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Behind the US's largest Rideshare Launch: Spaceflight's SSO-A

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ABSTRACT

Spaceflight's record-setting SSO-A mission successfully launched 64 customer spacecraft into orbit onboard a Falcon 9 launch vehicle on 3 December 2018. SSO-A is a unique mission because it was a dedicated rideshare mission without a primary spacecraft. All 64 cubesats and microsats shared a ride together to orbit. The diverse number of organizations represented on this mission were all at different levels of maturity for their spacecraft, and this resulted in numerous mission design revisions to SSO-A as the customer manifest changed significantly over the course of the mission. Spaceflight created a flexible hardware architecture, analytical tools to rapidly update mission analyses, strict configuration change control, and quality processes to facilitate these changes and ensure mission success.

SSO-A SMALL SAT EXPRESS: THE BEGINNING

Customer Demand

Spaceflight launched its first customer spacecraft on 19 April 2013. On the surface, this humble beginning was not particularly unique, as satellite have launched as secondary payloads to a prime satellite before. But this time the ride to space was provided by a commercial company that does not build the rocket, does not build the separation system, and does not build the satellite. It was a company that is truly independent of the hardware that sends spacecraft to orbit, and therefor able to leverage all the capabilities and capacities in the commercial market to bring cost-effective launch services to the underserved small satellite launch market. Shortly after this first cubesat launch, customer demand for launch services grew significantly, to include microsats as well as cubesats. The demand was greater than the existing launch capacity, so an audacious plan gradually took shape; to purchase an entire rocket and fill it with small satellites and make a dedicated rideshare mission. Since the majority of customers needed a sun synchronous orbit, and this was the first dedicated rideshare mission, the mission named itself: SSO-A.

Business Case

Space companies love to do cool things. Space companies that stay in business do cool things only if the business case closes. The same philosophy applies to rideshare. A dedicated rideshare mission sounded really cool, but did the business case close? The short answer is yes, but the longer answer involves the flexible mission architecture that enabled Spaceflight to make numerous changes to the manifest as customers dropped off and new customers were added onto the mission. This paper will describe the architecture that made SSO-A possible, the processes that Spaceflight implemented to ensure its success, and the flexible launch campaign plan that brought the plan to fruition.

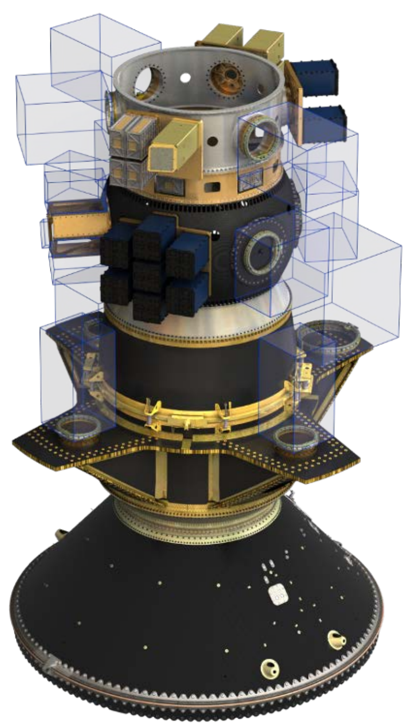

Figure 1: SSO-A "stack" on top of a payload attach fitting. Microsats are represented by opaque boxes.

Original Concept

The original mission architecture for SSO-A was simple; use several structures to launch about 15-20 microsatellites and some cubesats to orbit. Several of the Spaceflight customers were microsatellites that were larger than the Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) standard size, resulting in a mission physical architecture as follows:

- Multi Payload Carrier (MPC) manufactured by Airbus Defense and Space. A carbon composite structure that allow four microsats to be integrated parallel to the rocket thrust axis, with a large area inside for a fifth large microsat. The canister is released by a clampband.

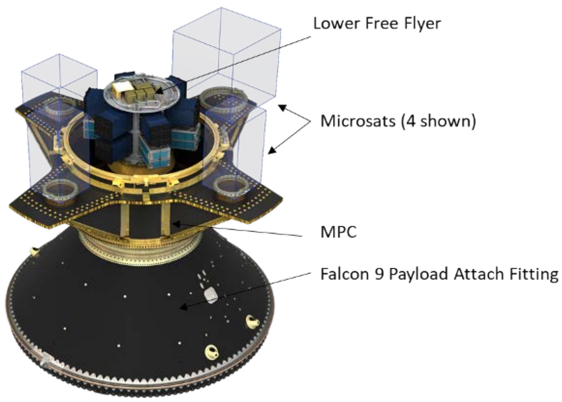

Figure 2: MPC. Note that the microsat that was originally inside the MPC was replaced by a structure called the Lower Free-Flyer that will be discussed later.

- HUB manufactured by Airbus Defense and Space. A composite ring structure that has six 24” circular microsat interfaces.

- ESPA manufactured by Moog CSA Engineering. An aluminum ring structure with six 15” circular microsat interfaces.

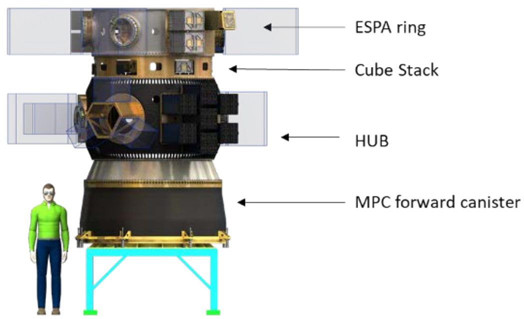

Figure 3: Upper Free-Flyer Configuration. Note that the MPC forward canister is bolted to the HUB above, and connected via a clampband separation system to the MPC lower canister.

The mission concept started with the launch vehicle commanding the separation of the MPC clampband, releasing the upper free-flying segment with a Spaceflight-provided avionics system to command the subsequent separation events. The launch vehicle would then command the separation of the five spacecraft on the MPC, followed by a deorbit maneuver.

This architecture was driven primarily by three factors. First was the quantity of microsats that were anticipated to fly on the mission which led to the two rings with six ports each. Second was the requirement from several customers to integrate vertically onto the stack which led to the selection of the MPC with its four microsatellite platforms. Third was the presence of two large microsat (350-600 kg). These microsats were the two biggest customers on the mission, and they needed a specific volume in excess of the standard offering. The heavier was located inside the MPC and the other on top of the ESPA ring. Ironically, neither of these mission-defining customer would ultimately fly on SSO-A.

MISSION ARCHITECTURE

Flexible Architecture

The key to rideshare is flexibility, and there are three components to flexibility in the space launch industry. The first element are multi-purpose structures and avionics. Flexibility allows Spaceflight to change one customer for another with little or no impact to the overall mission-specific analyses, mission profile, or hardware. Changing a customer no longer triggers complete mission redesign as long as the critical parameters stay within the design envelope. Changing a customer is more like changing an airline ticket than changing the airplane.

Structures

The basic mission architecture was designed to be flexible from the start with six 15” ports, six 24” ports, and four platforms that could accommodate 11” to 24” interfaces. Spaceflight’s engineering team added some unique port adapters to accommodate a much wider variety of interfaces. Some of these interfaces include:

- Dual Port Adapter (DPA). Allows two microsats to be mounted on a single 24” port.

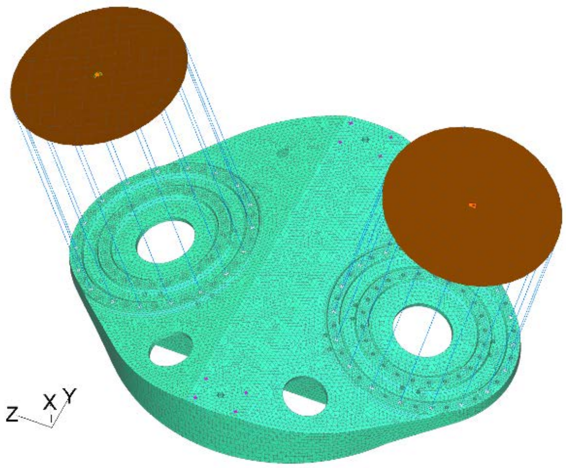

Figure 4: Finite element model of a DPA.

- X-Pod Adapter. Allows up to three X-POD DELTA dispensers a dispenser (built by UTIAS Space Flight Laboratory; not affiliated with Spaceflight, Inc) to be mounted on a 24” port.

- QuadPack Plate (QPP). Allows up to seven QuadPack dispensers to be mounted to a single 24” port.

- Cubesat Dispenser Adapter Plate (CDAP). Allows up to four cubesat dispensers to be mounted to a single 15” port.

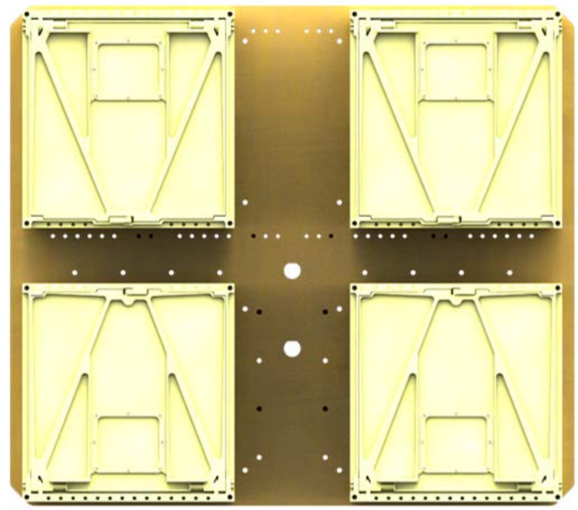

Figure 5: A CDAP with four 12U CSDs. Note the different bolt patters to allow different dispenser types to interface with this structure.

- CubeStack. A spacer between rings that allows up to six cubesat dispensers. Designed and built by LoadPath.

- Lower Free-Flyer. A structure that can carry up to twelve cubesat dispensers and avionics. This structure replaced the microsat customer inside of the MPC, and caused Spaceflight to rename the original free-flyer the Upper Free-Flyer. Designed and built by LoadPath.

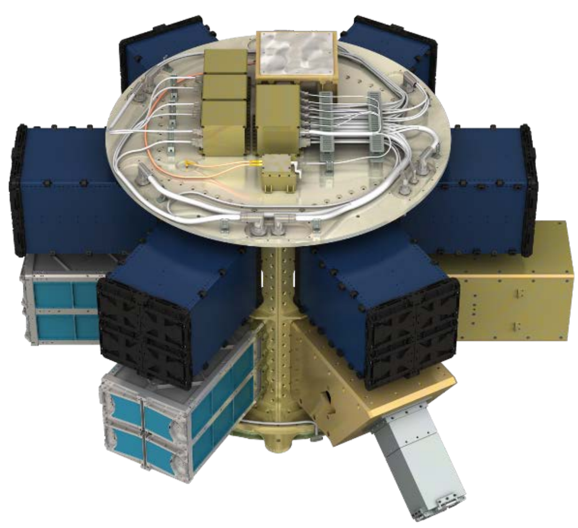

Figure 6: Lower Free-Flyer in flight configuration. Note the two different types of dispensers, the mass model (right) that replaced an unpopulated dispenser, and the DragSail (silver object to the lower right). The avionics system is on top.

- Cube Cone (not flown). A structure that interfaces from an ESPA standard 1575mm diameter to a reduced circular interface (38") with up to six cubesat dispensers. Designed and built by LoadPath.

As the mission developed, several other structures were added. Most notably were the SoftRide Isolation System consisting of sixty titanium spring-dampers built by Moog CSA Engineering, and the DragSail de-orbit devices consisting of a 16 square-meter aluminum sail built by Surrey Space Center. The isolation system was added by a customer with a microsat that was sensitive to high frequency vibrations. The DragSail was added by Spaceflight to ensure that the Upper and Lower Free-Flyers would deorbit within 25 years in the event that their avionics arrived dead on orbit and did not deploy any customer spacecraft.

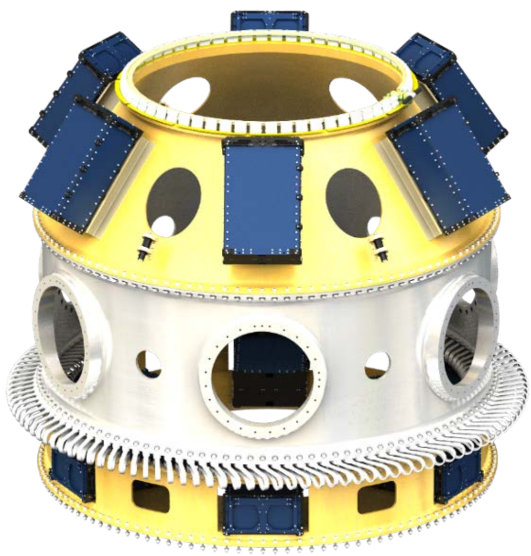

Figure 7: From top to bottom: Cube Cone, ESPA, SoftRide Isolation System, and the CubeStack. The Cube Cone was later removed from the mission when the microsat on top was not ready.

Avionics

The avionics system for SSO-A was designed to be a simple sequencer with a master controller that can supply any of the five types of separation signals on the mission, with expandable signal cards to provide primary and redundant signals to each separation system. The sequencer needed to be reprogrammable, even a few weeks before launch, to create a separation sequence based on the final configuration. The sequencer only had to last through the six-hour deployment sequence and telemetry download, so there were no requirements for radiation hardening or other environmental factors for long-duration space exposure. A total of six systems were procured, two sets for each free-flyer, with each set consisting of an engineering test unit, a flight unit, and a backup flight unit. Ecliptic Enterprises Corporation was selected to build the avionics system, modeled after a similar space-qualified system, after a competitive source selection.

The avionics system was also required to provide telemetry to confirm separation of all spacecraft. To do this, a Space Dynamics Laboratory Cadet UHF radio was used to transmit telemetry to the three Spaceflight Networks ground stations. The simple telemetry packets would provide telemetry confirming the separation signals and separation confirmation. This information was originally planned to be beaconed every minute until the batteries died; about seventeen hours. However, due to government weather spacecraft that use the same UHF frequencies, the mission CONOP was changed to beacon every two minutes only when over the three ground stations, and to shut off after the last pass post-deployment (after about six hours on orbit). This reduced the transmission time by 97%, allowing the government to concur with the frequency use.

There was no uplink capability to the SSO-A avionics. There was no requirement to provide an uplink, and there was no need for any ground commands since the sequencer was an automatic system triggered by free-flyer separation. Furthermore, a ground commanded system would greatly increase the complexity of the avionics and may have led to expensive downstream requirements such as cyber security, encryption, additional antennas or an attitude control system for what was essentially a six-hour mission. The decision to not have an uplink caused significant consternation during the FCC licensing process, to the point that an uplink will be used on future missions with free-flyers, even if the purpose is only to be able to turn off the transmitters in the event of signal interference with other satellite operators.

Two video cameras were part of the original avionics specification, but this element was removed once it became apparent that only a few pictures could be downloaded over UHF given the few ground station passes before the batteries were exhausted. The pictures would have made great promotional material, but they did not directly tie to mission success.

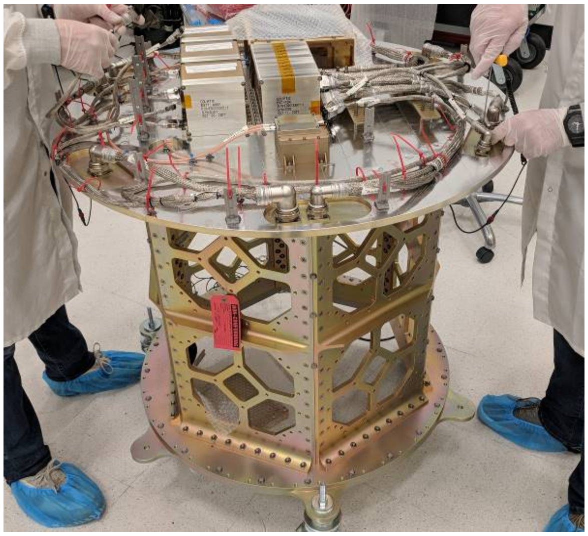

Figure 8: Spaceflight engineers install the avionics on the Lower Free-Flyer.

Having the Right Attitude

The SSO-A mission ended up with two free flying spacecraft dispensers, imaginatively named the Upper and Lower Free-Flyer. Each Free-Flyer had their own avionics and battery power, but neither had propulsion nor attitude control. None of our customers needed a particular deployment orientation, nor should they expect one as a rideshare customer.

Spaceflight's other concern regarding attitude control was the probability of recontact between customers after deployment. Early mission analyses by Spaceflight indicated that the two key factors to reduce the probability of recontact are the relative separation orientation and separation timing. The attitude of the free-fliers at the start of spacecraft deployment was not necessary as long as all of the subsequent deployments were correctly modeled. To do this, Spaceflight created a six degree-of-freedom recontact analysis tool that models the relative distance of every spacecraft given the separation time, spacecraft mass, separation velocity, tip off rates, and the cumulative body rates of the Free-Fliers themselves. This tool allowed engineers to quickly assess the merits of multiple separation sequences and ultimately develop rules for the ever-changing separation sequence (due to changes to customer manifest) so that the probability of recontact could be minimized. Spaceflight's ability to perform the high-fidelity separation analysis of free flying deployers eliminated the need for any attitude control system, and the cost savings were passed down to the customers.

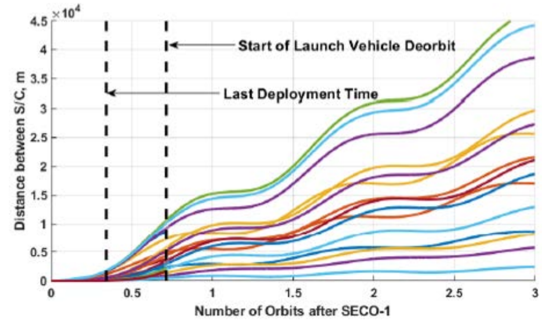

Figure 9: Graph showing the increase of relative distance between customer spacecraft over time.

MISSION PLANNING

Flexible physical architecture is only the first of three factors that enabled flexible launch and resulted in the success of the SSO-A mission. Mission planning is the second major element. Although one of the goals of flexible launch is to reduce the need for multiple mission analyses by the launch vehicle provider, Spaceflight had to run most mission analyses dozens of times to ensure that configuration changes stayed within the bounds expected by the launch vehicle. The critical elements that allowed Spaceflight to do this are discussed below.

Customer Requirements and Verification

Good mission design starts with good mission requirements. Spaceflight created two standard Interface Control Document (ICD) templates that covered all SSO-A customers; one for cubesats and one for microsats. Each ICD followed a standard format, with limited tailoring. All cubesats had the same environmental test requirements no matter where they were on the structure. Microsatellites also had similar requirements, although their specific environmental load test requirements did depend on where they were on the physical architecture. Spaceflight utilized digital tools such as Jama Connect to perform revision control of the ICDs as well as track the verification status of each requirements. Other software tools like JIRA were used to allow the Spaceflight Engineers and Mission Managers to collaborate on customer verification artifacts. These tools allowed everyone in Spaceflight to find the current "source of truth" about customer design, track the status of customer verification, and gave the Engineering team the data they needed to perform mission level analyses, which were then documented in shared internal webpages using Confluence software.

Configuration Control

One of the key tools used to track the configuration of the SSO-A mission was a Visio document called the SSO-A Physical Architecture. On a single page, the following information was documented using text, symbols, and formatting:

- Structural hardware and adapters
- Spacecraft name at each port
- Deployment system at each port
- For cubesats, door assignments and location within the door for sub-3U spacecraft

This document was under configuration control and displayed on a shared Confluence web page for the entire Spaceflight team to see. Underneath the Physical Architecture was a change log. Any time a customer change occurred, it was posted in the change log as a proposed change. Once enough proposed changes were posted to constitute a significant change (meaning a change to deployment system or requiring a new analysis to be performed), Spaceflight held a configuration change board that included Mission Managers (customer status), Engineering (hardware and analysis), Regulatory (licensing and export), and Sales (contracts and new customers). Each proposed change was summarized, and impacts to the entire mission, not just engineering, were discussed.

Often, a "simple" swap of spacecraft would lead to multiple second order effects. For example, microsat changes often required a rebalancing of the stack, updated mass properties, new thermal models, changes to separation system harnessing, and new umbilical harnessing. Even cubesat swaps needed a close look due to dispenser specific designs, mass differences, and deployables.

Once all factors were discussed, each proposed change was accepted or rejected, and a new Physical Architecture drawing was routed for review and approval by the mission leads. For SSO-A, there were 196 dispositioned changes, and revision W of the Physical Architecture is what flew (only 22 revisions published- "Rev O" was skipped because it could be confused with "zero").

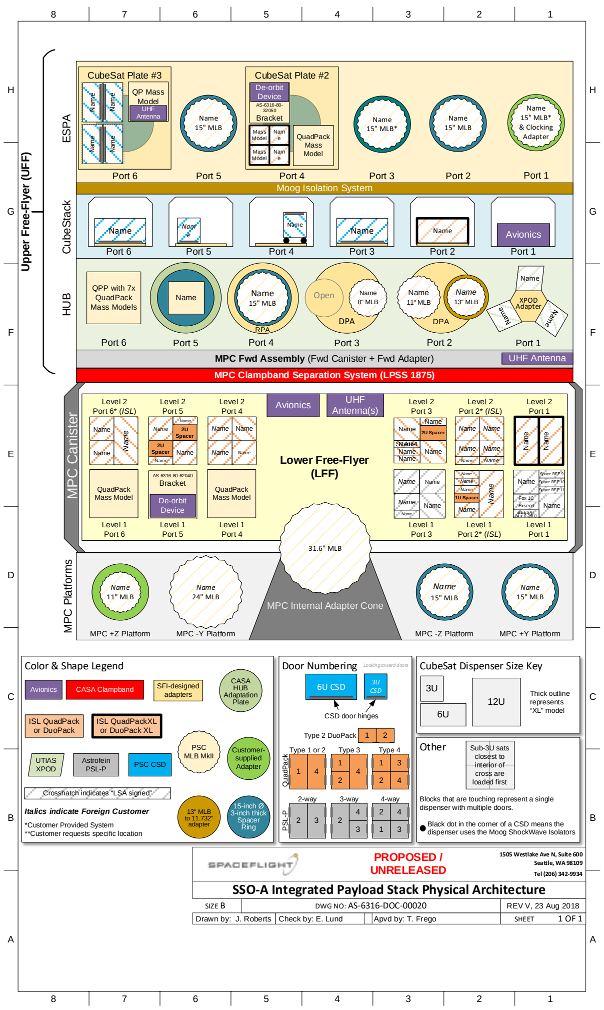

Figure 10: Example of the SSO-A Physical Architecture document which tracked the location of all customers and deployers on the mission.

Mission Analyses

To have a successful mission, all mission analyses must be complete and results reviewed and approved. Mass properties, tip off, thermal, venting, coupled loads, power budget, link margin, separation, loads, orbit lifetime, re-entry debris hazard, vibration, etc… and these analyses must be set up in a way so they can be re-run quickly and efficiently. For SSO-A, there were 88 versions of the SSO-A coupled loads analysis (CLA) model. Now, it is impractical to redo an analysis for every change, not to mention the mental health of the engineering team if they had to redo all analyses for every one of the 196 changes on SSO-A. To bound the problem of an ever-changing manifest, the engineering leads would look at each change to determine which ones need to be redone, and when. Most analyses were re-run before a major design review, but some did not need to be updated. For example, the thermal analysis was not re-run when customers with no thermal requirements were moved between thermally-isolated areas.

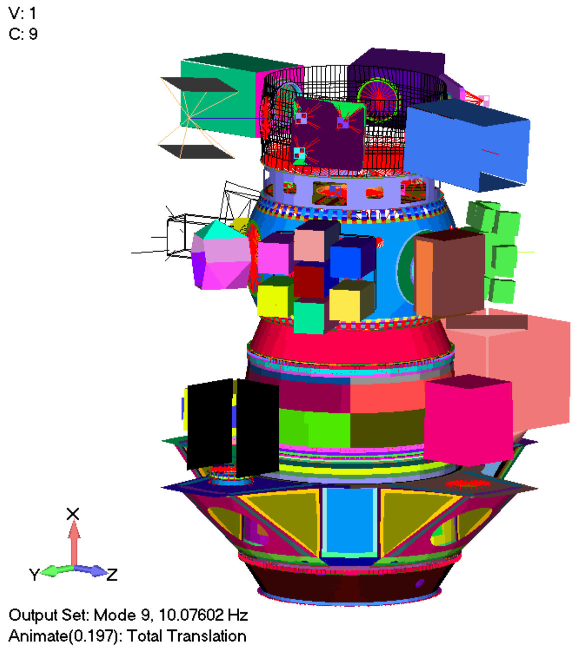

Figure 11: One of the finite element models used to run the couple loads analysis.

Mission Test and Simulation

There is a reason why they say “test as you fly” in the space industry; because you will not have a chance to fix it after launch. But the conundrum facing astronautical engineers is that there are few practical ways to test everything exactly as if it was in space. To address this, Spaceflight ensured that all deployment system hardware and electrical harnesses were tested according to specification. This includes thermal vacuum cycling and reliability testing. Once the hardware was delivered, receiving inspections were performed to ensure no damage occurred during transit and all specifications were met.

It was impractical to perform system-level testing with all of the flight deployers for various reasons, such as deployer cycle ratings and the sheer quantity of systems. So Spaceflight designed and procured sixty Separation System Simulators (SSS) that could be programed to simulate any dispenser, and provide separation signal measurements via ethernet to a test console. These SSSs were connected to the flight harnesses and flight structure for system-level testing. Spaceflight executed eight mission simulation tests and numerous supporting tests in this configuration with the SSO-A avionics system and harnessing. These tests increased in complexity until the full mission profile was tested, from last charge before launch until the near exhaustion of the rechargeable batteries.

Spaceflight encountered several anomalies and non-conformances during system level testing. Each time this happened, the appropriate action was performed per Spaceflight’s quality process, whether a failure review board, non-conformance report, or written product deviation. No issues were wished away; they were ruthlessly examined, documented, and resolved. Throughout the mission there were 16 Failure Review Boards, 75 Non-Conformance Reports, 42 Product Deviations, 57 Requests for Waivers, 62 recorded mission-level risks… and one successful launch! The success of SSO-A reflects a disciplined engineering team that fully embraced quality processes. The quality process and mission simulation tests gave the Spaceflight team confidence in the full system before shipping to the launch site.

Figure 12: Mission Director Adam Hadaller and Integration Engineer Jake Larkin prepare for a full system electrical check in Spaceflight’s Auburn Integration Facility. Note the Separation System Simulators (gray boxes) suspended by the ports to simulate spacecraft deployers.

MISSION EXECUTION

The final component of SSO-A was the successful execution of the mission from the arrival of the first customer, to the last confirmation of separation on orbit. The SSO-A launch campaign was planned to be 60 days from start to finish. This would allow cubesats that only had 90 days of battery charge to integrate with several weeks of margin in the event of a launch delay. The first twenty days of integration occurred at the Spaceflight Integration Facility (SIF) in Auburn, Washington, for all cubesats and four microsats. Integration was followed by five days of packing by Spaceflight and three days of trucking to Vandenberg Air Force Base (VAFB), California. The first 22 days at VAFB encompassed the processing, fueling, and integration of the final eleven microsats and the assembly of the SSO-A stack onto the Falcon 9 Payload Attach Fitting (PAF). At L-10 days, Spaceflight turned over the completed SSO-A stack to SpaceX for encapsulation and integration onto the Falcon 9 rocket.

Flexible Execution

Inevitably, something will not go as planned when you have 35 organizations trying to integrate 64 spacecraft in fifty days. So Spaceflight planned the integration schedule with that in mind. The launch campaign began at the Spaceflight Integration Facility with cubesats. The cubesat integration used two workstations, each focused on filling one dispenser at a time. There were usually two customers, one at each station, in the morning, and two customers in the afternoon to load their cubesats. This plan did deviate to account for sub-3U cubesats that were required to all integrate simultaneously, and for customers with multiple cubesats or pre-loaded cubesats in customer-provided dispensers. This sustainable flow deliberately had several vacancies in the schedule for the inevitable issues that cropped up. Seven spacecraft did not show up and missed the mission. Five customers had to reschedule for various reasons, but only by a few days. One spacecraft was lost for a week at a shipping hub in Memphis (note: pay the extra money for tracking services). And one customer completed integration as scheduled, only to realize that they wired their solar panels incorrectly two days later while reviewing their closeout photography (they were able to return, deintegrate, repair their spacecraft, and reintegrate). Even though Spaceflight could not anticipate these specific issues, the flexible schedule allowed all of our customers who showed up to integrate their spacecraft with enough time for Spaceflight to pack everything up and ship to Vandenberg.

Figure 13: Spaceflight Mission Managers rehearsing cubesat integration with a mass model at the Spaceflight Auburn Integration Facility prior to the start of the launch campaign.

Vandenberg integration was much more challenging because it involved ten customers (five US and 5 foreign) to be integrating at the same time in the same location on a U.S. Government military base. There were 29 Spaceflight employees and 235 customer employees who submitted badging information to participate in the launch campaign. Some of these customers are direct commercial competitors to each other, and some customers represented sensitive U.S. Government spacecraft. Spaceflight gave each customer a 10' x 16' (~3 by 5 meter) integration area that was visually and physically screened off from each other, and foreign and U.S. workers wore different colored hair nets on the Payload Processing Facility (PPF) floor. Each customer was limited to a maximum of five people in the clean room at a time. Spaceflight worked one 12-hour shift per day, with all hazardous operations occurring during a night shift. Spaceflight set up the master schedule based on inputs from each customer, with the output having one spacecraft complete integration onto the SSO-A structure per day. Although there were a fair share of issues encountered by spacecraft teams, all teams were able to meet their integration times and there were no major changes to the SSO-A processing schedule while at VAFB. This achievement was a direct result of having a clear understanding of each customer's processing requirements, establishing a reasonable integration schedule, communicating that schedule and integration facility constraints to each customer early, and having clear lines of communication throughout the launch campaign.

Legal and Regulatory

The legal and regulatory requirements to execute rideshare missions are massive. Not only did

Spaceflight need to obtain licensing for SSO-A, but also validated and verified the licensing of each customer on the mission. Several customers were from countries that do not have an agency that deals with licensing spacecraft, which made the verification of licensing rather challenging.

<u>Mission-Level Licensing</u>

- Federal Aviation Administration (FAA). Launch license (by the launch vehicle provider)
- Federal Communications Commission (FCC). Space station license (communication frequencies and orbit debris assessment)
- Department of Transportation (DOT). Special permit (for shipping lithium ion batteries over road)
- Department of State Technology Assistance Agreement (TAA). For technical discussion between foreign parties, Spaceflight, and the launch provider at the launch site.

<u>Customer-Level Licensing</u>

- Required licensing to ship, launch, deploy, operate and communicate with their spacecraft (e.g. FCC, NOAA, other country of origin based licenses).
- International Telecommunications Union (ITU) frequency registration.
- Department of State Technology Assistance Agreement (TAA) or Export Administration Regulation (EAR) licenses. . Foreign customers only, separate from the launch site TAA.
- Registration with Combined Space Operations Center (CSpOC). For on orbit identification and collision avoidance notifications.

One customer was unable to obtain the appropriate license in the timeline required and therefore the spacecraft was sealed inside of their dispenser. Several days later, the license was granted, but too late to unseal the dispenser or provide a technical solution to allow for deployment of the spacecraft. Although the specifics of this incident are beyond the scope of this paper, this was an unfortunate example of an uncertain regulatory requirements for a unique customer, and the consequences of not obtaining licensing.

RESULTS

So how did SSO-A really go? SSO-A launched 64 spacecraft on two free flyers into the desired orbit. One spacecraft was sealed into their dispenser due to delayed licensing and did not deploy. All spacecraft that were supposed to deploy were deployed. Of the 63 deployed spacecraft, 59 were successfully contacted by their owners, a 94% success rate.

In addition to the customer success rate, the Combined Space Operations Center (CSpOC) did not observe any recontact events between spacecraft on the mission. The DragSails for both free flyers deployed as expected based on observations taken by the Surrey Space Center.

Figure 14: Picture of the Spaceflight team during the SSO-A launch campaign.

CHALLENGES

The Spaceflight team overcame many challenges and established hardware, processes, and teams that will improve future rideshare missions. The small satellite community is still growing, and it is challenging to hold together a mission of this size without a fully mature customer base. Customer readiness (technical, regulatory, and financial) and experience with launching spacecraft spans a very broad spectrum. This introduces a variable of unpredictability in executing multi-manifest missions, which may translate to higher launch costs as launch providers budget for that risk. Spaceflight's approach, a mix of large and small flexible rideshare missions on different launch vehicles, is an answer to support the diverse small satellite market during this period of rapid growth.

Launch capacity is an issue that has been improving recently, albeit only to keep pace with the increasing number of spacecraft and still with poor schedule reliability. One of the reasons why SSO-A was created was due to an abundance of small satellite customers, but a lack of affordable launch opportunities.

Spaceflight continues to expand launch opportunities by making early strategic commitments to emerging small and medium launch vehicle providers, and creating new multi-manifest rideshare missions in partnership with our existing global portfolio of launch providers. More access to space is a win for everyone.

Regulatory issues are another challenge as the number of spacecraft in orbit increase. Particular to SSO-A is the need to identify all of the spacecraft on the mission. As of 10 June 2019, there are 12 spacecraft (18%) from SSO-A who have not self-reported their spacecraft to the CSpOC. This highlights a challenge to the small space community going forward, because accurate and timely identification of spacecraft is needed to perform space traffic management functions.

EPILOGUE: FUTURE OF RIDESHARE

SSO-A was a very unique mission designed to serve the growing small satellite market when there were few choices for affordable access to space. Spaceflight forecasts rideshare customer demand for more diverse launch opportunities, across a network of rockets, with flexible architectures and contracting terms. Combining over thirty organizations on one large mission may be part of meeting that market need, but it cannot sustain it alone. At least a dozen missions a year with up to fifteen customers at a time gives our existing smallsat industry the critical combination of both capacity and frequency to meet their mission needs and supports the growing launch vehicle industry as well. In whatever form they take, rideshare opportunities will remain essential to enable the next generation of new smallsat entrants and growth, just as it did with SSO-A.

Figure 15: The Spaceflight SSO-A mission patch. Each nation that had a payload on SSO-A is represented by their national flag. The spacecraft shown on the patch are not the actual spacecraft that flew in order to maintain customer spacecraft confidentiality.

Acknowledgments

Spaceflight would like to thank our key vendors on this mission: Ecliptic Enterprise Corporation, Airbus Defense and Space, Moog CSA Engineering, Planetary Systems Corporation, Innovative Space Logistics, Astrofein, ATA Engineering, and thank the U.S. Air Force 30th Space Wing and 18th Space Control Squadron, and Space Exploration Technologies, and most of all, our great customers who made this mission possible!

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