SSC18-IX-07

Setting the Standard: Recommendations on "Launch Unit" Standard SmallSat Sizes between CubeSats and ESPA-Class

Carrie L. O'Quinn, Barbara M. Braun, Allison B. Taylor, Danielle Piskorz
The Aerospace Corporation
2310 E. El Segundo Blvd., El Segundo, CA 90245; 703-808-4926
carrie.l.oquinn@aero.org

Chris Loghry
Moog, Inc.
2133 Nordhoff St., Chatsworth, CA 91311; 720-289-7041
cloghry@moog.com

Jeffrey Kwong
VOX Space
1240 Rosecrans Ave, Manhattan Beach, CA 09266; 435-512-2010
jeffrey@voxspace.com

ABSTRACT

Over the next ten years, more than 6000 SmallSats are expected to launch worldwide, an over six-fold increase from the previous decade. As the SmallSat market grows, launch remains the primary bottleneck to timely and affordable access to space. Just as the CubeSat form factor standardized the launch interface for CubeSats and allowed an ecosystem to flourish, SmallSat standards for satellites between 12U and ESPA-class size could have the same revolutionary impact on the industry. This paper explores the benefits of defining a "Launch Unit" standard for medium-class (25-200 kilogram) SmallSats and provides options for its development. Unlike the CubeSat standard that was generated around a new design, the Launch Unit standard takes into account existing and evolving launch options, existing separation systems, and examples of commercially available platforms that could fit into this standard. The Launch Unit standard would address the physical properties of the SmallSat (mass, volume, vibrational modes) as well as the mechanical and electrical interfaces to the launch vehicle for both large and small launch vehicles.

INTRODUCTION

For the first thirty years of the Space Age, space was primarily the domain of national governments and large commercial companies. The "standard" spacecraft was large, exquisite, and launched alone on a dedicated rocket. In recent decades, however, it has become increasingly clear that satellites on the lower end of the mass spectrum are providing more value despite their small volume and mass and often at a much lower cost point than traditional larger spacecraft. The proliferation of CubeSats has shown how a standard volume and mass, chosen for ease of flight, can lead to increasing launch opportunities and greater capabilities.[1] Commercial companies such as Planet have capitalized on CubeSat capabilities,[2] and governments are starting to follow suit. However, mission complexity and costs can easily skyrocket when a spacecraft manufacturer tries to fit a payload that typically requires a larger bus into a smaller spacecraft volume. For certain mission objectives, something larger than a CubeSat is required.

As satellites become lighter and smaller, a growing number of organizations are developing and manufacturing highly capable small satellites, larger than CubeSats, which can conduct more complex missions. Such SmallSats typically range in size from 12U CubeSats (approximately 24 x 23 x 36 cm and 25 kg)[3,4] to Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) class satellites (approximately 61 x 71 x 97 cm and 200 kg)[5,6]. However, the form factor of a SmallSat in this range has not been standardized as was done for the CubeSat and the ESPA-class satellite. Electrical interfaces and separation systems are not standardized at these sizes either, which can present a challenge.

This paper takes the first step to propose a "Launch Unit" as the standard form factor for medium-sized

SmallSats that fall in the range between a 12U CubeSat and an ESPA-class satellite. In choosing the parameters of the Launch Unit (LaunchU), a wide variety of launch vehicle options, launch interfaces, and SmallSats on the market were considered. This included many existing options and "near future" options in the growing Small Launch Vehicle market. This approach minimizes the number of non-compliant potential users. Additional considerations were made for separation systems, standard electrical interfaces, and interoperability between launch options (e.g., interchangeability between launch vehicles and integration hardware, similar to that in place with the ESPA ring).

As part of this "grassroots" standards development process, a LaunchU working group has been established and is open to interested participants. The working group is meant to bridge the gap between government and industry interests and provide a solution for both domestic and international users. The LaunchU working group reviews inputs and makes recommendations and The Aerospace Corporation (the group's lead organization) performs the majority of the verifications. Public campaigns notifying the greater industry have already begun, including discussions at technical conferences and other forums with relevant users. Implementing an American Institute of Aeronautics and Astronautics (AIAA) or similar industry standard has been discussed, but such efforts at this point are preliminary.

RIDESHARES AND SMALLSATS

Multi-manifest or "rideshare" missions launch multiple spacecraft, often from different agencies or organizations, on a single launch vehicle. Rideshares take advantage of excess lift capability on civil, commercial, and national security space launches[7] by storing secondary or auxiliary manifested payloads in the fairing of a rocket around or below the primary payload.

The first rideshare occurred in 1967 when the Department of Defense Space Test Program launched two satellites on a single launch vehicle.[8] Since then, rideshares have played a critical role in space exploitation and exploration. For example, NASA regularly deployed satellites from human spaceflight missions.[9] Commercial Resupply Service (CRS) missions, such as Orbital ATK's Cygnus, provide external payload satellite rideshares access to the International Space Station (ISS) orbit or some other orbital altitude.[10] SpaceX's Falcon 9 can deploy multiple satellites to multiple orbits on a single mission and can store secondary payloads on ESPA-rings, Surfboards, or other mission-unique structures.[11]

Small satellites at both ends of the mass spectrum that are manifested as rideshares face challenges because they have little direct control over mission parameters. On the lower end of the mass spectrum, CubeSats have two options: they can go through a broker who can look for a suitable launch opportunity, or they can work through a Mission Integrator who can consolidate a number of similar payloads together and find a ride for the entire set of payloads. The former option has its drawbacks, as the orbit or the schedule of the larger mission might not meet the CubeSat's needs. For the latter option, the requirements of the entire set of payloads must be balanced. Here, a mix of organizations both within the Government and within Industry perform these roles, often per their established procedures and practices and not an industry adopted standard. Rideshares can weigh in on specifications, such as their desired orbit and release time, but these inputs are typically weighed against the requirements of the rest of the satellites. If a specific small satellite's requirements are drastically different from the available launch opportunities, then the satellite will have to wait until the next suitable ride into space comes along.

ESPA class payloads typically go through a broker. As with CubeSats, the orbit and schedule of the larger mission may not be ideal for the SmallSat. Additionally, ESPA-class payloads are typically at the mercy of the primary mission. If the primary satellite is delayed or the launch vehicle fleet suffers a failure, the launch of the secondary small satellite will be delayed until those issues are resolved. Conversely, if the small satellite has development issues and is delayed, it may miss its launch opportunity and will have to restart the process with another launch vehicle. Dedicated Small Launch Vehicles are being developed to alleviate these issues, but even those are faced with similar challenges of mixing and matching small satellites and CubeSats.

MOTIVATION AND NEED FOR A STANDARD FORM

Though the process of finding an acceptable rideshare for a CubeSat or ESPA-class satellite has its pitfalls, it is straightforward compared to the rideshare process for a SmallSat that is neither a CubeSat nor an ESPA-class satellite, but somewhere in between. Without an established standard for such SmallSats, the developer has to design a custom-sized satellite solution and then figure out a launch that works. The developer can either procure an entire launch vehicle, work with a launch provider on a mission unique rideshare solution, or go through a launch vehicle broker. All of these options can be expensive, complicated, and inflexible. Since each solution is mission-specific, the mid-sized satellites can't simply be swapped out onto another ride if something goes wrong, or if another opportunity arises.

The development of a standard SmallSat form factor, or LaunchU, can play a pivotal role in achieving high launch availability and flexibility.[12] The ability to swap out launchers and payloads on short notice is key for resiliency and addresses some of the shortcomings of modern launchers. Similar to the CubeSat standard, a SmallSat standard can positively influence the industry by reducing integration complexity and costs, maximizing launch fairing efficiency, and decreasing time to launch. Just as a “rising tide lifts all boats,” the LaunchU standard benefits launchers, satellite manufacturers, and end users alike. The LaunchU is not intended to be a top-down requirement that spacecraft and launch vehicle developers will have to adhere to, but like the CubeSat and ESPA-class standard, an industry “understood” standard. Following it will simply increase the launch opportunities and potentially decrease the launch costs. Unique or otherwise non-compliant spacecraft will always exist but just as today they will likely incur additional cost and a reduced number of launch opportunities.

MARKET RESEARCH AND VETTING

The LaunchU standard is intended to have widespread industry acceptance. To facilitate this, we generated a database of publicly-available volume and mass limitations gleaned from company user guides.

In all, over 30 different launch options were identified. For small launch vehicles, the available volume in the payload fairing was converted to a cubic structure (i.e. a square inscribed in a circle) as most spacecraft are cubic in structure as opposed to cylindrical. This study avoided proprietary, export control, or trade-restricted information and focused primarily on mature launch or near-mature launch options available to the US industry. This study also does not endorse or discredit any particular option.

A separate database of publicly available information on small satellite buses was developed to verify that preliminary standard volumes would be applicable to existing platforms.

RECOMMENDATIONS

Volume, Mass, and Fundamental Frequency

Based on the market research above, the recommended volume for the LaunchU is 45 cm x 45 cm x 60 cm as show in the Figure 1. This volume includes the separation system for the satellite and the deployment direction is identified as being along the height direction. The center of gravity is 30 +/- 5 cm along the height and within 2 cm of the centerline. Initially, a series of four different sizes were notionally selected, similar to the selection of US Postal Service flat rate boxes, but these did not build off each other like CubeSats and led to more overall packaging inefficiencies.

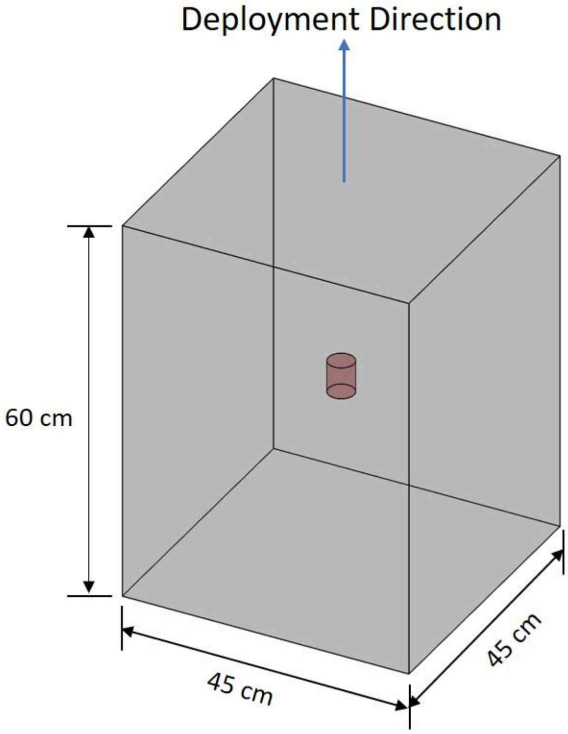

Figure 1: LaunchU Volume

The recommended mass for the LaunchU, including separation system, is 60-80 kg. This mass range is roughly half of that of an ESPA-class spacecraft and aligns with the notional concept of “half ESPA” that has been discussed in recent years. While it is typical to specify a not to exceed (NTE) mass rather than a range of masses, the LaunchU seeks to reduce mission specific analyses on both sides of the interface. For this reason, it is critical for the launch vehicle developer to identify a specific mass range of the LaunchU for all analyses. If the LaunchU satellite is less than the range specified, it is recommended that ballast be applied to increase the mass to that range.

The recommended first fundamental frequency of the satellite is greater than 50 Hz, including the separation system, in both axial and lateral directions. By constraining the first fundamental frequency to be above 50 Hz, there is less chance for the LaunchU satellite to couple with modes of the launch vehicle.

Mechanical Interface Requirements

A survey of commercially available separation systems indicated the 11.732" Planetary Systems Corporation Motorized Lightband as the circular system most appropriately sized for the LaunchU satellite.[13] The bolt hole pattern for that system is provided in Figure 2.

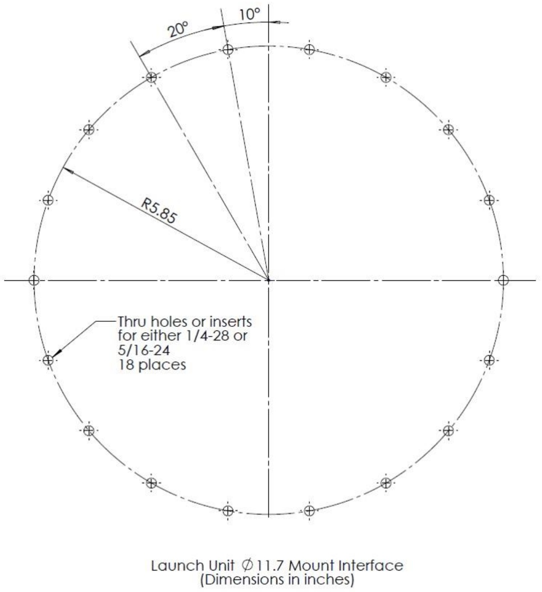

Figure 2: LaunchU Interface - Circular Pattern

A number of separation nuts are also commercially available and can be used as a separation system.[14,15,16] In fact, a separation nut system was proposed for similarly sized "express class" satellites in 2013.[17] To accommodate these systems, the bolt pattern in Figure 3 is provided as an additional mechanical interface for the LaunchU.

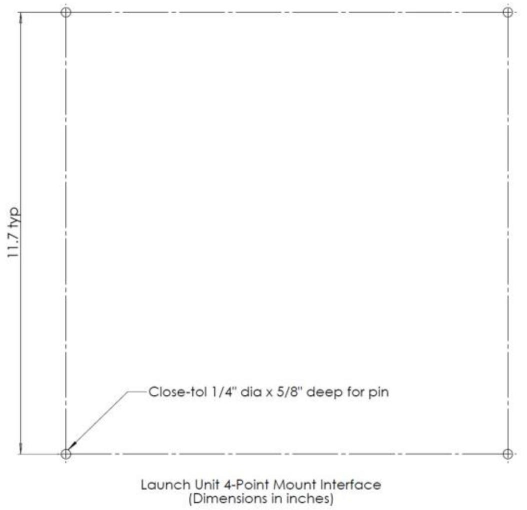

Figure 3: LaunchU Interface - 4 Bolt Pattern

Electrical Interface Requirements

The electrical interface to the launch vehicle is limited to the signals required to initiate the separation system and loopback circuits for separation indication. The launch vehicle will send the signal to initiate separation. No LaunchU satellite telemetry data is passed through for transmission via the launch vehicle telemetry units. LaunchU satellite telemetry transmitters will not be radiating until after separation.

Future enhancements to the LaunchU standard may include provisions for trickle charging to the satellite and signal pass through from the satellite to the satellite ground support equipment, prior to liftoff. As each launch vehicle umbilical and avionics system is unique, specifying connector and umbilical requirements for all launch vehicles is challenging. A more thorough discussion of connector and umbilical constraints is required before such recommendations can be made.

Load Requirements

The large variety of launch vehicles makes it difficult to envelope all load requirements for the LaunchU. However, to assist in the design of the LaunchU satellites, the working group recommends random vibration acceptance levels as shown in Table 1. This curve addresses the random vibration environment of various launch vehicles by enveloping the TOR-2016-02946 levels[7], the GEVS random vibration curve for a 22.7 kg component[18], and the EELV SIS Rev C random vibration levels.[19]

Table 1: LaunchU Recommended Random Vibration Levels, All Axes

Frequency (Hz)	Acceptance Level PSD (g^2/Hz)
20	0.018
30	0.030
50	0.200
100	0.200
125	0.080
1300	0.080
1350	0.040
2000	0.040
gRMS	11.76

The recommended static loads are 8.5 Gs applied at the center of gravity in each direction. As described in Appendix A of TOR-2016-02946,[7] the spacecraft should apply the maximum static load in any direction (use the root sum square of simultaneous loads) to every axis to ensure the spacecraft survives loads applied in any direction.

The recommended shock levels, as experienced at the interface to the launch vehicle, were derived by enveloping a number of launch vehicles and the EELV SIS Rev C shock levels.[19] These levels are shown in Table 2. While not all launch vehicles are encompassed by these levels, it is expected that the actual launch shock environments at the LaunchU satellite will be lower than published levels due to additional shock attenuation through joints and distance.[20]

Table 2: LaunchU Recommended Shock Levels

Frequency (Hz)	Shock Response Spectrum (g)
100	100
1500	2500
10000	2500
	Q=10

ACCOMMODATIONS IN CURRENT LAUNCH SYSTEMS

Once the volume recommendations were developed, the Aerospace Corporation's Vehicle Design and Innovation Department (VDID) developed several satellite layouts within the launch vehicles to show how the LaunchU might fit within the various launch options studied. The VDID considered only the volume of the LaunchU with respect to the launch vehicle's published fairing volume. These layouts are shown in Figure 4 through Figure 8.

It is understood that intermediate support structures, such as a Dual Payload Attach Fitting (DPAF) or similar structure, would need to be utilized, but this is not a new concept for larger launch vehicles.[21,22] An oversized dispenser similar to those used for CubeSats is another potential option. Additional efforts will need to be undertaken by launch vehicle providers and launch adapter manufacturers for these structures, but that effort could not begin until a standard spacecraft size was determined.

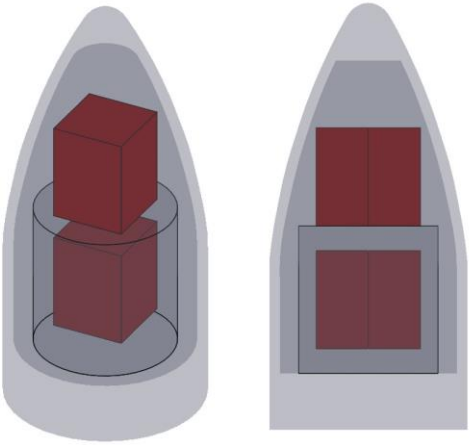

Figure 4: RocketLab Electron[23] with two LaunchU satellites

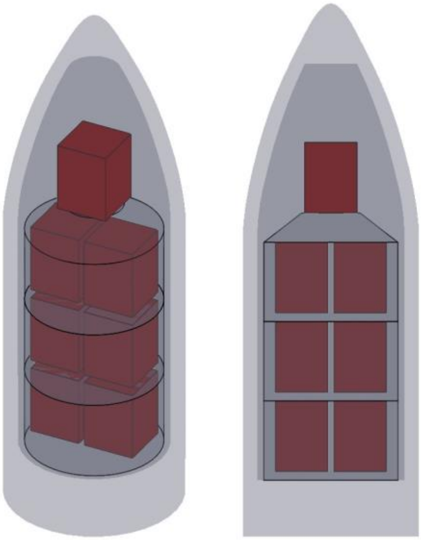

Figure 5: Virgin Orbit LauncherOne[24] with seven LaunchU satellites

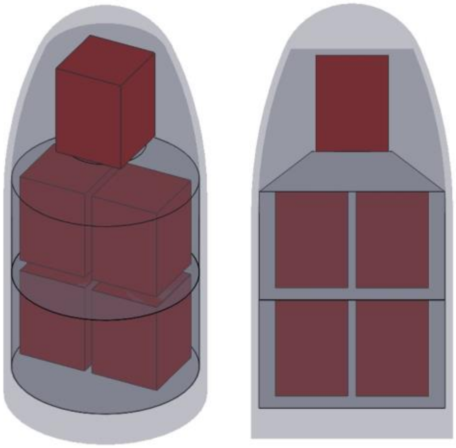

Figure 6: Minotaur I 50" Fairing[25] with five LaunchU satellites

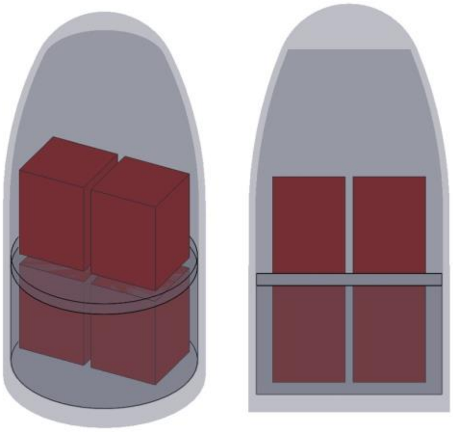

Figure 7: Orbital ATK Pegasus XL[26] with four LaunchU satellites

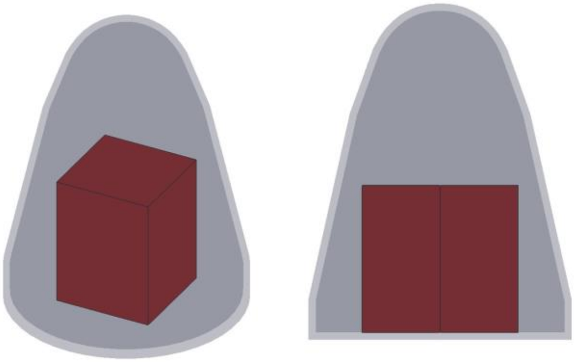

Figure 8: Vector-H[27] with one LaunchU satellite

As shown in Figure 9, a LaunchU satellite fits in the Kaber[28] deployment system for the International Space Station.

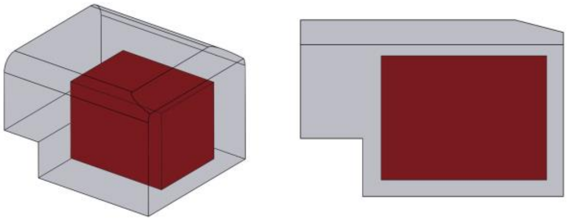

Figure 9: Kaber deployment system on International Space Station with a LaunchU satellite

Additionally, the VDID examined various CubeSat dispensers to determine if the same LaunchU volume could hold CubeSat dispensers instead of a LaunchU satellite. One potential layout is shown in Figure 10. It is likely that the CubeSat dispensers and associated CubeSats would be heavier than the LaunchU mass recommendations, but the volume could be repurposed on a launch system to hold CubeSats instead of a LaunchU satellite, if the mass margin was available.

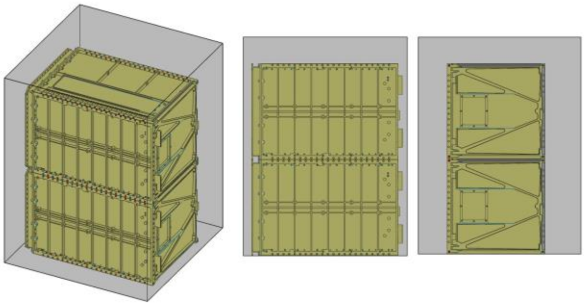

Figure 10: Two 12U PSC Canisterized Satellite Dispensers[29] inside LaunchU volume

ADDITIONAL CONSIDERATIONS FOR LAUNCH SWAPPING

Meeting the requirements of the LaunchU standard is only half of the story. In order to increase flexibility in launch opportunities and be able to swap satellites late in the mission, a number of other items must be addressed, including imaging, frequency, debris mitigation, information assurance, and do no harm policy.[7,30]

Export Control

U.S. national policy and export control regulations state that sensitive satellite components cannot be launched on foreign launch vehicles without a license and that U.S. government satellites must use U.S. launchers unless they obtain a White House-level waiver.[31] Foreign governments have similar requirements for exporting sensitive satellite components. To maximize the ability to swap satellites late in the integration, concerns over export control must have already been addressed.

Transparency in Regulatory Regimes

As discussed in Sims & Braun (2017),[30] many aspects of the path to launch and policy compliance for SmallSats, even aside from interfacing with the launch vehicle, are vague. This includes current regulation for orbital debris, spectrum allocation, cyber security, and imaging. Streamlining and clarifying regulations is especially critical in a LaunchU era to maximize launchability.

Do No Harm

All rideshares, including LaunchU satellites, require additional environmental test, analysis, and safety documentation, which may be specific both to the launch vehicle as well as the launch range. This will ensure that the LaunchU does no harm to a primary mission, other LaunchU satellites, or the launch vehicle. Considerations include vibration and shock (see *Load Requirements*), contamination (cleanliness standards may depend on the most contamination-sensitive payload) and electromagnetic interference (note that units should be quiescent prior to a designated time after separation from the launch vehicle). Further specifications on Do No Harm criteria are described in TOR-2016-02946.[7] While not a requirement of a LaunchU satellite, it is recommended that all LaunchU satellites adhere as closely to established "do no harm" criteria as possible to maximize space access opportunities as well as the ability to swap into a mission late in the integration flow.

Range Safety

Range Safety considerations include the determination that sufficient inhibits are present to prevent accidental activation of energized systems (batteries, springs, pressure vessels, etc.). Existing US orbital test ranges have well codified safety instructions documented in AFSPCMAN 91-710[32], but it is possible that future launchers and ranges may have different requirements.

Propellants

Spacecraft propulsion systems and their propellants present a potential issue for launch swapping. This adds a level of complexity and considerations with Do No Harm standards. CubeSats traditionally did not have propellant or stored pressure sources but as these mission become more capable, propulsion becomes increasingly desired.[33] The CubeSat Design Standard[34] specifically removed the restriction on propulsion systems, but defers to the AFSPCMAN 91-710[32] requirements imposed on most large spacecraft launched in the US. These standards were developed for hazardous and/or toxic propellants such as Hydrazine, but have not been updated for new classes of propulsion systems including green propellants. Many ESPA-class spacecraft have propulsion systems with toxic propellant such as Hydrazine.[35] CubeSat class propulsion systems utilize novel technologies such as electrospray and other kinds of electric propulsion and even systems that use water to avoid the cost and complexities associated with toxic or hazardous propellants.[35] It is expected that LaunchU spacecraft will likely include provisions or at least a desire for propulsion, including capabilities outside the current state of the art for CubeSat-class propulsion. This will need to be assessed to potentially develop CubeSat or SmallSat propulsion system requirements in conjunction with Range Safety organizations.

PATH FORWARD FOR THE LAUNCHU

The space access industry is changing rapidly, driven by the development of CubeSats, small satellites, and small launch vehicles; the increasing popularity of multi-manifest missions; and widespread interest in reducing launch costs and timelines while deploying more spacecraft. The LaunchU is meant to be an industry-wide effort to provide launch providers and spacecraft developers with a standard volume and mass for satellites that fall between typical CubeSat sizes and ESPA-class sizes. Similar to the CubeSat Design Standard (CDS)[34] or EELV Rideshare Users Guide (RUG),[6] the LaunchU is not meant to be a requirements document per se but a series of guidelines that, if followed, would maximize launchability.

This paper represents the first customer engagement on this standard. The data and recommendations presented here are not static and are considered a “minimum viable product.” The LaunchU is not envisioned to be a requirement levied on spacecraft developers but rather a standard that organizations can develop for mutual benefit.

For industry, the next step is to develop hardware and other technical solutions needed to support the LaunchU. Each stakeholder plays a specific role in the implementation of the LaunchU:

- Launch vehicle providers, as well as brokers and aggregators, could begin considering how LaunchU satellites will affect their business models once implemented. For example, these companies might publish information on LaunchU launch costs, as Spaceflight Industries and other commercial entities currently do for CubeSat launch costs.
- Spacecraft developers could build platforms that are LaunchU-compliant, similar to the many “ESPA-Class” spacecraft platforms available from different vendors.
- Satellite manufacturers could build to the LaunchU standard and make it available to the community at-large.
- Launch vehicle developers and payload adapter hardware organizations could determine the best way to mechanically package LaunchU satellites.
- The LaunchU working group itself will need to determine the best method to document and control the standard.
- The overall community can work to develop solutions to the issues addressed in the previous sections related to considerations for launch swapping. In some cases, this may require regulatory or statutory changes.

To allow for the evolution of the standard, any early LaunchU designs must be flexible and adaptable. Technologies that allow for swapping spacecraft with minimal impact to the rest of the launch system have strong potential.

New, viable business models will arise as space access becomes more easily procured and spacecraft can be delivered to their target orbits like a standardized shipping container to a port or a “flat rate box” to your doorstep. These business models are ecosystems for not only the LaunchU but also for on-orbit tugs and on-orbit fabrication of spacecraft and platforms. By sharing costs across all of industry, each user gets an overall lower cost and higher launch frequency that could not be achieved by traditional means.

Acknowledgments

The authors would like to acknowledge the entire LaunchU working group for their contributions, including: Meg Abraham (Aerospace), Brooklyn Bratton (ULA), Ryan Burke (Aerospace), Dave Callen (Tyvak), David Caponio (Virgin Orbit), Justin Carnahan (Tyvak), Andre Doumitt (Aerospace), Bradley Hirasuna (Aerospace), Matt Kanter (Aerospace), Robert Markin (Aerospace), Riaz Musani (Aerospace), Ryan Nugent (Cal Poly), Jordi Puig-Suari (Cal Poly), Randy Riddle (US Air Force), Scott Schoneman (Spaceflight Industries), Catherine Sedam (Aerospace), Dave Stephens (Aerospace), Kyle Yang (SpaceX), Emily Yee (Aerospace), Megan Youngs (Aerospace).

References

1. National Academies of Sciences, Engineering, and Medicine. Achieving Science with CubeSats: Thinking Inside the Box. Washington DC: The National Academies Press, 2016.
2. Schlingler, R. *Planet launches satellite constellation to image the whole planet daily*. Planet. Feb 2017. https://www.planet.com/pulse/planet-launches-satellite-constellation-to-image-the-whole-planet-daily/ (accessed Apr 29, 2018).
3. National Aeronautics and Space Administration. *CubeSats Overview - NASA.* NASA. February 14, 2018. https://www.nasa.gov/mission_pages/cubesats/overview (accessed April 29, 2018).
4. Planetary Systems Corporation. "Payload Specification for 3U, 6U, 12U and 27U." Aug 4, 2017. http://www.planetarysystemscorp.com/wp-content/uploads/2018/03/2002367E-Payload-Spec-for-3U-6U-12U-27U.pdf (accessed April 30, 2018).
5. Moog CSA Engineering. *ESPA.* http://www.csaengineering.com/products-services/espa/ (accessed April 29, 2018).
6. Space and Missile Systems Center. "Evolved Expendable Launch Vehicle Rideshare User's Guide." El Segundo, CA, 2016.
7. Read, A., Chang, P., Braun, B., and Voelkel, D. *TOR-2016-02946: Rideshare Mission Assurance and the Do No Harm Process.* El Segundo, CA: The Aerospace Corporation, 2016. (Restricted Access)
8. Braun, B., Sims, E., McLeroy, J., and Brining, B. "Breaking (space) barriers for 50 years: The past present and future of the DoD Space Test Program." *31st Annual AIAA/USU Conference on Smal Satellites.* Logan, UT, 2017.
9. Moskowitz, C. *Space Shuttle Releases Final Satellite Into Orbit.* SPACE.com. July 20, 2011. https://www.space.com/12354-final-space-shuttle-satellite-deployment-picosat.html (accessed April 29, 2018).
10. Orbital ATK. *International Space Station Payload Opportunities on Cygnus.* https://www.orbitalatk.com/space-systems/human-space-advanced-systems/commercial-resupply-services/docs/ISS_Payload_Opportunities_Cygnus.pdf (accessed April 29, 2018).
11. SpaceX. "Falcon 9 User's Guide Rev 2.0." October 21, 2015. http://www.spacex.com/sites/spacex/files/falcon_9_users_guide_rev_2.0.pdf (accessed April 29, 2018).
12. O'Quinn, C., Piskorz, D., and Jones, K. *Setting the Standard: Launch Units for the Smallsat Era.* El Segundo, CA: The Aerospace Corporation, 2018.
13. Planetary Systems Corporation. "2000785F MKII MLB User Manual." July 30, 2015. http://www.planetarysystemscorp.com/web/wp-content/uploads/2015/09/2000785F-MkII-MLB-User-Manual.pdf (accessed April 29, 2018).
14. Ruag. "Payload Adapters and Separation Systems." https://www.ruag.com/sites/default/files/2016-11/PLE-Brochure-Payload-Adapter-and-Separation-Systems.pdf (accessed April 29, 2018).
15. Sierra Nevada Corporation. "Sierra Nevada Corporation's Space Systems Space Technologies Product Catalog." 2017. https://www.sncorp.com/media/2086/space-technologies-product-catalog-2017.pdf (accessed April 29, 2018).

16. TiNi Aerospace. “Ejector-TiNi Aerospace.” https://tiniaerospace.com/products/space-ejector/ (accessed April 29, 2018).

17. Apland, C., Rogers, A., Persons, D., Summers, R., and Kee, C. "A Flexible Rideshare Adapter Sysetm to Increase Space Access for "Express" Class 20-50 kg Small Satellite Missions." *27th Annual AIAA/USU Conference on Small Satellites.* Logan, UT, 2013.

18. NASA Goddard Space Flight Center. *GSFC-STD-7000A: General Environmental Verification Standard (GEVS) for GSFC Flight Programs and Projects.* Greenbelt, MD: NASA, 2013.

19. Space and Missile Systems Center Launch Systems Directorate. "Evolved Expendable Launch Vehicle Standard Interface Specification Rev C." El Segundo, CA, 2017.

20. National Aeronautics and Space Administration. *NASA-STD-7003A: Pyroshock Test Criteria.* Washington, DC: NASA, 2011.

21. Orbital ATK. "Minotaur IV V VI User's Guide, Release 2.2." August 2015. https://www.orbitalatk.com/flight-systems/space-launch-vehicles/minotaur/docs/MinotaurIV_V_UG.pdf (accessed April 29, 2018).

22. United Launch Alliance. "Delta IV Launch Services User's Guide." June 2013. https://www.ulalaunch.com/docs/default-source/rockets/delta-iv-user's-guide.pdf (accessed April 29, 2018).

23. Rocket Lab USA. "Payload User's Guide, Version 4.0." December 2016. https://www.rocketlabusa.com/assets/Uploads/Payload-User-Guide.pdf (accessed April 29, 2018).

24. Virgin Orbit, LLC. "LauncherOne Service Guide, Version 1.0." August 7, 2017. https://static1.squarespace.com/static/5915eeab9de4bb10e36a9eac/t/5a5fcb70ec212d98c9f51374/1516227453251/180117_service-guide_reference.pdf (accessed April 29, 2018).

25. Orbital ATK. "Minotaur I User's Guide, Release 3.1." September 2015. https://www.orbitalatk.com/flight-systems/space-launch-vehicles/minotaur/docs/MinotaurI_UG.pdf (accessed April 29, 2018).

26. Orbital ATK. "Pegasus User's Guide, Release 8.0." October 2015. https://www.orbitalatk.com/flight-systems/space-launch-vehicles/pegasus/docs/Pegasus_UsersGuide.pdf (accessed April 29, 2018).

27. Vector Launch, Inc. "Vector-H Forecasted Launch Service Guide VSS-2017-023-V2.0." n.d. https://vector-launch.com/download-vector-h-launch-user-guide/ (accessed April 29, 2018).

28. NanoRacks LLC. *NanoRacks Kaber Deployment System Interface Definition Document (IDD), NR-KABER-50001.* NanoRacks, 2016.

29. Planetary Systems Corporation. "Canisterized Satellite Dispenser (CSD) Data Sheet, 2002337B." July 21, 2014. http://www.planetarysys.com/web/wp-content/uploads/2014/08/2002337B-CSD-Data-Sheet.pdf (accessed April 29, 2018).

30. Sims, E. and Braun, B,. *Navigating the Policy Roadmap for Small Satellites.* El Segundo, CA: The Aerospace Corporation, 2018.

31. Obama, B. "National Space Transportation Policy." *Presidential Policy Directive 26.* Washington, DC, November 21, 2013.

32. Air Force Space Command. "AFSPCMAN 91-710 Volume 3: Range Safety User Requirements Manual Volume 3 - Launch Vehicles, Payloads, and Ground Support Systems Requirements." 2004.

33. Tappan, B. *CubeSats have 1 Major Shortcoming, But Not for Long.* August 10, 2017. http://blogs.discovermagazine.com/d-brief/2017/08/10/cubesats-fuel-source/#.WuW7Be-ovmI (accessed April 29, 2018).

34. The CubeSat Program, Cal Poly SLO. "CubeSat Design Specification, Rev 13." February 20, 2014. https://static1.squarespace.com/static/5418c831e4b0fa4ecac1bacd/t/56e9b62337013b6c063a655a/1458157095454/cds_rev13_final2.pdf (accessed April 29, 2018).

35. NASA Ames Research Center. *State of the Art of Small Spacecraft Technology: 04. Propulsion.* March 29, 2018. https://sst-soa.arc.nasa.gov/04-propulsion (accessed April 29, 2018).