Secondary Spacecraft in 2015: Analyzing Success and Failure

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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.**

We review the census data (mass, lifetime, mission category, contributing organizations). examining trends and identifying deviations from (or confirmations of) previous predictions. For 2015, we introduce mission success metrics. We have assessed every secondary mission on a granulated scale of success, including milestones such as launch, ejection, first contact, commissioning and primary mission success.

With this new data, several factors stand out: as expected, university-class missions have a much lower rates of mission success, with as high as 40% of missions failing to achieve all the primary objectives, compared to 20% of professional missions. However, there is good news: the very high failure rate can be explained by the fact that so many of these schools are flying their first-ever spacecraft; success rates increase significantly for follow-on missions.

In this paper, we will address three questions:

1) Are there any lessons that new programs can glean from this high-level study of success and failure? (Answer: Yes! First, it is important to persist to that second launch. Second, certain types of missions and performance objectives lend themselves to increased success.)

2) Are there new trends emerging in terms of the organizations and missions participating in CubeSats? (Answer: NASA, the DoD and universities are all greatly increasing participation. And we think this will all change again in 2015.)

3) Is there a response/change in the rest of the secondary payload market? Are those missions continuing in the same numbers? Are there changes in the kinds of missions pursued among the "larger" secondaries? (Answer: we still don't know. The market is very fluid.)

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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. Even with new systems such as the SpaceX Falcon 9 promising to reduce those costs by a factor of 2-3, it is extremely expensive to put hardware in space. And, at the same time, almost every launch vehicle lifts off with extra capacity – tens to hundreds of kilograms.

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.

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 U.S. military missions. In 1981, commercial secondary opportunities became common with the advent of the Ariane ASAP platform; the second flight attempt of the Ariane-1 launch vehicle carried the AMSAT Phase-3A spacecraft. Since that time, there have been hundreds of secondary payloads. The rate of secondary payloads has increased drastically in the last three years, due to the widespread adoption of CubeSat-class launch adapters [1-4].

We have discussed secondaries in each of the four previous conferences: four years ago, 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 the CubeSat-scale and ESPA-scale categories. Two years ago, 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 P-POD); and that the sharp increase in the number of CubeSat flights represented a significant change in the nature of secondaries. Last year, 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]. Last year, we further discussed the shift to having large numbers of secondaries on the same launch, and the regulatory / mission success implications [4].

Better Data, Better Papers

Why, then, are we submitting a fifth paper? Because, before 2013, there had not been more than 40 secondaries launched in any given year. And then 104 secondaries were launched in 2013, and 112 were launched in just the first three quarters of 2014. In fact, in 2014, the total number of secondary payloads exceeds the total number of primary payloads for the first time, ever.

In short, there is so much new data each year that 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.

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 2000-2014. 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. With this new data, we will further refine our forecasts of the launches available for various mission categories in the next few years. Particular attention will be paid to CubeSats, the largest and fastest-growing category of secondaries.

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 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 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 2014. Spacecraft information was collected from several online databases [5-9], double-checked against the Ascend SpaceTrack database, and assembled into one master list of the more than 7500 spacecraft launched through the end of 2014. 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 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, and the Dove constellation is arguably a single mission spread over dozens of spacecraft launched over a period of years. The implications of these taxonomy-busting examples will be further discussed, below.

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 we had 2013 and 2014. Typically, this is the point in the paper where we speculate that this is an outlier year, and that the number of secondaries will drop for the next few years. We will not write that sentence this year.

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 2014 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. As shown in Figure 2, the manifests of 2013 and 2014 are each dominated by three launches. 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. 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!

It must be noted that Figure 2 does not include the 52 spacecraft ejected from the ISS in the past three years. We are unsure of how to categorize these launches; one could argue that the NanoRacks/J-SSOD ejector carries 28 payloads at once. One could also argue that, since the payloads are ejected over a period of days or weeks, they are separate "launches".

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 30 per year for the near future. This is not a bold prediction: the Qb50 launch (1 rocket, 50+ spacecraft) is set for 2015.

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 United States government have embraced the CubeSat standard.

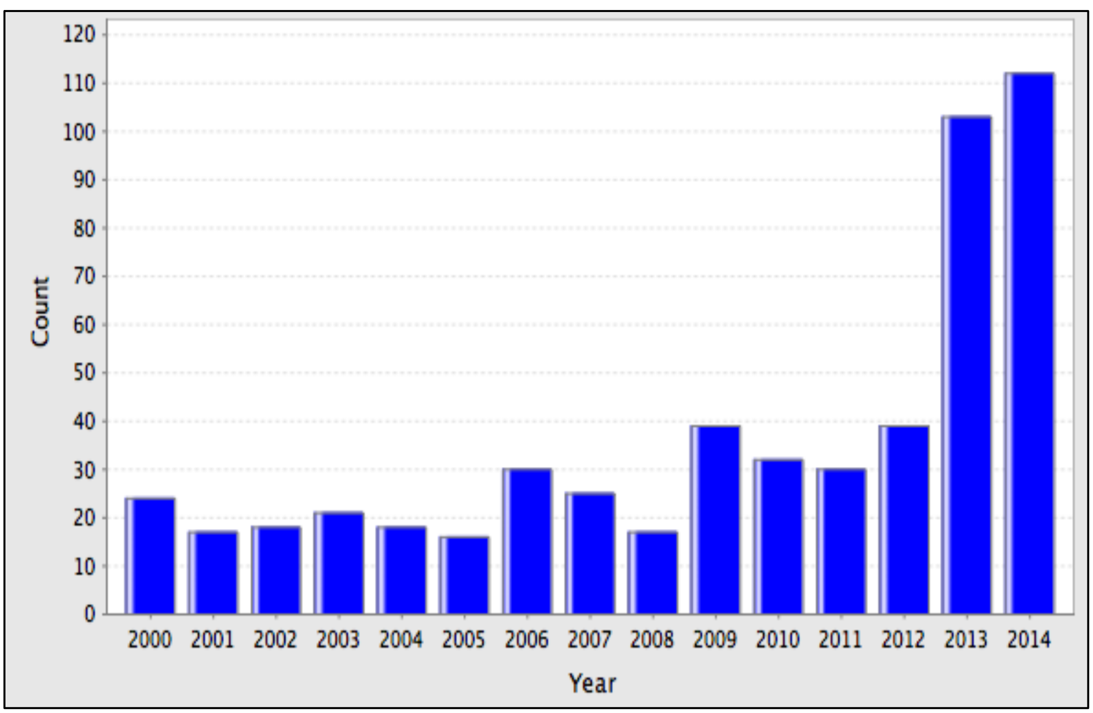

Figure 1. Secondary Missions Launched Per Year, 2000-2014

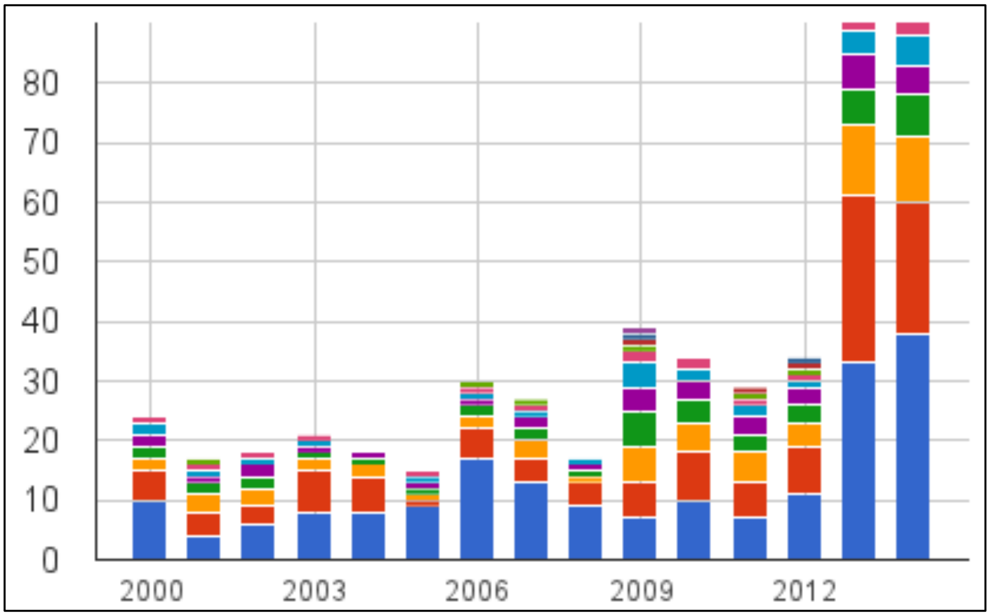

Figure 2. Number of Secondary Missions on Each Launch, 2000-2014. Each launch is color-coded, with the largest launch of the year at the bottom in blue, the second-largest launch atop it in red, etc. ISS ejections are not included.

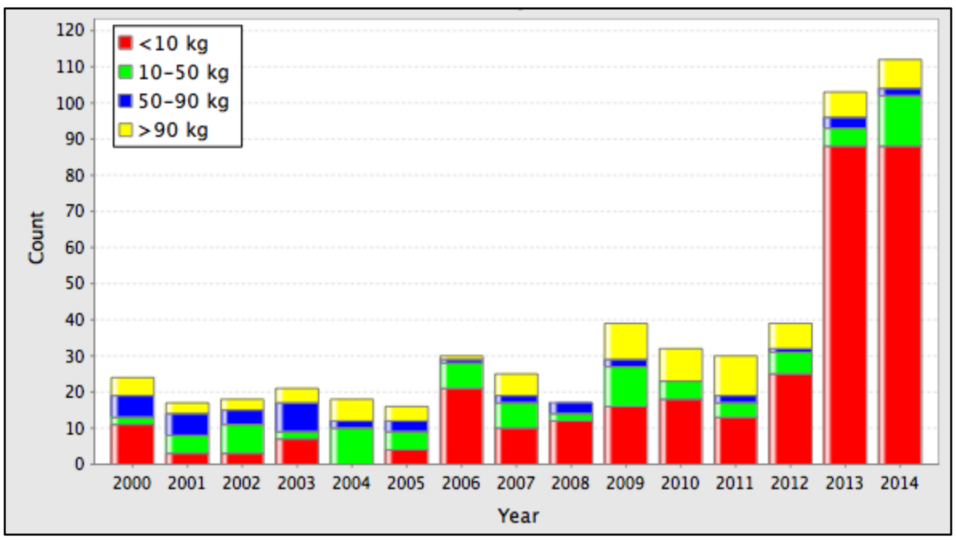

Figure 3. Secondary Missions by Launch Mass, 2000-2014

CubeSats

As shown in Figure 3, 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, with the first true CubeSats were launched in 2003). As shown in Figure 4, 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. 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 3, 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. 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 for five years, so we are not holding our breath.)

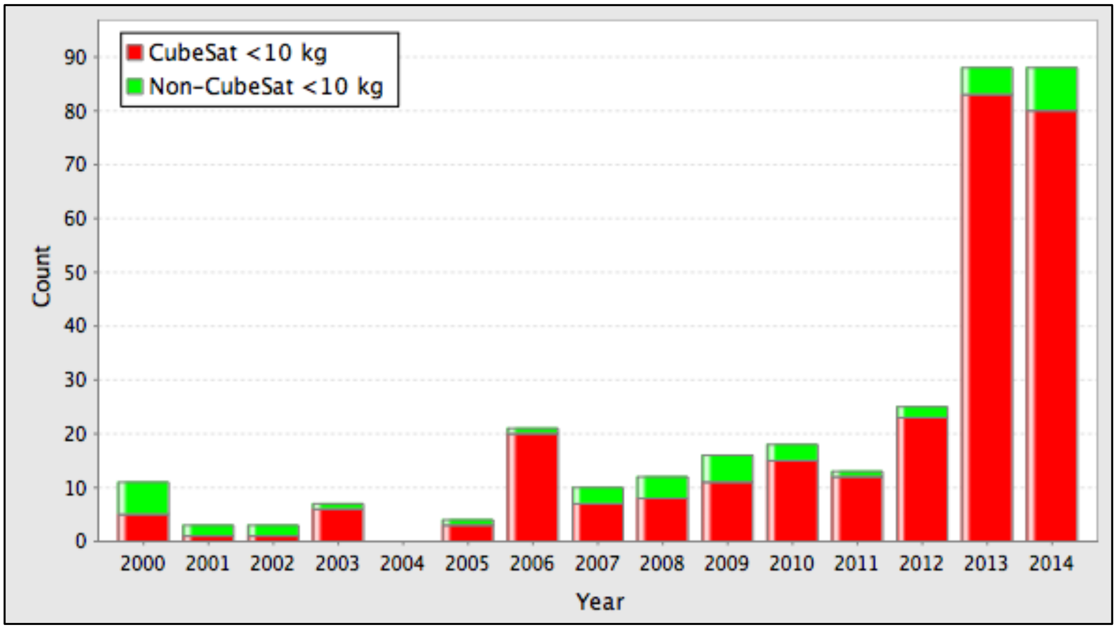

Figure 4. Number of Spacecraft Under 10 kg by Category, 2000-2014

National and International Trends

Using our database, we have also categorized secondaries by the launch provider (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. But, as shown in Figure 6, the customers served by those nations are quite different. The US, Japan, Europe and China serve mainly their own nations, while India and Russia are open for business. As noted above, India and especially Russia have shown a willingness to 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 ITAR (now EAR) restrictions 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 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 commercial market. What market there is for commercial secondaries is going to Russia, apparently.

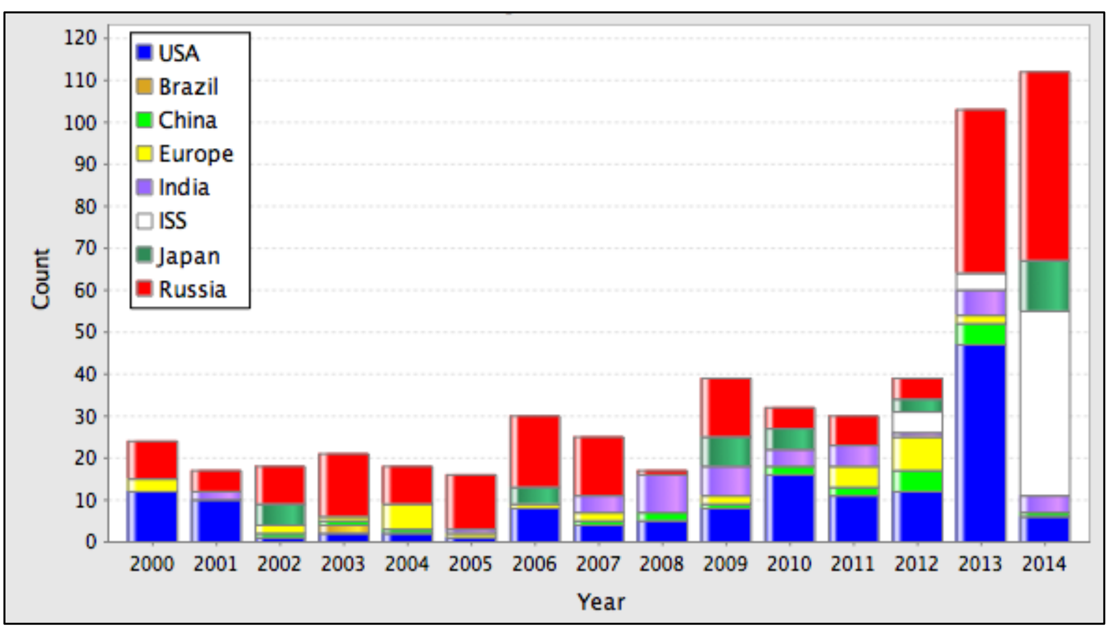

Figure 5. Missions Manifested per Year According to the Nationality of the Launch Provider, 2000-2014

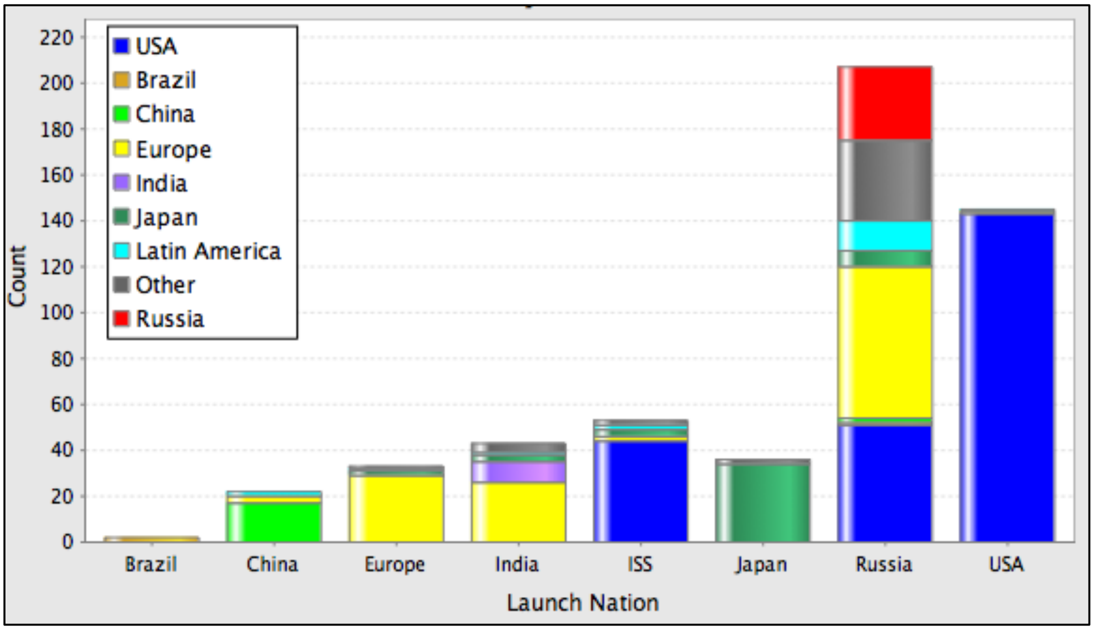

Figure 6. Nationality of Secondary Missions, Categorized by Nationality of Launch Provider

The United States was the leading developer of secondary missions from the early '60s through the mid-'90s, when Europe overtook them. As shown in Figure 7, the US is leading again. Qb50 notwithstanding, 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 Educational Launch of Nanosatellites (ELaNa) program, and PlanetLabs 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 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.

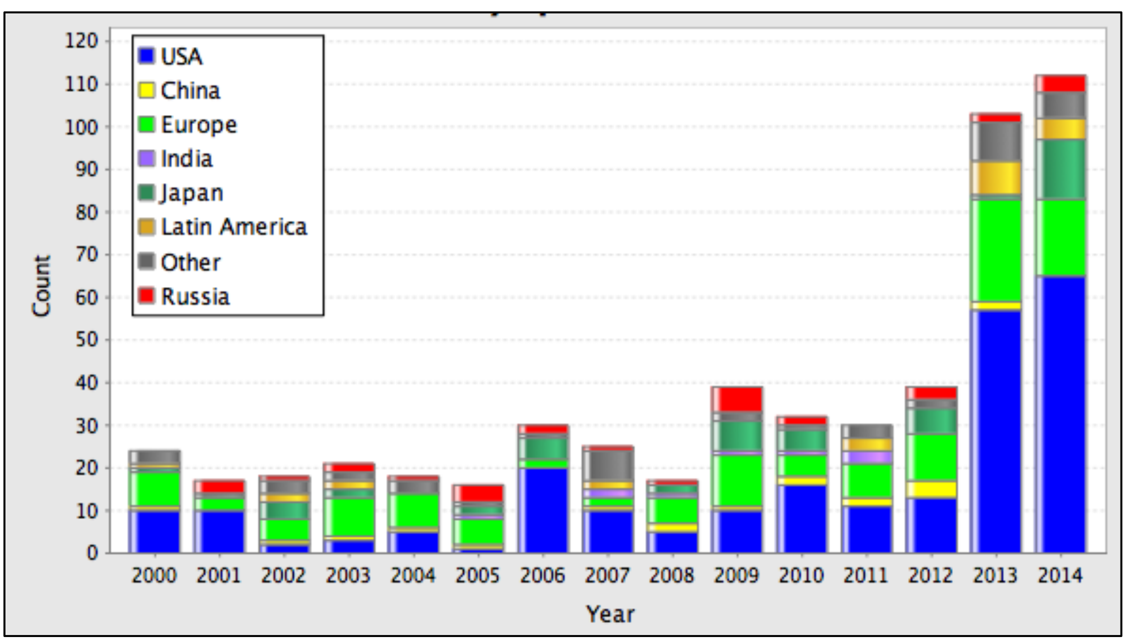

Figure 7. Secondaries by Spacecraft Nation, 2000-2014

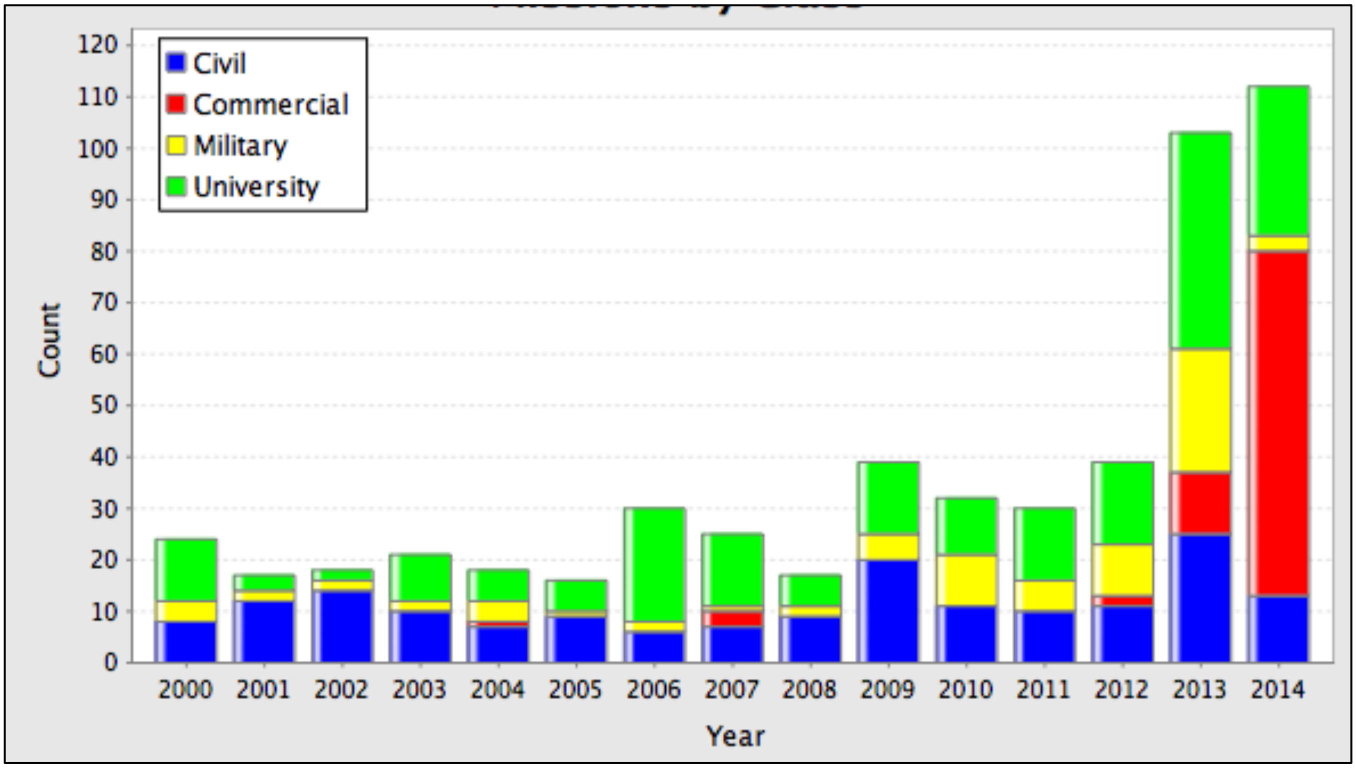

Figure 8. Secondary Payload Mission by Type of Spacecraft Developer, 2000-2014

We have also designated each missions as military, civil government, commercial or university (Figure 8). University-class missions indicate that the spacecraft was designed, built and operated by students, with student training elevated to one of the most important aspects of the mission. As discussed in prior papers, the first 20 years of secondaries were dominated by US military missions. Civil space missions became the dominant class of mission from 1980 until the early 1990s, when university-class missions began being manifested in large numbers. The spike in University-class missions in 2013 is due in large part to the NASA ELaNa program. The spike in commercial missions in 2014 is almost entirely due to Planet Labs' Dove constellation of 49 CubeSats (and counting). We expect that trend to continue, however, we do anticipate to see larger numbers of military secondaries in 2015, mainly CubeSats.

We have categorized each secondary payload by the class of its primary mission, typically communications (including Automatic Identification System – AIS), science measurements, or a technology demonstration. As shown in Figure 9, some missions don't fit into these three categories: "other commercial" includes missions such as the Celestis capsules carrying ashes into orbit; "other military" includes ELINT and similar functions, and "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.

Mission Success

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 2000-2014, and assigned each mission a status corresponding to the major milestones in a mission's operation.

- 0 (**Prelaunch**). The mission has been manifested, but has not launched.
- 1 (**Launched**). The mission has launched. Missions lost to launch failure will have Mission Status 1.
- 2 (**Ejected**). The secondary has been confirmed as ejected from the rocket. Missions that are ejected, but never contacted, remain at status 2.
- 3 (**Commissioning**). Two-way communication has been established, and the spacecraft is being commissioned for operations.
- 4 (**Initial operations**). The spacecraft has commenced primary mission operations.
- 5 (**Mission success**). Minimum mission success criteria have been achieved.

Where mission success criteria have been available, we have checked the mission status against these criteria. 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 10, of the 353 secondaries to have launched between January 1, 2000 and the writing of this paper (October 2014), 10% were lost to launch failures, and

23% were either never contacted or were lost soon after commissioning began. Only 67% of secondaries launched have commenced primary operations, and only 45% can be confirmed to have achieved mission success. Some of the 18% that began primary operations but have not been declared a success, 14 missions (4%) have been launched in the last two years, and can be assumed to be still working towards mission success. Another 5% are unknown, and thus might fit in the success category.

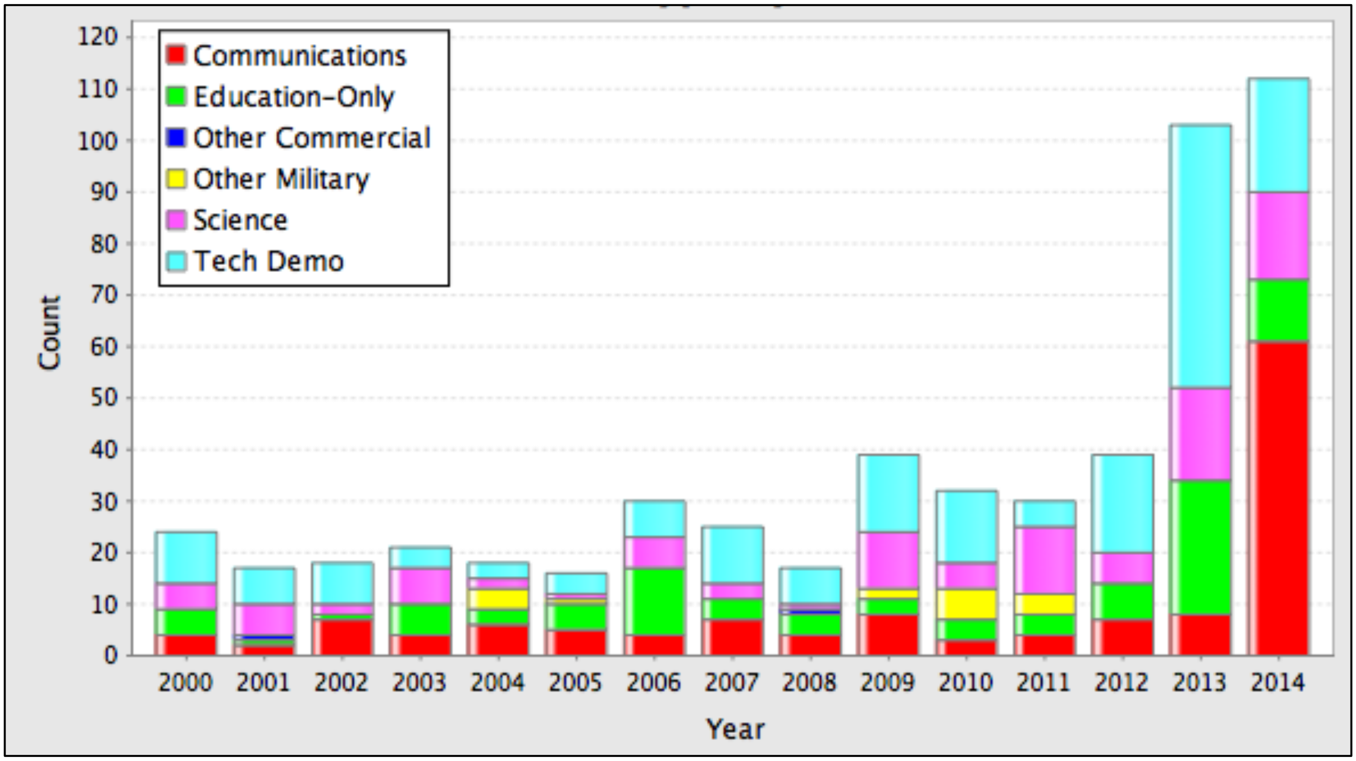

Figure 9. Mission Class of Secondary Missions, 2000-2014

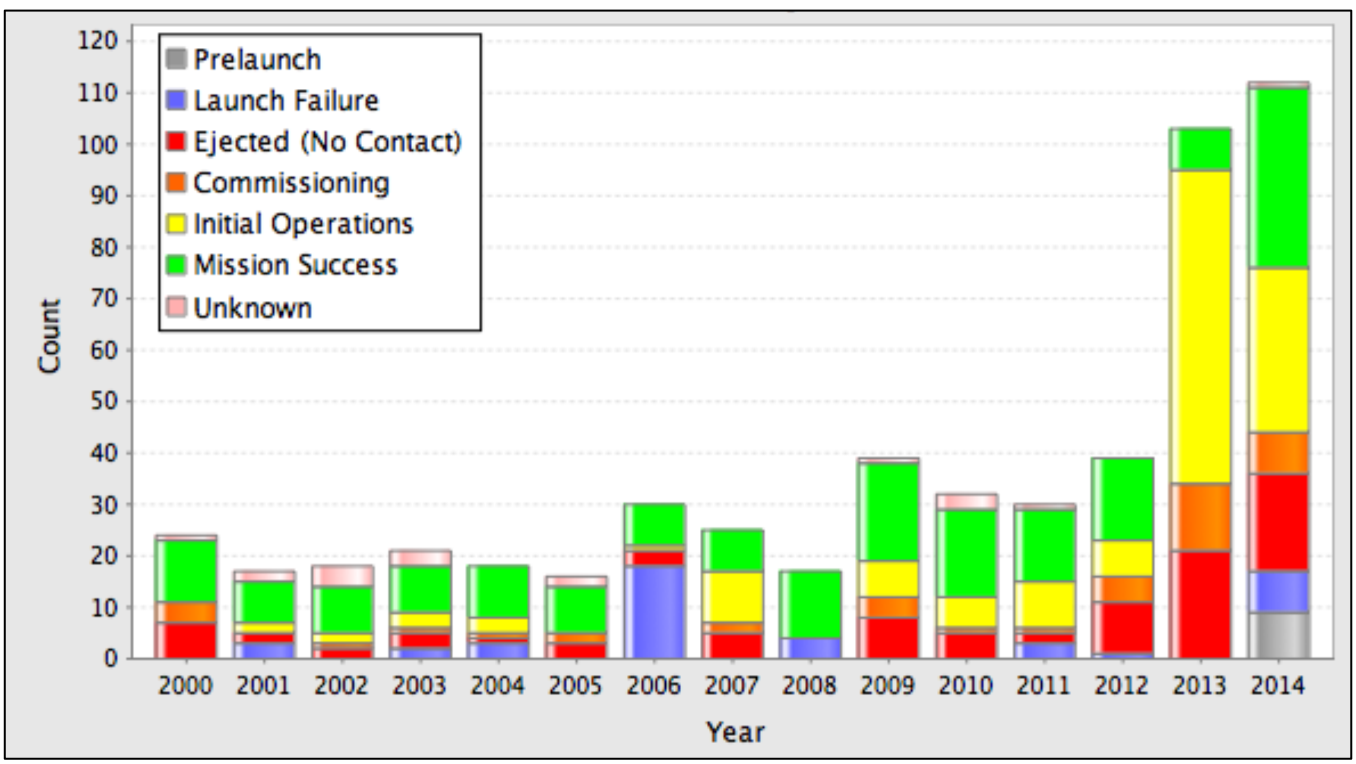

Figure 10. Level of Mission Success of Secondary Missions by Year, 2000-2014

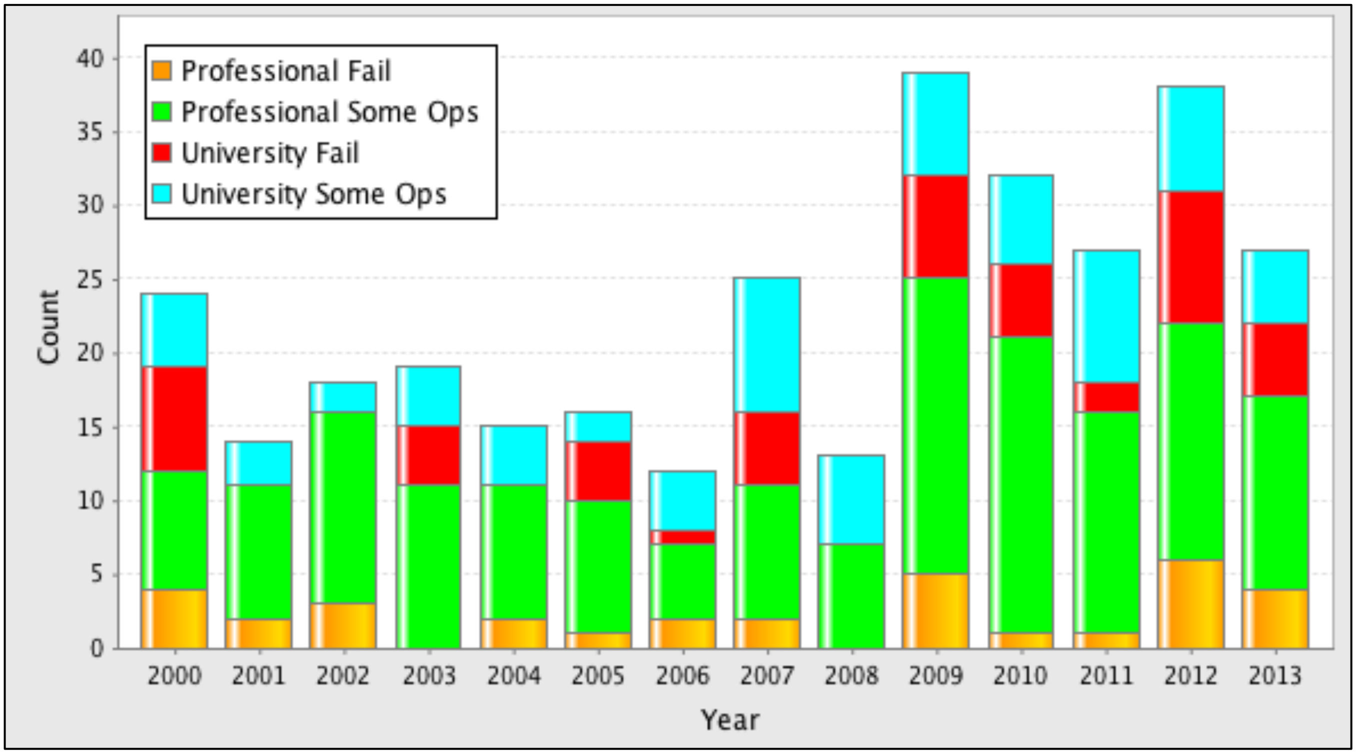

Figure 11: Mission Success by Type of Spacecraft Developer, 2000-2014

Why do so many secondary missions fall short of mission success? Well, bluntly, those failure numbers are amplified by universities (Figure 11). Of the 319 secondaries to reach orbit from 2000-2014, 197 were professional missions, and 122 were from universities. (As an aside, note that more than 60% of recent secondaries are from government agencies, contractors and private organizations. The increase in secondaries cannot be attributed to universities alone.) Worldwide, professionally-led secondary missions achieve some or all of their mission objectives 83% of the time. When looking at that number, one should note that many of the failed missions were high-risk/high-reward flights of opportunity (e.g., solar sail demonstrators). By contrast, university-led missions have a success rate of 60%. A very large proportion of these failures are during initial separation and checkout, indicative of errors in assembly and test (e.g., correctable errors). This 40% failure rate is consistent over the past 15 years, which could indicate that universities are not getting better.

However, one must take into account the fact that most of the failed missions are from programs launching their first-ever spacecraft. As shown in Figure 12, universities launching a mission for the first time achieve even partial mission success less than half the time. However, among universities that launch a second spacecraft, that success rate improves significantly (Figure 13). The fraction of missions that are never contacted on-orbit is cut in half, and the fraction of missions in primary operations is increased by the offset.

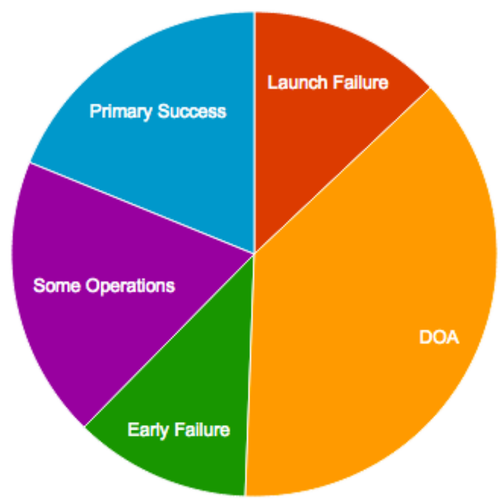

Figure 12. Success Rates of First Launches by Universities (2000-2014)

Why do programs do so well with their second launch? From personal experience on several university missions, and anecdotal evidence collected from other missions, we believe that university spacecraft developers dramatically underestimate the time required to perform assembly, integration and test. Therefore, they dramatically under-budget and under-schedule for these development steps, with predictable results. The second time, these developers intentionally budget for assembly, integration and test.

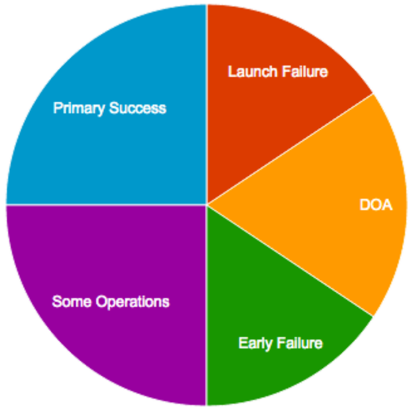

Figure 13. Success Rates of Second Launches by Universities, 2000-2014

3. PREDICTIONS

It is easy to look at the manifest for 2010-2014 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 3), 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.

Orbit Debris

With the sharp increase in CubeSat launches (and secondaries in general), the contribution of CubeSats to the orbital debris problem has received scrutiny [11]. In the author's opinion, this concern is overblown. Using the same databases for compiling the other analyses, we have divided low-Earth orbit into three regions: ISS (orbits that pass through the 200-500 km altitude range), mid-LEO (orbits that pass through the 500-700 km range), and high-LEO (orbits that pass through the 700-900 km range). Since highly-elliptical orbits (such as GTO) might pass through all three regions, some spacecraft will pose a collision risk to more than one region.

As shown in Table 1, the number of secondary spacecraft launched since 2000 make up a very small fraction of the total number of objects in orbit. Secondaries are only 4% of the objects in orbits that might affect the ISS, and spacecraft in this region will deorbit within months to a few years.

Table 1. Total Number of Objects and Total Number of Secondary Spacecraft Passing through Three LEO Regions

Orbit Region	All Objects	Secondaries	Percentage
ISS Altitudes (200-500 km)	1400	56	4.0%
mid-LEO (500-700 km)	3300	223	6.8%
high-LEO (700-900 km)	6100	57	0.9%

Similarly, in the highest region of LEO (above 700 km), there are only a few dozen secondaries, less than 1% of the total number of objects. Secondaries are a noteworthy fraction (7%) of the objects in the middle region (500 – 700 km). Still, even there, the secondary spacecraft are outnumbered more than 5-to-1 by fragmentation debris.

Fragmentation is the true on-orbit threat, not a dozen more CubeSats. When larger spacecraft break up or collide, they create debris fields larger in number (and size) than all the CubeSats ever launched. When Iridium-33 and Cosmos-

2251 collided, they created about 1,000 pieces of CubeSat-sized debris – which is about 6 times as many pieces as there are CubeSats in orbit. When China performed an ABM demo on its own Fengyun-1C spacecraft, at least 2,400 CubeSat-sized chunks were created – or about 15 times as many debris pieces as there are CubeSats in orbit.

Without diminishing the importance of expecting all spacecraft (including CubeSats) to observe the 25-year deorbit rule, it must be stated that, even in aggregate, secondary spacecraft pose an order-of-magnitude less risk to on-orbit collisions than do the existing fragmentation debris already on-orbit. We applaud the efforts by NASA and the Air Force to place all secondaries (including and especially CubeSats) into naturally-decaying orbits with lifetimes well under 25 years. Such actions help ensure that secondaries continue to pose a lesser risk to on-orbit collision.

4. 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 J-SSOD, NASA has joined the fray with its own ISS ejection system, 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].

Launchers and Debris

For that reason, we are skeptical of the calls for a dedicated launcher for spacecraft of this size. CubeSats work very well as secondaries, allowing the prime to shoulder the bulk of the launch and integration costs. Without the prime to pay the bills (or at least without NASA and/or the Air Force to pay the bills), how many CubeSats will fly?

Our skepticism also extends to the "threat" posed by the large numbers of CubeSats being placed on orbit. The large number of CubeSats is dwarfed by the extremely large number of extant pieces of fragmentation debris and old spacecraft. CubeSats should be placed in naturally-decaying orbits to ensure that they continue to pose lesser risk. But their risk is comparatively small to begin with.

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 U.S. 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. Finally, the aftereffects of the mega-launches of 2013 and 2014 will be worth reviewing.

5. ACKNOWLEDGEMENTS

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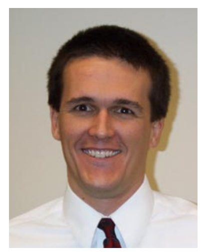
BIOGRAPHY



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