The Right Rocket for the Job: Small Launch Providers Target Small Satellites

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by

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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Peter Norton, Department of Engineering and Society

The University of Virginia Department of Mechanical and Aerospace Engineering has its first satellite, *Libertas,* now in orbit and plans to launch two more within the next three years. This sudden activity is representative of the vastly increased smallsat[1] launch cadence by a variety of groups around the world. The trend is facilitated by the reduced cost and relative ease of assembly conferred by CubeSats, which collectively make up 70 percent of satellites launched today (Halt & Wieger, 2019). Startups, underdeveloped countries, and universities that, just ten years ago, would have been incapable of any kind of space mission are now launching several. From 2012 to 2019, 663 CubeSats were manufactured by private companies, nearly 300 by governments or militaries, and 371 by academic institutions. Yearly satellite launches have increased six-fold in this time (Halt & Wieger, 2019; fig. 1). This marked increase in customers underscores a sociotechnical problem in the rocketry industry: most rockets are fairly large and cater primarily to large satellites, leaving behind a large number of customers in the smallsat domain.

Satellites broadly fall within four categories of use: remote sensing, communication, technology demonstration, and scientific investigation. Miniaturization of electronics has made smallsats for all these uses possible. Compared with conventional satellites, smallsats tend to have shorter development cycles and smaller development teams, incurring lower costs (Lal et al., 2017). Lower-cost satellites can be quickly replaced or deployed in large numbers, providing an opportunity for higher risk missions and experimentation, leading to innovation.

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[1] It is important not to confuse "smallsats" with "Small satellites." While the Federal Aviation Administration Office of Commercial Space Transportation (abbreviated AST) defines a Small spacecraft as having a mass between 601 and 1200 kg, it uses the term "smallsat" as an umbrella term for the five smallest mass classes, all under 600 kg (FAA, 2018).

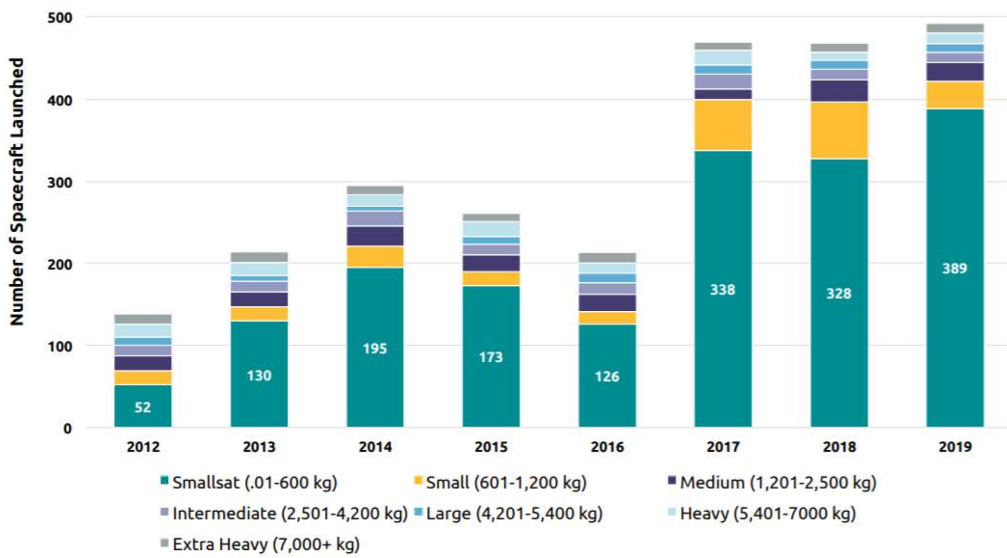

Figure 1. Smallsat Growth in the Context of All Spacecraft (Halt & Wieger, 2019)

One step beyond the innovations of smallsats are CubeSats. These satellites have masses less than 1.3 kilograms and fit within a standardized form factor of 10 cubic centimeters (California Polytechnic State University, 2014). These cubes can also be stacked together modularly, for larger satellites as the mission requires.[2] This standardization allows companies to mass produce CubeSat parts, meaning all the components of a functioning satellite can easily be purchased commercially on a 5-figure budget (National Academies of Science, 2016). As they did for other disruptive innovations, many experts in the field initially dismissed CubeSats as novelties with no real use beyond college student education (Lal et al., 2017), but the platform has advanced to the point that CubeSats are now an essential part of our space infrastructure, enabling everything from global communications to geophysical research.

[2] Such as for another planned UVA spacecraft, Global Nitrogen Oxide Measuring Experiment (GNOME), which consists of three standard CubeSat Units, currently on track for launch in 2022.

The University of Virginia (UVA) began offering Spacecraft Design as an alternative to Aircraft Design in fall 2011. Professor Christopher Goyne advocated for this addition to the curriculum because he “saw how rapidly the space industry was developing and wanted students to be fully prepared to work in the field.” Originally the class was more theoretical. In November 2014, Congress removed CubeSats from the U.S. munitions list, and thus they were no longer restricted by International Trade in Arms Regulations. This change made offering hands-on experience in satellite construction infinitely easier for UVA and universities across the country because, as Professor Goyne explains: “now you can work on the project without worrying about the citizenship of your students. We can’t limit registration just to U.S. citizens.” These student projects are more than educational projects. Data from one such project from MIT, MicroMAS-2a, was recently compared to that of a NOAA spacecraft. Angela Crews, the lead author of the comparison study, said: “The bottom line is that this tiny satellite collected data that is as good as the data from a billion-dollar government satellite” (Ranalli, 2018).

Review of Research

The Intelligence Defense Agency Science and Technology Policy Institute (STPI) conducted an extensive investigation to characterize the smallsat ecosystem as it existed in early 2017, culminating in a database of 650 actor organizations. While there are far too many to enumerate here, STPI separates the actors into three broad categories. Upstream organizations include material suppliers, part manufacturers, and spacecraft development teams. Midstream organizations are the launch providers and satellite operators. Teams of satellite operators are responsible for receiving and processing the data, so that it can be sold to downstream consumers, usually governments[3] and corporations (Lal et al., 2017). Clearly, the smallsat value chain has huge economic impacts in both the public and private sectors and past growth rates are expected to continue. The Northern Sky Research group forecasts 8,100 new small satellites to be launched before 2028 with a resultant $37 billion increase in cumulative revenue (Northern Sky Research, 2019).

The availability of timely and low-cost launch to orbit has historically been the biggest constraint upon the growth of the small satellite market (Sweeting, 2018). When smallsat development teams finish their project, they must purchase a ride on an orbital rocket. The three current leaders in the launch provider industry – the United Launch Alliance, Northrop-Grumman, and SpaceX – all require smallsats to fly as secondary payloads, limiting both opportunities to fly and control over the launch date or target orbit. The leading launch companies are seek to develop even larger rockets for emerging markets such as future Moon[4] and Mars missions, neglecting the opportunity to serve the high demand for small payload delivery. Far from short-sighted, these companies are looking only at the long-term, missing out on the near-term opportunity.

The Small-lift Space Race

Several start-ups have seized upon this mistake by the corporate giants. Rocket Lab, Firefly Aerospace, Vector Launch, and Relativity Space are among the companies attempting to fill this new niche by developing rockets which deliver only about 1,000 kg to low Earth orbit

[3] The United States Government is by far the largest consumer of satellite data, with the National Geospatial Intelligence Agency spending nearly $1 billion per year from 2010 to 2017 on commercial remote sensing data (Lal et al.).

[4] Although there has been a fair amount of research into profitable mission architectures for cislunar or lunar surface missions enabled by small-lift vehicles (Coogan, Scholtes, Markusic, & Runge, 2019).

(LEO) per launch. Of these, Rocket Lab is the only company with a vehicle actually on the market, having already launched 48 satellites from their launch complex in New Zealand (Rocket Lab, 2020). The company is now expanding to a second launch site in the United States (Rocket Lab, 2019). This investment is primarily motivated by the fact that the U.S. Department of Defense, the largest single customer in the spacecraft industry (Halt & Wieger, 2019), is far more comfortable with keeping their payloads on American soil, where secrecy is easier to maintain. The United States operates the vast majority of government and military spacecraft (fig. 2), making it a key customer for any prospective launch providers. For most U.S. government projects, reliability, schedule certainty, and secrecy are prioritized above cost, making them the ideal target customer for these start-ups. Firefly, Vector, and Relativity all claim they will be ready to begin operations by the end of 2020 (Machi, 2019). With a full three-year late start, these less-established companies will have to find some way to bring costs down to compete with Rocket Lab's Electron rocket.

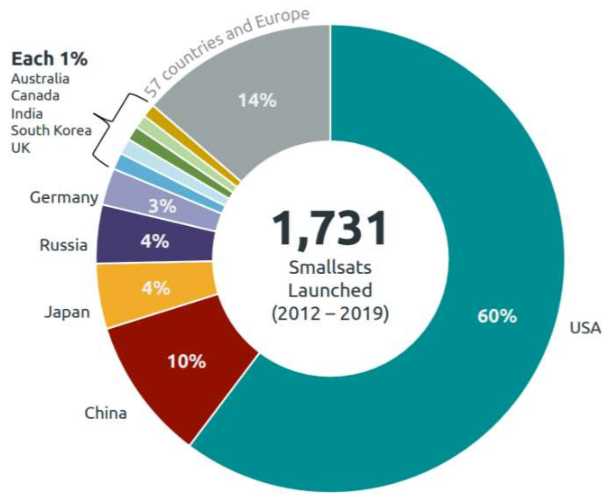

Figure 2. Government Smallsats by Operating Country (Halt & Wieger, 2019).

The U.S. National Reconnaissance Office (NRO), known for buying numerous launches for behemoth spy satellites, has recently been adjusting its approach to make better use of the growing role of small-lift launch vehicles. In April 2018, the agency issued a lucrative contract bid for "Rapid Acquisition of a Small Rocket." NRO typically requires a very precise orbit and a quick launch in order to surveil specific targets in the appropriate time frame. The then-director of NRO, Betty Sapp, told *Aerospace America*: "The dynamic nature of surveillance targets requires the NRO to keep on innovating at an even faster rate. Commercial space will be fully considered in the development of every future space system" (Risen, 2018).

One alternative approach for dedicated smallsat launch that has been attempted is to launch a small rocket from under the wing of an airplane at cruising altitude. The notion that the rocket benefits from the altitude and velocity already attained by the far more efficient plane is certainly an interesting one, but the concept has only been implemented in two projects to date: Orbital ATK's Pegasus XL and Stratolaunch. The Pegasus XL has launched 44 times, with 5 mission failures. Since the project's inception, there have been industry rumors that the logistical difficulty and extremely niche capability make the project very unprofitable. When Northrop-Grumman inherited the project through the acquisition of Orbital ATK in 2018, it published a statement proudly declaring "Pegasus has become the world's standard for affordable and reliable small launch vehicles" (Northrop-Grumman, 2018). The fact that there has not been a launch scheduled since that statement may be the true evidence of the project's impracticality. On a similar note, Stratolaunch built the largest airplane in history, with a wing span of 385 feet and a carrying capacity of 250 tons, for its air-launch program, only for the company to fold within a month of its first and only test flight (Grush, 2019). It is possible but unlikely that Virgin Orbit's LauncherOne will reverse this trend and prove the viability of the air-launch architecture with their planned test launch later this year (Foust, 2020).

As of 2015, heavy-lift rocket companies do have a tool to fight back for a share of the smallsat market (fig. 3): rideshares. Seeing the dramatic growth of the smallsat market, Spaceflight Industries was founded exclusively to serve as the middleman between individual smallsat operators and SpaceX, grouping together up to 80 spacecraft into one Integrated Payload Stack that can be easily packed onto the rocket as if it were one full-size satellite

(Spaceflight, 2018). This innovative compromise costs much less than being the only payload on a small-lift vehicle, so it addresses the issue of expense but suffers from a similar lack of control over the orbit and launch date. When asked by *Forbes* why small launchers are more desirable than rideshares, Robert Cleave of Vector Launch explained, “If too many of these constellations ride share [*sic*] they end up in these 50 degree inclinations. You get all this stuff in the same altitude and inclination as the space stations. We can avoid clogging these orbits and give people what they want, like maybe a zero-degree, equatorial orbit” (Autry, 2019). Furthermore, rideshares do not fit the privacy criteria necessary for national security payloads, and thus miss out on a valuable customer.

Figure 3, courtesy of Lal et al., demonstrates the price per kilogram to launch on several small and large rockets, air launch platforms, and the Spaceflight rideshare service. While some of the data is out-of-date, it is important to note the general trends: larger rockets are more efficient and thus can charge a more competitive fee, rideshares are a decent compromise from a price perspective, and air launch options such as Pegasus XL are disproportionately expensive when compared with the rest of the industry.

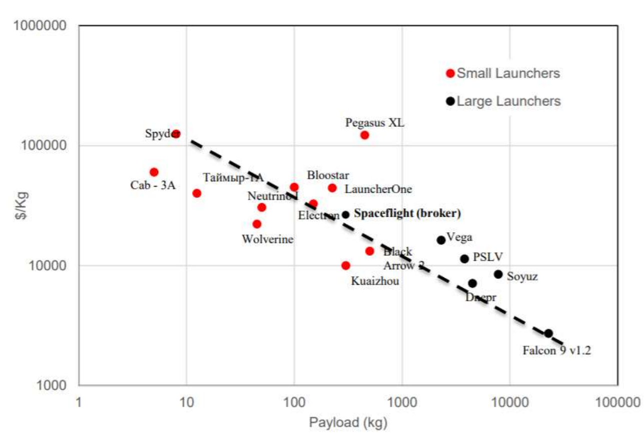

Figure 3. Price per Kilogram Launched vs. Maximum Lift Capacity of Various Launch Options (Lal et al., 2017).

Environmental Impact

While this proliferation of satellites in orbit around the Earth has generally positive impacts on the global economy and technological innovation, such growth may not only be unsustainable but perhaps dangerous. In February 2009, an inactive Russian communications satellite collided with an active commercial satellite operated by U.S.-based Iridium Satellite LLC over Siberia. This event was the first unintentional satellite collision in history and it produced nearly 23,000 pieces of debris larger than 10 centimeters in diameter that now further increase the collision risk in LEO (Weeden, 2020). Debris smaller than this also exist in great number, but are almost impossible to track. This class of orbital debris poses serious risk to more fragile elements such as solar panels. This cascading risk of collision with orbital debris is popularly known as Kessler syndrome, after NASA scientist Donald Kessler, who, in 1978, warned that it could eventually render all space travel from Earth impossible (Kessler & Cour-Palais, 1978). Most researchers and policy makers believe this apocalyptic scenario is no less than 15 years away (Lal et al., 2017), but nearly every qualified party agrees that the spacecraft industry needs to dramatically improve its capability to deorbit[5] spacecraft at the end of the mission as well as track and remove inert debris. Smallsat proliferation contributes to this problem not only in their great number, but also because most CubeSats lack the space for on-board propulsion necessary to deorbit or avoid collision.

The exact impact of rocket exhaust on atmospheric pollution is difficult to quantify and a proper investigation of this issue falls outside the scope of this paper. The most common elements in exhaust, listed in descending order of mass fraction, are carbon dioxide, water vapor, carbon soot, carbon monoxide, and oxides of nitrogen, chlorine, aluminum, and sulfur (Dodd,

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[5] An alternative notion is to push the satellite further away from the Earth into what is known as a "graveyard orbit."

2020). Different fuel and oxidizer pairs produce these in different proportions, with liquid hydrogen or methane burning much cleaner than the far more common choices of RP-1 or toxic hypergolics like hydrazine and red fuming nitric acid. These emissions are certainly problematic, especially considering how a rocket traverses many regions of the atmosphere throughout flight, and there is reportedly an effort to develop engines that pollute less, such as monopropellant engines that burn hydrogen peroxide and emit only water. By comparison, in 2018, the airline industry contributed over 40,000 times more greenhouse gasses than global rocket launches.

Technical Barriers to Profitability

While it may seem straightforward to simply scale existing rocket technology down to launch smallsats, there are a great deal of technical innovations left to make this industry just as profitable, if not more so, than the existing options. With smaller rockets, the ratio of vehicle structure to fuel is lower. Achieving high propulsive efficiency is essential to overcoming this disadvantage. For example, Rocket Lab has developed a new electric turbopump system that increases feed cycle efficiency from the traditional 30-40 percent to over 90 percent (Kwack, Kwon, & Choi, 2018). This dramatically decreases the fuel wasted in running the engine, at the expense of having carry heavy batteries that do not get lighter as they are consumed.

Business leaders in the aerospace industry such as this have repeatedly stressed the importance of optimizing not just the rocket, but the overall production process. This is especially important for small-lift launch vehicles, whose entire business model depends on frequent launches. In a recent Twitter[6] exchange between Elon Musk and Peter Beck, the two

[6] Rocket tycoons tend to be very active (and far more open with their plans and opinions) on Twitter, so it would be a mistake to ignore the website as a source. Several SpaceX engineers have told me that Elon Musk's tweets are a more up-to-date reflection of the company than internal company memos.

emphatically agreed that "Production is the most underestimated aspect of space vehicle development. Building 10 rockets is 100 times harder than building your first rocket" (Musk & Beck, 2020). To keep up with the large demand, smaller rockets must either be produced at a higher rate or recovered and reused. For example, Relativity Space has opened a factory in Missouri theoretically capable of 3d-printing an entire rocket in 60 days (Howell, 2019) and Rocket Lab has successfully recovered one booster stage by catching it from a helicopter (Rocket Lab, 2020).

Are these operations actually profitable? A significant number of rocket companies were founded and partially funded by billionaires, possibly implying that orbital launch companies are simply the trendy vanity project of the 21st century. Elon Musk's SpaceX, currently valued at $33 billion (Cao, 2020), is unquestionably profitable, and has far outgrown the initial investment. Small-lift companies, especially the majority that have yet to generate any revenue at all, are much more difficult to evaluate. Again, Rocket Lab, being the only operational company of its class, is the only concrete insight into the viability of the small-lift niche. The company was reportedly valued by The Motley Fool at over $1 billion dollars in March 2017 and has since doubled its infrastructure and employee headcount (Smith, 2018). This is either an auspicious sign for the number of other start-ups with similar goals or an indication that Rocket Lab has achieved a virtual monopoly with its head-start. When the five most promising companies were interviewed by Forbes Magazine, all agreed that "The next 2-3 years will see a culling of small launch aspirants, maybe acquisition of small launchers by larger traditional aerospace companies." Despite the grim consensus, each company's representative feels confident that their operation has a unique competitive advantage that will carry them through (Autry, 2019).

The competition may thin earlier than expected as the present coronavirus shut-down will be disproportionately devastating to small companies without much revenue.

Conclusion

Satellite infrastructure has been important to the U.S. and world economies for half a century, but recently the low cost and standardization of CubeSats have led to the dramatic growth of spacecraft in orbit. This growth has stimulated demand for raw materials and yielded vast geospatial data, but it has also exposed new needs in the orbital launch industry. Furthermore, as growth continues, the problems of space junk and rocket exhaust in the upper atmosphere worsen.

On even the cheapest of the small rockets, costs per kilogram will always be greater than for its heavy-lift competitors. However, just as the demand for taxis remains substantial even though buses are much cheaper, the demand for small rockets will persist despite higher costs for the very same reason: customers' desire to control schedule and destination. As more infrastructure moves to space, a handful of small-lift launch vehicles will likely be a profitable and lasting part of the aerospace sector.

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