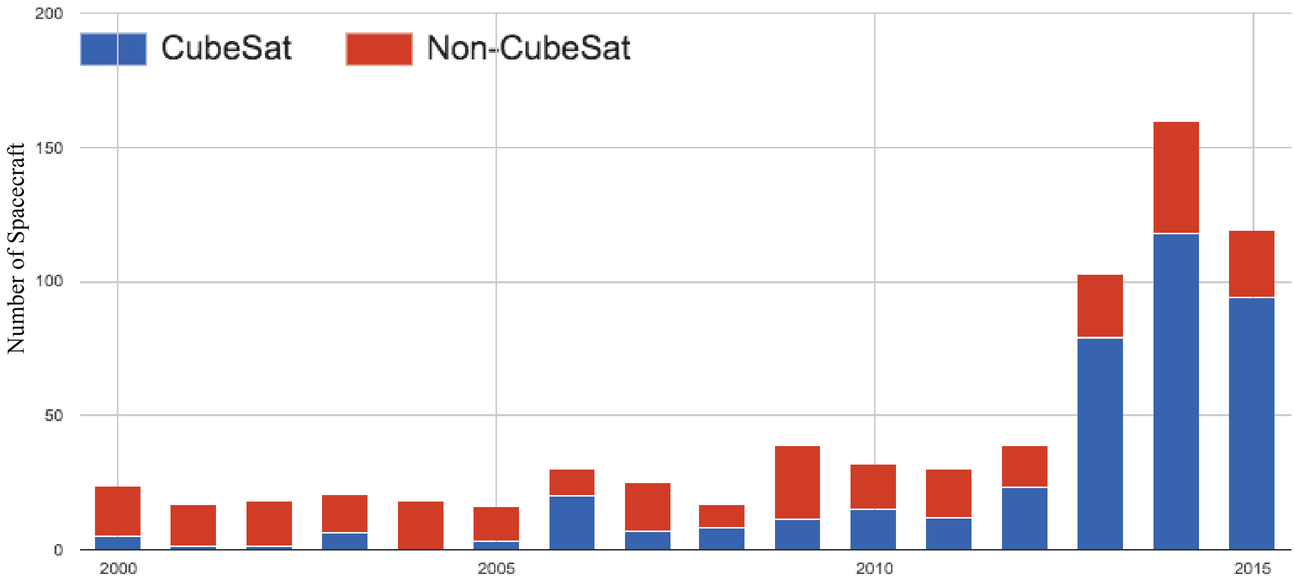

Figure 3. Spacecraft Under 10 kg by Category, 2000-2015

National and International Trends

Using our database, we have also categorized secondaries by the launch provider (Figure 4 and Figure 5). One can see that the main four providers (US, Russia, India and Japan) are all increasing their capacity over the past few years; China launched many secondaries in 2015, so we will watch to see whether this is an outlier or a new trend. As discussed in [4], the US, Japan, Europe and China serve mainly their own nations, while India and Russia are open for business; these nations sell excess capacity to secondaries. We cannot presume to know whether this is a profitable strategy, other than to note that these nations are flying more secondaries each year, not fewer.

And while one could make the argument that the International Traffic in Arms Regulations (ITAR) and/or Export Administration Regulations (EAR) are limiting the US secondary market to only American payloads, it should be noted that almost all of the secondaries launched in the US in recent years have been US government sponsored flights, either Department of Defense (DoD)-sponsored secondaries or NASA, through the Educational Launch of Nanosatellites (ELaNa) Program. With the US government supplying so many secondary opportunities to government and university payloads, there is little opportunity or interest in a private market. The exception is the ISS, which forms a hybrid public/private launch opportunity. NanoRacks sells flights via the ISS, purchasing space on the upmass capability of all the cargo flights. NanoRacks is responsible for most of the 50+ ISS deployments each year. What market there is for privately-funded secondaries in other orbits is going to Russia, apparently.

The US was the leading developer of secondary missions from the early ‘60s through the mid-‘90s, when Europe overtook them. As shown in Figure 6, the US is leading again. We believe that the United States will continue to be the largest developer of secondaries, driven by the launch availability. For example, NASA has a backlog of nearly 50 CubeSat missions it has selected for flight through the ELaNa program, and Planet Labs is making routine launches of dozens of Dove CubeSats to the ISS.

By contrast, Russia does not seem to be invested in building its own secondaries, with only a handful flown in the past 10 years. This reluctance to build secondaries is surprising, given that Russian rockets have flown an average of 10 secondaries per year for the past decade! However, it must be noted again that the Soviet/Russian Strela/Gonets program is responsible for producing in excess of 600 missions flown over the past 40 years, easily matching the total of all other secondaries. As noted in Section 1, we have not considered Strela/Gonets missions to be true secondaries, as multiple copies of the same spacecraft are launched together. We, at least, would find it interesting to further study the history of Russian secondaries to see if there are other cultural/economic reasons for their lack of secondary payloads.

We have categorized each secondary payload by the class of its primary mission: military application (e.g. signals intelligence), science, Earth imaging (e.g., Planet Labs), technology demonstration, communications (including Automatic Identification System – AIS). As shown in Figure 7, some missions don’t fit into these three categories: “other commercial” includes missions such as the Celestis capsules carrying ashes into orbit; “educational only” indicates that the mission had no real function other than sending down telemetry and low-resolution images for the edification of the design team. Educational-only missions are sometimes called “BeepSats”, and are almost all built by universities. But, as we will see, not all university missions are BeepSats.

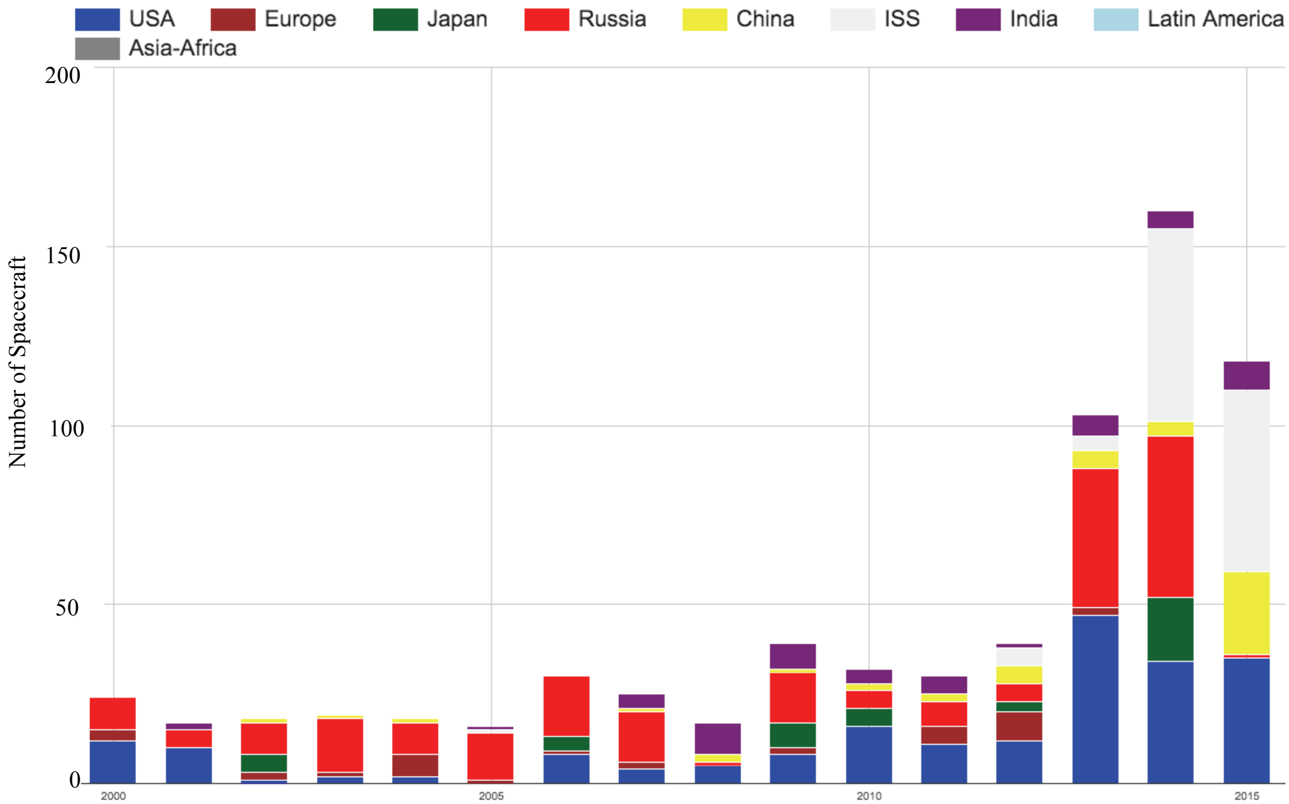

Figure 4. Missions Manifested per Year According to the Nationality of the Launch Provider, 2000-2015

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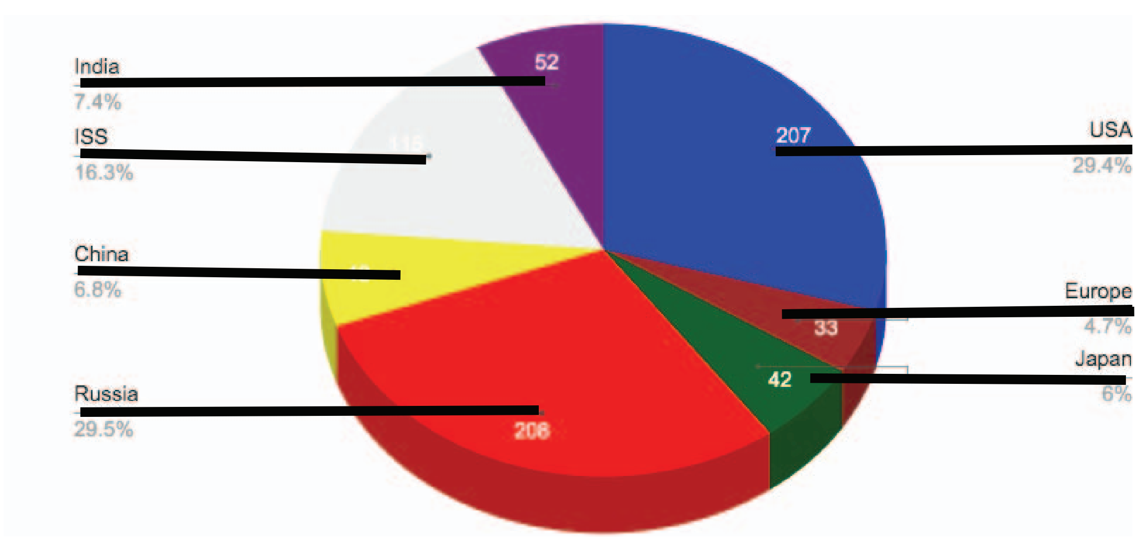

Figure 5. Aggregate Counts of Secondaries by Nationality of the Launch Provider, 2000-2015

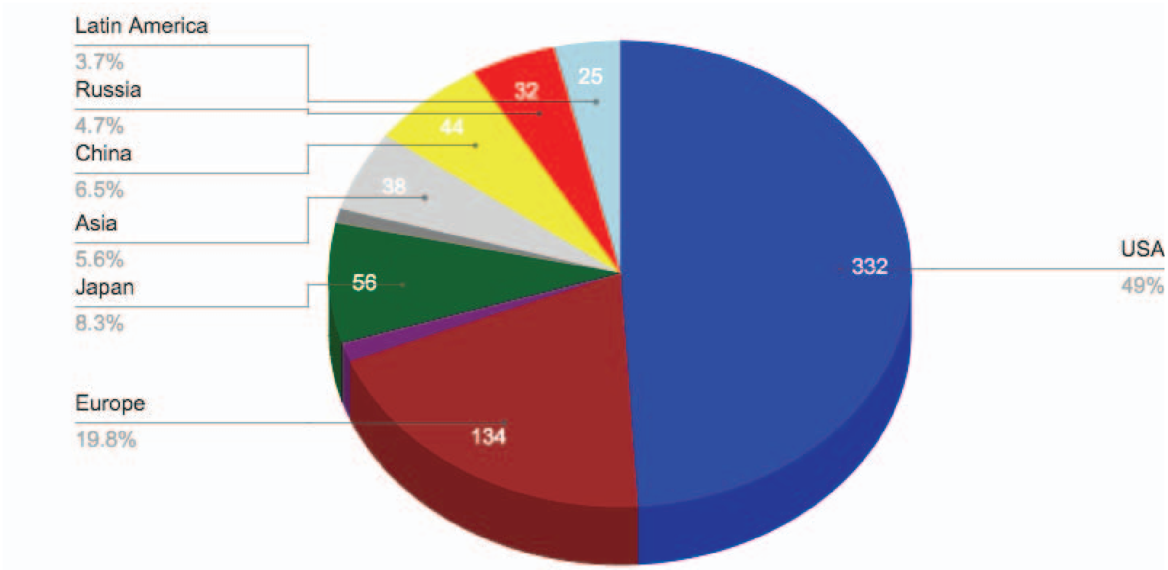

Figure 6. Secondary Payload Mission by Nation of Spacecraft Developer, 2000-2015

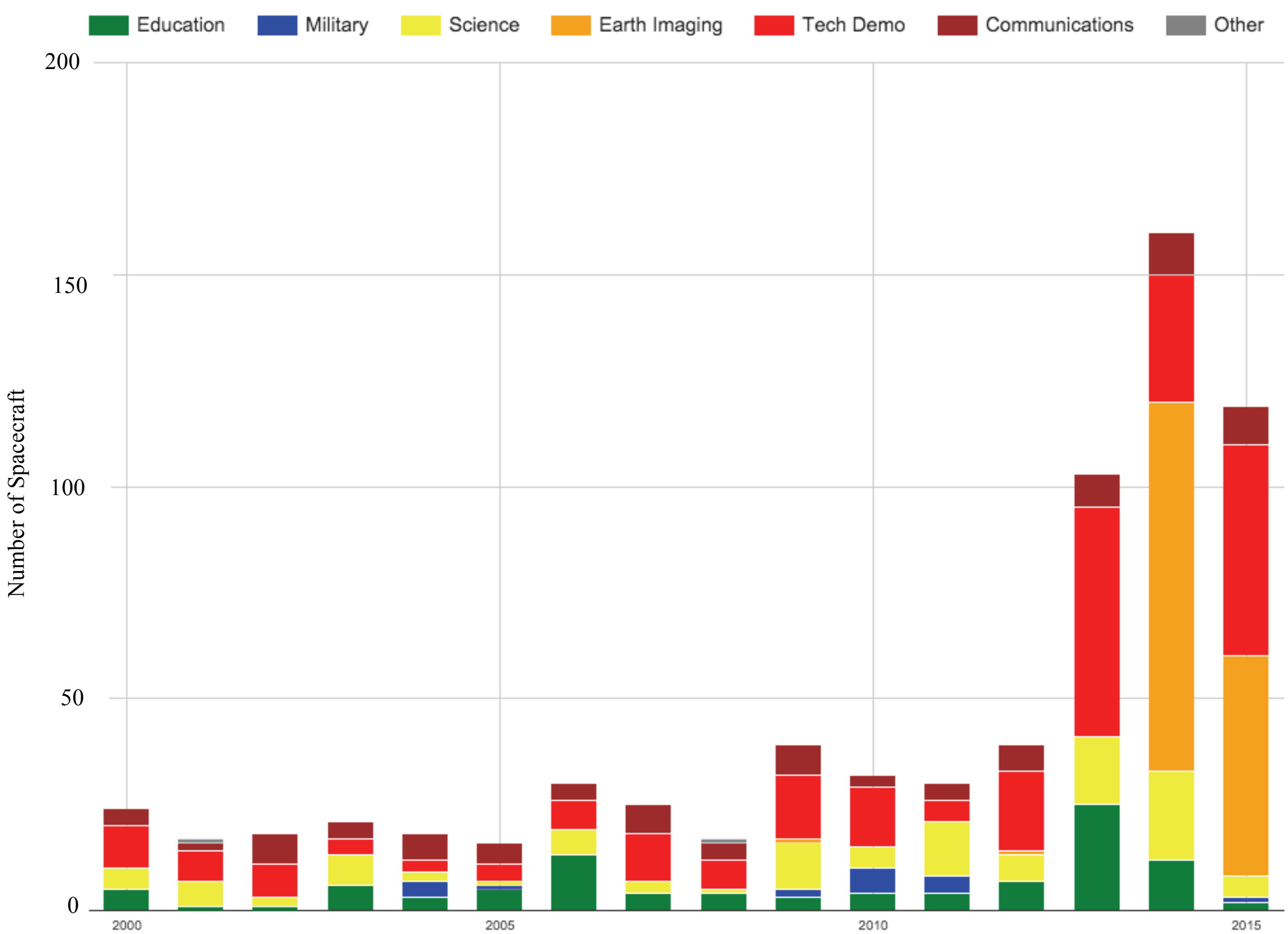

Figure 7. Mission Class of Secondaries, 2000-2015

Mission Status

The database has been improved for 2015 with metrics for mission success. We have reviewed the reports for as many missions as we could find covering the years 2000-2015, and assigned each mission a status corresponding to major milestones. It is expected that a mission would progress from Stage 0 to Stage 5; if a mission remains at a certain Stage, it is an indication of failure.

- 0 (**Prelaunch**). The mission has been manifested, but has not launched.
- 1 (**Launched**). The mission has launched. Missions lost to launch failure remain at Status 1; they are listed as ***Launch Fail*** on the charts.
- 2 (**Ejected**). The ejection of the secondary from the launch vehicle has been confirmed. Missions that are ejected, but never contacted, remain at Status 2 and are listed as Dead on Arrival (***DOA***).
- 3 (**Commissioning**). Two-way communication has been established, and the spacecraft is being commissioned for operations. Missions that remain at status 3 are marked as ***Early Loss***.
- 4 (**Initial operations**). The spacecraft has commenced primary operations and are listed as ***Partial Mission***.
- 5 (**Mission success**). Minimum mission success has been achieved; these are marked as ***Full Mission***.

We have checked the mission status against these mission success criteria, as available. We have also looked for failure and anomaly reports, indicating whether a mission has completed its objectives before succumbing to failure.

As shown in Figure 8, of the 455 secondaries to have launched between January 1, 2000 and the writing of this paper (October 2015), 13% were lost to launch failures, and 21% were either never contacted or were lost soon after commissioning began. Only 67% of secondaries launched have commenced primary operations, and only 30% can be confirmed to have achieved mission success. Another 7% are unknown. The yearly results are shown in Figure 9. When we remove the launch-failure numbers (Figure 10), the rates don't change significantly.

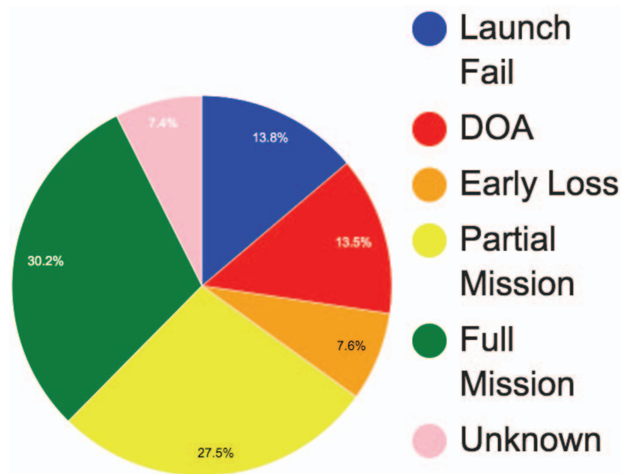

Figure 8: Mission Success of All Secondaries, 2000-2015

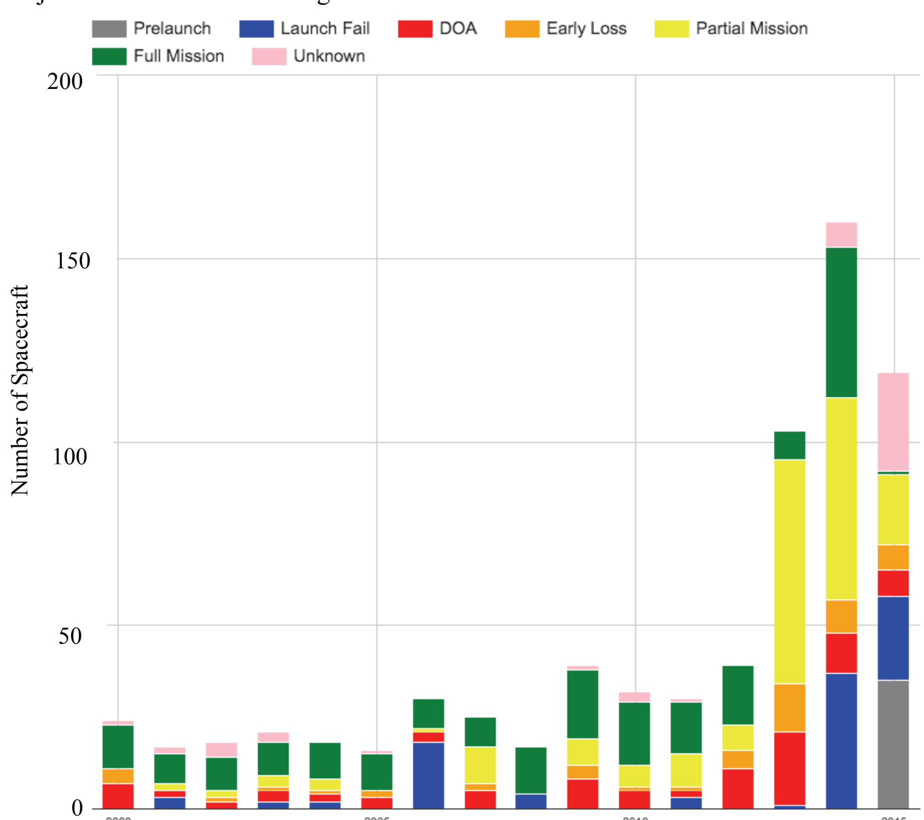

Figure 9. Mission Status of Secondary Missions, 2000-2015

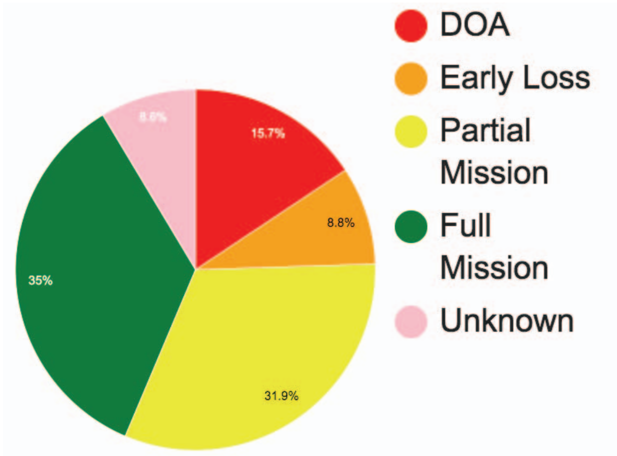

Figure 10. Mission Status of All Secondaries That Reached Orbit (2000-2015)

New Categories

In previous years [4,5], we tried to ascribe the high failure rates to universities. However, this classification didn't capture the significant difference between schools that have flown many missions using graduate students and staff technicians, and schools that are flying their first-ever spacecraft with an all-undergraduate team. Similarly the professional programs demonstrated very different organizational structures, leading to different outcomes. For this paper, we define four categories of mission developer

- **Hobbyist**. As the name implies, the hobbyist category is made up of the teams that approach the mission as a hobby/club/maker group. New universities are the primary set of hobbyists. Hobbyists are characterized by low-cost, fast-turnaround and a lack of standard practices when it comes to integration & test. Hobbyists have a high tolerance for risk.
- **Traditional Contractor**. This group are the Boeings and Lockheeds; contractors with a long history of building spacecraft and an established set of practices for integration & test. Traditional contractors build a secondary in the same way as they would build any spacecraft; size matters not. These missions are expensive and typically have high performance objectives. Traditionalists have a low tolerance for risk.
- **SmallSat**. SmallSat developers occupy the region between Hobbyists and Traditionalists; they have experience in building satellites, and have developed their own set of practices and risk profiles, tailored to the nature of secondary spacecraft. The AMSAT spacecraft would fall under this category, as would university and some government agencies with extensive experience.
- **Planet Labs**. Planet Labs would normally fit the SmallSat profile, but their single, constellation-based mission and the sheer number of spacecraft flown puts them in their own category.

The author has only been able to collect information on CubeSats using these four categories. Therefore, in Figure 11, we revisit Figure 10, but only consider CubeSats. This provides us the basis for further study.

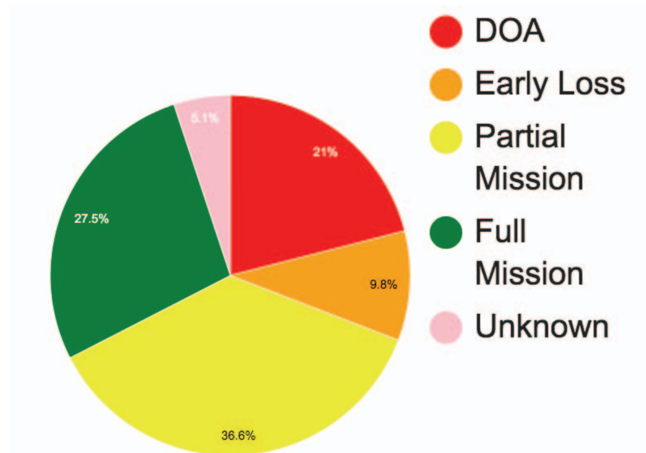

Figure 11. Success Rates of CubeSats That Reached Orbit, 2000-2015

The breakdown of CubeSat by developer class is shown in Figure 12. Until 2012, Hobbyists and SmallSat teams were the dominant providers; we expect to see more Traditionalists flown in 2016, and many, many more Planet Labs missions.

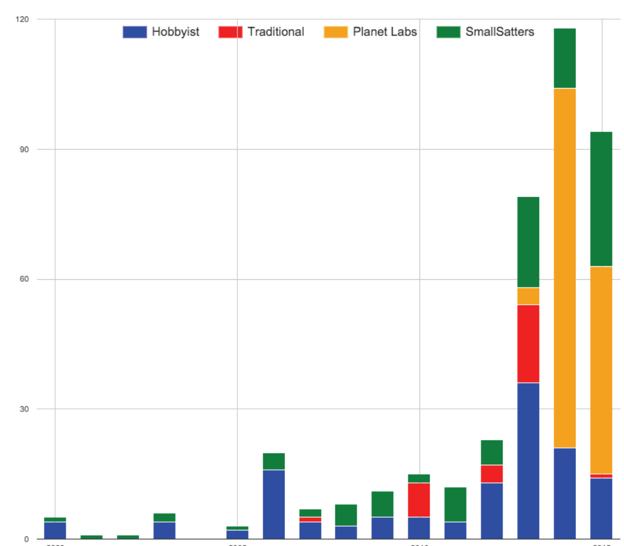

Figure 12. CubeSats By Developer Class, 2000-2015

As noted above, the mission success status of the Planet Labs Dove constellation is difficult to categorize, so we remove them from consideration. In Figures 13 and 14, we revisit earlier figures, looking only at CubeSats that were not Planet Labs. Finally, in Figures 15-17, we look at on-orbit success rates for the three remaining categories.

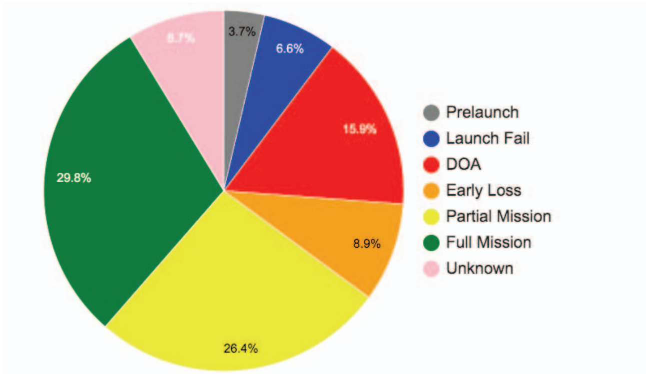

Figure 13. Mission Status for All CubeSats (Except Planet Labs), 2000-2015

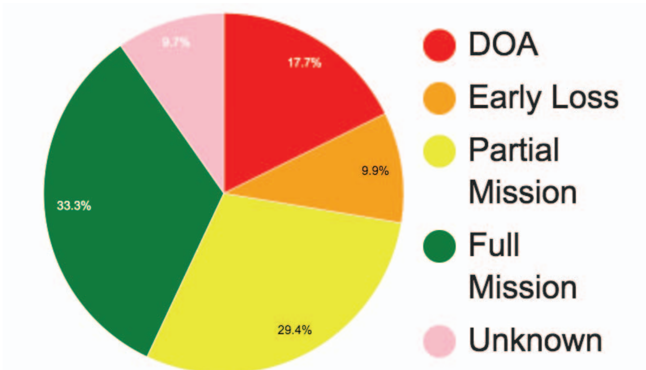

Figure 14. Mission Status for all non-Planet-Labs CubeSats That Reached Orbit, 2000-2015

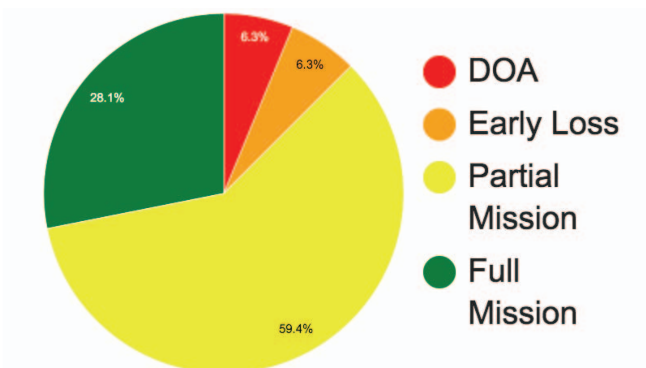

Figure 15. Mission Status for Traditionally-Built CubeSats, 2000-2015

As one would expect, Traditionalists have very high rates of mission success; these are the most expensive missions, after all. (Anecdotal evidence points to millions of dollars for a single CubeSat.) As one might also expect, hobbyists have extremely poor success rates (less than 40% of missions achieve even a subset of their objectives). And, because Hobbyists make up so many of the new CubeSats on orbit, their failure rates are over-represented in the aggregates (Figure 14).

SmallSat missions, again, fall in between the Traditionalists and the Hobbyists. SmallSat-class missions have an increased risk profile, but deliver at a lower cost than Traditionalists.

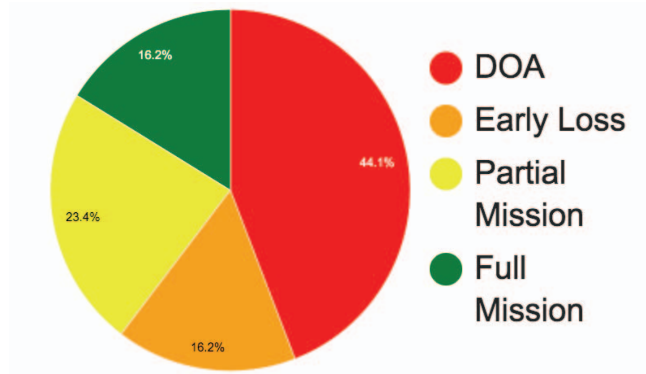

Figure 16. Mission Status for Hobbyist CubeSats, 2000-2015

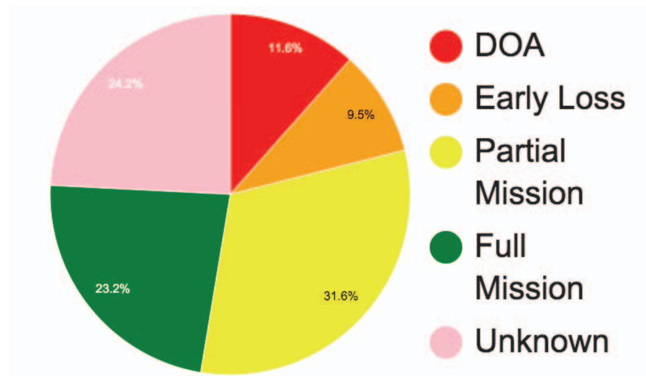

Figure 17. Mission Status for SmallSat-Built CubeSats, 2000-2015

3. Why Do They Fail?

Why, then, do secondary missions fail at higher rates than is expected for space missions? First, as has already been stated, the high failure rates and high numbers of Hobbyist-class missions have skewed perceptions of failure rates among secondaries. It is the author's opinion that the failure rates of SmallSat-type developers (20%) and Traditionalists (10%) are approaching the expectations of low-cost, rapid-turnaround missions. While there may be some opportunity to bring those failure rates down as more secondaries are flown and best-practices are developed for these types of missions, it is doubtful that these rates will change significantly.

Why do the Hobbyists fail so frequently, and what, if anything can be done about this? Comprehensive data on mission failures is lacking, and thus no one can provide a rigorously-defensible answer. Still, given the author's experience in the field and time spent compiling and studying this data, some educated guesses are possible.

In short, it is the author's opinion that Hobbyists fail in significant numbers because they underestimate the complexity of even a "simple" spacecraft, which causes significant schedule slips during development, and thus inadequate resources are set aside for environmental and functional testing.

In a closely related issue, critical best-practices for design, assembly, integration and test are known to the SmallSat and Traditional developers, but are either unknown to Hobbyists or ignored by them. The most direct example of this situation was the ORS-3 mission flown in 2013. There were 28 secondaries on that flight, 13 of which were Hobbyists, and 15 Traditionalists. Almost all of the Hobbyists failed (11 of 13), while almost all of the Traditionalists succeeded (14 of 15). It is important to note that all payloads on the mission were required to pass the same vibration acceptance tests, perform the same thermal bakeout, and were subject to detailed mission readiness reviews by NASA and/or the DoD. Clearly, the Traditionalists were doing something that the Hobbyists were not – and whatever they were doing exceeded the restrictions/requirements for acceptance testing!

The best hope for improving the performance of Hobbyists is to have them implement best-practices in design, assembly and test that the other developers utilize. However, in doing so, we would convert Hobbyists to SmallSat developers. As long as there are new teams of CubeSat developers, there will be high failure rates among CubeSats.

4. PREDICTIONS

It is easy to look at the manifest for 2010-2015 and predict that CubeSats will dominate the secondaries for at least the near future. As noted above, the largest number of non-CubeSat secondaries launched in a given year was 30, which happened in 2014 – but there were 80 CubeSats launched in that year. However, there are five factors to keep in mind:

(1) As noted above, the launch rates for missions above 10 kg have been quite consistent for a decade (Figure 2), on the order of 15-20 per year (and 30 in 2013). It is only by comparison to CubeSats that they seem to be shrinking. There is every reason to believe that these opportunities will continue to be available.
(2) Some missions require more aperture for optics/antennas than is available on a CubeSat, and thus there will be a need for larger secondaries. The 6U dispenser was first used in 2014; as it finds more launches in 2015, it will be interesting to see whether it provides sufficient size/mass for such missions. We expect to see a migration of the professional missions away from the 3U size to the 6U size.
(3) With large numbers of CubeSats launched each year, large datasets are now available to assess mission utility and mission success. (Arguably, over the past three years, the CubeSat database is larger than any other spacecraft class.) And, if anything, the failure rates have become worse in the past two years (owing to so many new university programs). Are 60% success rates acceptable to NASA, ESA, JAXA, etc?
(4) Will JSPOC, the FCC/IARU and NOAA continue to accept record-numbers of missions to track and license? Thus far, the agencies have all cooperated, but we do not assume that these programs will continue to accept the strain on their systems indefinitely.
(5) If/when the ESPA platform becomes standard on US EELV flights, we may see an increase in the 100+ kg class missions. But we're still waiting.

For missions originating in the US, we recommend that the CubeSat platform be given serious consideration (including the 6U dispenser). The sheer number of available launches is worth the tradeoff in mission performance; missions can be performed at a fraction of the cost and in greatly reduced time. A descoped mission that fits the P-POD dispenser has a much greater chance of timely success than a larger system.

For missions originating outside the US, the CubeSat dispenser does not provide such dramatic benefits over other form factors. For now, the US CubeSat launch market (and its large supply of available launchers) is unavailable to international payload developers. ESA created the "Fly Your Satellite" program to nurture the development of university payloads, but this opportunity is limited to a half-dozen schools in the first year. Moreover, as demonstrated by the many Russian and Indian launches, there is ready capacity for spacecraft larger than CubeSats. Thus, for international missions, the sacrifice in mission performance by cramming the mission into a 6U will not be offset by a significant increase in flight availability.

5. CONCLUSIONS

Historically, secondaries were a small fraction of the total number of payloads manifested (about 7.5%). However, they have been launched in steady numbers worldwide, and those numbers are poised to increase in the coming years; in 2013, for the first time ever, more than half the missions launched were secondaries, and that continued in 2014. Whether the manifests for 2015 have such a skewed percentage, we can confidently attest that in both absolute numbers and in terms of "market share", more secondaries will fly than have ever before. Some of the credit goes to more international flight opportunities for larger secondary payload missions, but the bulk of the new manifests will go to CubeSat-class spacecraft.

Making Sense of All Those Numbers

What are the implications? First, it appears that Russian launch vehicle companies have made a business case for "prime-less" launches, where dozens of spacecraft are lofted on the same launch vehicle, but none have the rights of the primary payload. After the December 2013 Dnepr launch of more than 30 missions, we wondered whether that would be one-time event or the new normal. Well, the Dnepr set a new record for co-manifested missions in 2014 with 38.

There has been some lamentations over the fact that these 2014 missions do not comply with the 25-year de-orbit rule, but we think that single Dneprs with dozens of missions is the new normal in Russia.

On the other hand, even though the DoD put 28 CubeSats on the 2013 ORS-3 flight, 2014 DoD missions have flown smaller co-manifests (on the order of 8-10). We believe that this is the new normal for American secondaries. And, despite the momentary technical challenges for NanoRacks, the ISS is poised to become a significant launch platform. In addition to NanoRacks ejector and the Japanese Experiment Module (JEM) Small Satellite Orbital Deployer (J-SSOD), NASA has joined the fray with its own ISS ejection system, the Space Station Integrated Kinetic Launcher for Orbital Payload Systems (SSIKLOPS). That deployer is capable of releasing larger, non-containerized spacecraft into orbit.

There can be no disputing that CubeSats have significantly changed the secondary launch market. Now, in the past 18 months, multiple agencies have started using the ISS as a low-cost, streamlined launch platform. With the demonstrated ability to release 20-30 CubeSat-class spacecraft per month, the ISS system could lead to a second phase of CubeSats. If someone were to develop an ISS-friendly propulsion system capable of raising a CubeSat-class spacecraft to 500-1000 km (or beyond), a new set of low-cost, short-turnaround science and technology missions become available.

But, in our opinion, there are limits to the optimism. In the US, the CubeSat revolution has been driven by the "free launches" given out by NASA and the DoD. If those free launches were taken away, it's not clear how many of these missions would fly. Certainly, at the very least, the number of participating universities would be greatly diminished; few of us could afford to pay the $125,000 sticker price for a CubeSat launch [12].

Although the new Venture-Class awards have been announced, promising the advent of a CubeSat-class dedicated launcher, this author remains skeptical. Rockets are extraordinarily difficult to make work, and the market for CubeSats is largely driven by Hobbyists, who could not afford $1 million for a launch.

Future Work

We are still open to a revision to our original definition of secondaries. It would be beneficial to look at the Soviet Strela program (with its 600 orbital vehicles). Despite the fact that Strelas launched in groups of six on the same rocket (with no other payloads present), they might fit a modified definition of secondary payload. (In which case the Soviets were the dominant secondary payload provider/customer for the first 40 years of spaceflight.)

There are other logistic challenges to this database. NORAD has catalogued more than 40,000 distinct manmade objects in orbit since 1957. We relied on NORAD/SpaceTrak definitions to determine which of those 40,000 objects were spacecraft (as opposed to fragmentary debris and rocket bodies). It is entirely possible that secondaries were counted among the debris (or left on rocket bodies). Similarly, given the classified nature of the majority of the US secondaries in the 1960s, it is very difficult to acquire data on those systems.

The task of classifying each secondary payload according to its civil, commercial, government or university nature proved to be much more difficult than anticipated; the sheer number of secondaries, the challenge of acquiring secondary payload data from the first 20 years of space flight, and the other issues with the database meant that the work is not ready completed. We believe that this topic is worth continued study. For example, the aftereffects of the mega-launches of 2013 and 2014 will be worth reviewing.

Finally, this paper provides the first detailed look at mission success and failure across all known secondary spacecraft flown since 2000. However, the conclusions and predictions are largely anecdotal. In order to better identify the root causes for mission failure, and thus solutions, we need more comprehensive information from mission developers, especially data around issues leading to the loss of missions.

6. Acknowledgements

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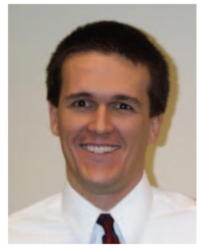
BIOGRAPHY



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