Herding Cats: Key Takeaways from Wrangling 28 Payloads on One Mission

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ABSTRACT

In November of 2013, a US Government organization launched a record-breaking mission comprised of 31 total payloads. The lead mission integrator of that highly successful mission integration effort for this highly complex multi-spacecraft rideshare mission consisting of 28 distinct separating CubeSat payloads presents key observations and lessons to facilitate future government and commercial multiple spacecraft rideshare missions. This mission was executed under an aggressive schedule relative to the physical integration of the smallsats into their flight dispensers and the dispensers onto the launch vehicle adapters. Additionally, this mission utilized a mix of CubeSats integrated in both Poly-Picosatellite Orbital Deployers (P-PODs) and the first flight of the NASA Launch Adapter System (NLAS) dispenser, as well as the first flight of the CubeStack launch adapter. This mission integrator was able to successfully integrate all 28 CubeSats in a six-day operation with zero anomalies during processing.

This paper begins by providing an introspective assessment of the objectives associated with the aggressive mission schedule, specifically how they positively or negatively affected the payload providers for the mission. Additionally, the paper presents the integrator's personal perspective on the mission integration effort as a whole, focusing on his perspective of key lessons from the process that are most value-added for future rideshare missions. In particular, the paper will state recommendations for industry standard practices and outline possible pitfalls to avoid through careful and knowledgeable planning based on the lessons gleaned from this effort.

The contents of the paper provide specific examples from this groundbreaking mission and its associated integration activities. However, the paper does not address the particular payload providers, supporting contractors, or associated agencies. The discussion focuses on the advantages and challenges associated with the approach applied for this mission, purposefully avoiding mere opinion or speculation.

RIDESHARING IS ATTRACTIVE, BUT VERY DIFFICULT

Mission integration of a single satellite onto a launch vehicle (LV) is a highly complex endeavor that requires the close coordination of requirements and expectations between the LV and spacecraft providers. This complexity increases exponentially when considering the integration of multiple spacecraft on a single mission. With the current market conditions for small satellite (smallsat) space access, high price points for launch and limited access to affordable dedicated small LVs to boost smallsats to orbit has generated an increased interest in ridesharing, that is, manifesting multiple spacecraft on a single mission. Jason Koebler from *Motherboard.com* states, *"The sharing economy is hitting spaceflight. A slew of new companies are trying to democratize space access using the mantra that, if you're all going to the same place, why not go together?"*[1] Ridesharing spacecraft provides economies to launch costs by making space access more affordable by dividing up the launch costs among several spacecraft providers.

However, mission integration for these types of mission is not a simple affair. Mission success for multi-spacecraft manifests is predicated on the program management and systems engineering rigor to orchestrate the integration effort and reach agreement between the competing requirements of each spacecraft provider and the LV provider. Oftentimes, the labor of executing these types of missions is romantically analogized as herding cats.

TriSept Corporation's mission integration manager architected and led the integration of 28 distinct CubeSat spacecraft, leading to a highly successful launch in November 2013. Numerous lessons were learned from planning and orchestrating a mission integration campaign of this magnitude with respect to the successful integration of multi-spacecraft missions. However, this brief paper will provide a generalized set of advantages and disadvantages of four of the mission objectives specified for this mission. This paper overviews some of the benefits and detractors to methodologies and practices as it relates to manifesting, adapters and dispensers, separation timing and sequence as well as programmatic communications and process. It is to be noted that this paper is not intended to provide specific details or examples from the November 2013 mission; it will genericize some of the approaches, but the actual decisions or decision makers are deliberately left out of the narrative.

PROVIDING CONTEXT: THIS ONE WAS A DOOZIE

This particular campaign was a record-breaking United States Government (USG) mission consisting of 31 separate payloads on a single Orbital Sciences Corporation Minotaur-class LV. The manifest consisted of a single Evolved Expendable Launch Vehicle (EELV) Standard Payload Adapter (ESPA)-class spacecraft, 28 CubeSat-class satellites, and 2 non-separating tertiary experiments. The LV was configured with a new CubeStack adapter system and associated hardware, as well as a new NASA Launch Adapter System (NLAS) dispenser, to enable the delivery of these payloads for operation in Low-Earth Orbit (LEO). The complexity of the mission was also increased because the 28 CubeSats were furnished by 20 different spacecraft providers.

This mission had many top-level demonstration objectives associated with new hardware and software solutions, as well as policy and process approaches to drive towards the goal of seeking out a more cost-effective small satellite launch capability. The following discussion is organized around evaluating four of these objectives.

WEIGHING THE OBJECTIVES: DID THEY HELP LOWER COSTS/COMPLEXITY?

Objective A: Accelerated Physical Integration

The overall aim of this objective was to speed up the process of physically integrating spacecraft to their respective launch interfaces. The mission sought to demonstrate rapid integration of payloads late in the mission flow in order to de-conflict the rideshare payload timelines from the mission critical path integration schedule. In one of the author's papers entitled "The Tremendous Advantages of FANTM-RiDE™-Enabled Dedicated Rideshare vs. Hosted Payloads", the author outlines the disparity that exists between the mission integration timelines of many US launch missions and the program lifetime of smallsat providers[2]. This paper outlines how this incongruence emerges because the majority of USG launches are identified three to four years prior to launch, and several costly analyses, such as coupled loads analyses (CLAs) and electro-magnetic interference/compatibility (EMI/C) are accomplished around 24 months prior to launch. The long integration timeline is problematic for many smallsat providers because their spacecraft development timelines are much shorter than larger spacecraft, and therefore, many smallsat providers obtain funding for launch in a timeline that is closer to launch minus (L-) 18 to 12 months, thus driving the smallsat mission integration timeline to fit within the L-18 or L-12 month timeframe. This disparity in mission integration flows not only affect the long-lead integration, it also has the potential to interrupt the primary mission critical path during physical integration of the smallsats with the primary mission. This inconsistency in integration timelines has precluded many smallsats from finding rideshare opportunities. It is no wonder, then, that an accelerated physical integration is a key consideration for more frequent and cost-effective launch. To minimize the physical integration portion for this mission, the mission integrator sought to demonstrate the advantage of integrating all of the rideshare payloads on the launch pad through a payload fairing access door and still allow for verification of the status of the dispensers without addition major risk to the mission. The hope is to drive down the current practice of requiring CubeSat providers to supply their launch assets 90 to 120 days prior to launch.

In order to meet this objective, TriSept's integrator established an Integrated Payload Stack (IPS) approach to create a simplified, singular representation of the group of rideshare spacecraft with the other mission stakeholders. This approach enabled more efficient communication and coordination with the LV provider, mission owner, and launch range, to include their safety organizations. Furthermore, from a systems engineering perspective, treating the composite group of payloads as one integrated payload at the system level greatly reduced the complexity associated with requirements traceability and verification.

TriSept's integrator also utilized an Integrated Product Team (IPT) management approach to ensure each spacecraft provider was afforded equal input and review of all integration processes, schedules, planning, and documentation. This also facilitated their ability to participate in issue and anomaly identification, tracking, disposition and resolution.

Moreover, the combination of the IPS approach with the use of IPTs reduced the amount of launch site procedure development because it allowed for clearer demarcation of sub-groups within the IPS. For this mission, the integrator was able to break the procedures in to obvious groups that were consolidated by like type dispensers and sizes of spacecraft. This enabled the creation of a set of procedures that was applicable to each appropriate set of spacecraft and clearly delineated which tasks were specifically required for these subsets. This introduced a substantial efficiency into the physical integration at the integration facility.

Additionally, TriSept's integrator set up system-level certification testing such that it was able to be performed in the IPS configuration without the presence of the payloads. This allowed for the spacecraft providers to continue in their development flow without the disruption brought about by requiring the flight hardware to be delivered for system-level testing before completing the remainder of their spacecraft preparations. At the same time, this approach enabled the primary mission and LV to maintain their production schedules and to keep the test environments and configurations to valid. The LV fitcheck, mission simulation testing, IPS structural qualification and functional performance testing was accomplished without the payloads. Also, the non-separating tertiary payload interface validation testing and flight integration was executed as hosted payloads without interruptions to standard integration flow.

The choice of launch integration hardware further reduced the physical integration timeline for this mission. The CubeSats were integrated into NLAS and P-POD dispensers loaded within CubeStack adapters provided by LoadPath, Inc., which are depicted in Figure 1[3]. Each CubeStack adapter was configured to allow for eight 3U spacecraft slots each, and the design was such that additional attach fittings, shelves or cantilevered positions were not required, simplifying the integration process.

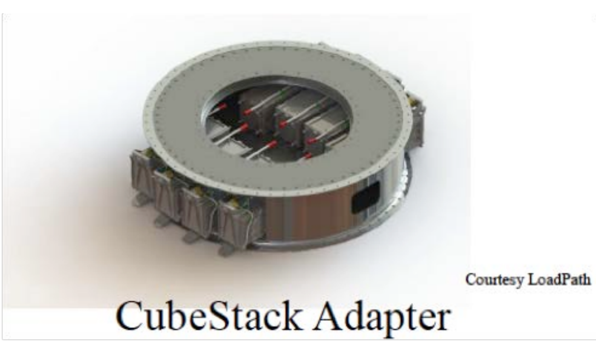

Figure 1: Launch adapter that allowed for simple integration of 8 3U spacecraft slots.

Specifically, the utilization of this mix of hardware provided the following advantages because it simplified mission analyses and integration operations:

- The physical configuration kept all of the dispensers within the static LV payload fairing envelope while placing the stack's forward center of gravity (Cg) near the physical interface plane. This reduced the complexity of the mission statics/dynamics analyses.

- The design placed the LV bolted interface plane normal to the flight load path, minimizing transfer function accelerations to the individual spacecraft.

- The configuration utilized a single stack electrical harness that brought the management of the separation signaling and ground processing access interface to the LV ICD level. This also greatly simplified the physical electrical interface operations at the launch site.

- The stack utilized a separation sequencer, which allowed for a straightforward LV electrical configuration and avoided the need for additional mission specific LV hardware that could alter the vehicle class certification.

- The CubeStack design simplified stack lifting and handling of the adapters for LV integration and transportation.

Finally, TriSept's integrator purposed to constrain the delivery, checkout and physical integration activity to a six day period. This forced a level of efficiency that fostered expeditious physical integration of the IPS. It also reduced the travel cost for each of the smallsat providers. Although some were skeptical about the ability to integrate that many CubeSats within a 6 day operation, the IPS integration team successfully integrated all 28 CubeSats within the six days with zero recorded anomalies.

Despite all of these positive aspects of compressing the physical integration timeline, two detractors emerged through this experience. First, the specific desire to demonstrate rapid integration required that the dispensers be installed in the IPS prior to spacecraft delivery, which is a deviation from typically industry-recognized spacecraft to dispenser loading procedures. This drove the need for the development of an additional process for the visual verification of footswitch depression and pusher plate set screws.

Another issue that arose with respect to physical integration was that the primary spacecraft provider refused to integrate the ESPA-class spacecraft to the IPS and ship to launch site as a single stacked unit. This added unnecessary costs and complexity at the launch site. While the process performed did not result in any specific failure or mission impact, a decision to stack the primary spacecraft with the IPS would have reduced the total range fee and schedule by approximately 40%.

Objective B: Optimized Spacecraft Separation Scheme and Re-Contact Assessment

Spacecraft collision and re-contact is of great concern when considering the deployment of numerous spacecraft from a single launch mission. The complexity extends beyond concerns of re-contact of satellites with other objects or satellites during the initial ejection of the spacecraft. As described in the paper written by the late Steve Buckley called "A systems approach to select a deployment scheme to minimize re-contact when deploying many satellites during one launch mission," he described the concern about the potential collision of spacecraft ejected from the same proximity in space when the satellites return to the same orbital node in subsequent orbital revolution[4]. Therefore, one of the mission goals was to demonstrate a multiple orbit normal separation plane approach to minimize the risk of re-contact and reduce the relative velocity between spacecraft should it occur to manage risk of damage and orbital debris.

All in all, the focused analysis and deliberate approach to specifically affect the probability of the rideshare payloads re-contacting with either the primary spacecraft or the upper stage of the LV proved effective for this mission. Figure 2 depicts the basic premise of the separation scheme to distribute spacecraft in the same orbital plane. Noteably, the post-flight reviews and assessment of the orbital propagation of all of the payloads revealed that the two LV Contamination Collision Avoidance Maneuvers (CCAMs) were the primary influence in the separation between the 28 CubeSats deployed on this mission and the LV and primary.

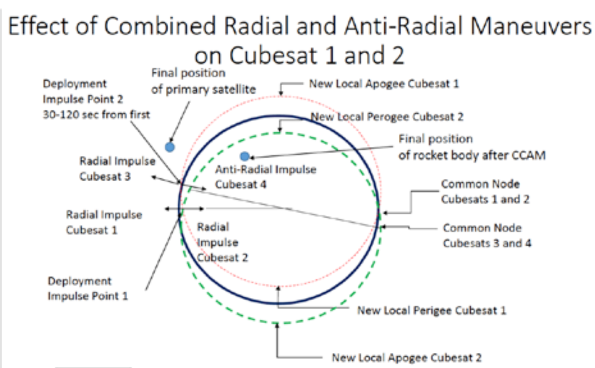

Figure 2: Separation scheme optimization to avoid spacecraft re-contact

Nevertheless, the intent of the designed separation scheme relative to CubeSat-to-CubeSat re-contact yielded the expected results. Deploying the spacecraft in four specific radial planes normal to the LV velocity vector provided four closely-grouped clusters of satellites, per the intended mission design. These results also demonstrated the low relative velocities between objects that was anticipated and intended to reduce the risk of possible damage and debris should there have been a re-contact event. There were no reports or observations of any collision events, demonstrating the effectiveness of the separation scheme to avoid satellite re-contact.

Even though the scheme was highly effective, there were three negative effects of employing this approach to avoiding re-contact. First of all, the mission's specific design resulted in extremely low payload-to-payload separation velocities, causing the spacecraft within each of the four satellite clusters to remain very close to each other early in their orbital lifetimes. This created significant complications in the sorting of each individual spacecraft's two-line element (TLE) data. The close grouping of these satellites also increased the difficulty of some spacecraft providers to make first acquisition communication with their payloads.

Additionally, the mission design increased complexity in the mission planning for LV collision avoidance. The increasing pressure to significantly decrease the orbital lifetime of LV upper stages to foster good stewardship of the space environment drives requirements to blow down and de-orbit the upper stages. This particular mission scheme necessitated the addition of a second LV CCAM event to ensure that the booster would avoid re-contact with the 28 separating CubeSat rideshares and to properly dispose of the upper stage. Additional propulsion events increase the amount of mission design analyses and would require sufficient propellant margin to accomplish all required maneuvers, which could appreciably increase launch costs.

Finally, the deployments required for this particular scheme were expected to impart some delta velocity on upper stage of the LV. Incidentally, this phenomenon turned out not to be as much of an issue than expected from pre-mission analyses. Knowing this could have allowed for more staggering of the CubeSat separation events to better optimize re-contact avoidance.

Objective C: Schedule Savings Through Fitcheck Acceptance with Flight-Like Hardware.

Many USG launch missions require spacecraft providers to furnish their flight hardware for fitchecks with the flight dispensers and/or launch adapter interfaces at a single specified integration facility. To increase mission efficiency, TriSept's integrator alleviated the requirement for the spacecraft providers to provide their flight hardware to a single test location for these fitchecks to reduce cost and schedule impacts brought by the need for spacecraft providers to make numerous trips by with flight hardware. Furthermore, the requirement was relaxed to reduce mission risk for each of the CubeSat providers because the flight assets may encounter mishap or incur damage during the additional packaging, shipping, handling, and operations during the fitcheck process. However, the requirement for the flight hardware presence for fitchecks reduces the risk of possible discrepancies in the physical integration of the spacecraft to their dispensers/adapters in the critical phase of spacecraft mating in the launch flow.

For this mission, the TriSept's integrator instituted two measures to both allow for fitchecking of flight hardware, yet relax the requirement for the numerous spacecraft providers to be present at a single location for a fitcheck test. First, the mission integrator specified the location of the fitcheck operation that would maximize the number of spacecraft providers that could easily transport their flight hardware. This was a highly effective alternative to specifying an arbitrary location for the fitcheck, and then requiring all flight spacecraft to be present for operations. Further, this measure simplified the complexity of the fitcheck events because the coordination of operations between 20 different spacecraft providers would have been very unwieldy.

Secondly, for the spacecraft providers that were not within the vicinity of the main fitcheck were afforded the option for the mission integration team to bring flight dispensers to the spacecraft builders' locations. This reduced the shipping and handling risks for the flight spacecraft and minimized the disruption of the spacecraft providers' preparations for launch.

This approach was not fool-proof, however. Some of the spacecraft or experiments were not in their flight final configuration at the time of the fitcheck. Subsequently, this made the mission integrator have to carry a fit risk all the way through flight physical integration. Also, one experiment was complete with flight build and test, but the provider had not dressed and tied down harnessing. When the CubeSat arrived for flight integration, the protective wrapping and tie-downs created a clearance issue that required a Non-Conformance and created the addition of stand-offs to disposition prior to launch. This example demonstrates the necessity to force the spacecraft providers to supply the full flight configuration for fitchecks.

Objective D: Use of a Qualified Sequencer Device to Demonstrate Programmable Control of Payload Separations

For missions that require a large number sequencing events for numerous rideshares, such as the 31 payloads on this manifest, a secondary sequencer provision is highly preferable. Most LV separation command systems have a discrete number of independent signals available to command and deploy the satellites on a particular mission. Increasing the number of discrete separation signals to accommodate manifests with large numbers of spacecraft may require hardware changes or additional hardware that would most likely violate their range safety-approved flight configurations and thus drive up launch costs. The use of a mission-specific certified sequencer system downstream of the LV sequencer allows for LV to obtain approvals for a nominal, pre-specified in-flight signaling scheme that will remain unchanged based on mission-specific needs. Figure 3 shows the secondary sequencer used on this mission, which is the box on the top right hand side of the CubeStack adapter. The sequencer scheme was that an LV signal was sent to a sequencer on the top CubeStack adapter, which commanded all of the dispensers on that adapter, as well as the sequencer for the bottom CubeStack adapter.

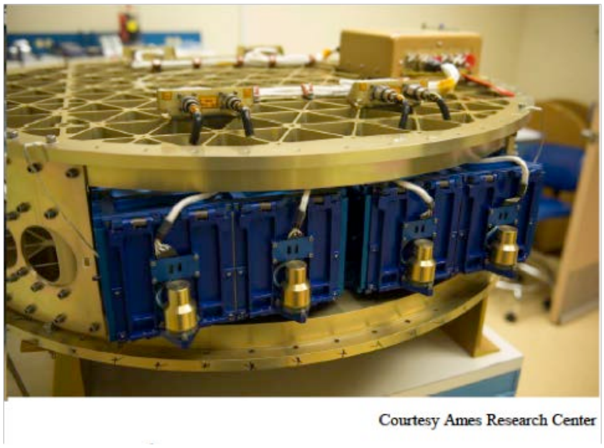

Figure 3: NASA sequencer device flown on this mission[5].

Applying a secondary downstream sequencer scheme allowed the mission integrator to adequately satisfy the LV fitcheck and testing requirements without perturbing the spacecraft build timelines. This also provided more time for separation and re-contact analysis optimization efforts that were devised to satisfy the re-contact requirements discussed earlier in this paper. The flight sequencer systems allowed for reprogrammable timing and sequencing that could be easily modified to accommodate optimized separation sequences that would otherwise not have been possible if the sequencing scheme was locked down much earlier in the mission integration timeline. Finally, a key benefit of using an independent sequencer system was that it allowed for separation or other signaling even after LV mission has been completed.

The benefit of added flexibility brought by using a separate sequencer system was offset by two factors. Firstly, it introduced additional risk concerns for payload providers due to the use of a third-party hardware that was introduced to mission critical events. Also, employing this independent sequencer system complicated mission requirements and the determination of the jurisdictional responsibilities of the separation events. Since the LV provider was only required to prove that a single signal was sent to each independent sequencer, the responsibility of spacecraft separation transitioned from the LV provider to the owner of the mission and/or mission integrator. Not all spacecraft providers may be willing to accept this transition of responsibility.

SUMMARY

Overall, this mission successfully demonstrated many innovative processes, methodologies, approaches and integration hardware that serve to reduce mission complexity and costs for multiple-spacecraft manifest rideshare missions. For the four mission objectives focused on in this paper, each of the concerns raised in the paper's discussion can be further evaluated for improvements to further bring efficiencies and simplicity to the mission integration of these rideshare missions. These advancements, when appropriately applied to both USG and commercial rideshare missions, should aid in reducing the barriers to frequent low-cost access to space for smallsats by reducing real and perceived risks and complexity for LV and primary spacecraft providers.

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[3] Photo courtesy of LoadPath, Inc.

[4] Buckley Steven J, "A systems approach to select a deployment scheme to minimize re-contact when deploying many satellites during one launch mission," Paper presented at the 2013SmallSat Conference, Logan, UT, August 2013.

[5] Photo courtesy of NASA Ames Research Center