SSC18-XII-06

PLANNING FOR END-OF-LIFE SATELLITE DISPOSAL; THE STORY OF A HIGH STRAIN COMPOSITE TIP-ROLLED DE-ORBIT SAIL

Bruce Davis, Andrew Tomchek, Dana Turse,
Ryan VanHalle, Kamron Medina, Will Francis, Chris Pearson
Roccor
2602 Clover Basin, Suite D, Longmont, CO 80503; (303) 200-0068
Bruce.Davis@roccor.com

ABSTRACT

In Q4 of 2017, Roccor of Longmont, Colorado was approached by an ESPA class spacecraft provider with the request to deliver a de-orbit sail within a six-month period. The 140kg spacecraft was to be placed in a circular ~750km, high inclination orbit and needed to deploy a drag device at the end-of-life with a surface area greater than 4m^2. After a series of concept iterations with the customer, dual rectangular tip-roll sails were selected, each supported by a deployable High Strain Composite (HSC) boom and offset 45º from the spacecraft's structure maximizing the cross-sectional area and aerodynamic stability. The rectangular sails, each measuring 4m x 0.5m, are named Roll-Out Composite, FCC Approved Life Limiting Deorbit Devices otherwise known as **ROC-FALL**. Their low-cost design boasts a simple and robust deployment mechanism utilizing few machined parts that is easily resettable to allow multiple deployment-cycle tests for mission assurance. This paper first provides a broad overview of the space debris problem and a summary of current technologies that are known for end-of-life satellite disposal. This paper then details the ROC-FALL design, and chronicles the recent flight build and lessons learned.

INTRODUCTION

In 2009, a 1,000kg deactivated Russian Kosmos satellite flying at approximately 790km altitude collided with an operational US-built Iridium communication satellite. The incident was the first accidental hypervelocity collision disabling a functional spacecraft in low Earth orbit and *created a debris cloud of approximately 1,000 pieces larger than 10 cm (4 in)*. This followed another larger, intentional event in 2007 when the Chinese government successfully conducted an anti-satellite weapon test on a Fengyun weather spacecraft *releasing over 3,400 detectable objects* at an altitude around 860km. Collectively, these two events increased the number of catalogued space debris in low earth orbit by 50%, shown in Figure 1 and dramatically increased international awareness of the growing orbital debris problem [1, 2].

During the early years of spaceflight, minimal consideration was given to end-of-mission disposal of objects placed in orbit. In select cases, assets were intentionally brought down or placed in a '*graveyard orbit*' prior to final shutdown, however the overwhelming majority of these spacecraft were simply turned off at the end-of-life and left adrift, putting their fate in the hands of orbital mechanics alone. While this practice caused a gradual increase of orbital debris, the concern of risk to future spacecraft was not a primary focus. This was in part due to the limited number of assets in space as well as the practice of launching generally large spacecraft allowing for ease of tracking and avoidance via ground-based systems.

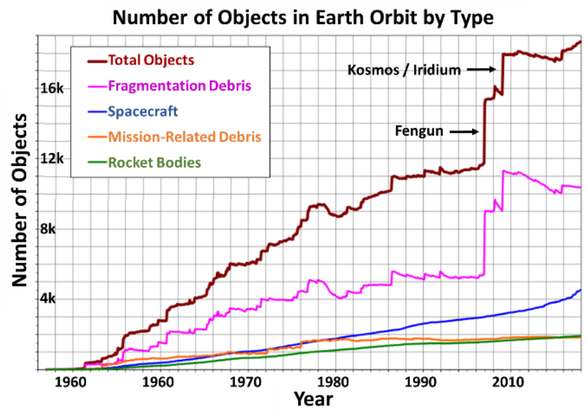

Figure 1: Number of known objects in space from the NASA Johnson Orbital Debris Office [3]

Around turn of the century, the emergence of the '*small satellite*' and supporting launch capabilities kicked-off a general diversification of the space faring industry. The introduction of the CubeSat and ESPA class standards as well as an increase in commercial launch providers enabled government and commercial entities, of various economic backgrounds, to be patrons of the once elite space realm. Today, the small satellite industry is growing with hundreds of commercial ventures suppling full spacecraft and components in support of space exploration, earth science, military reconnaissance, and global communication, among others. In numerous cases, commercial entities are currently developing constellation-based satellite systems, each consisting of more than 1000 small spacecraft providing global communication and internet services. This explosive growth, illustrated in Figure 2, has increased the concern of orbital debris and the need for regulation especially for higher orbits where aerodynamic drag via the earth's atmosphere is limited and the "natural" de-orbit process takes generations.

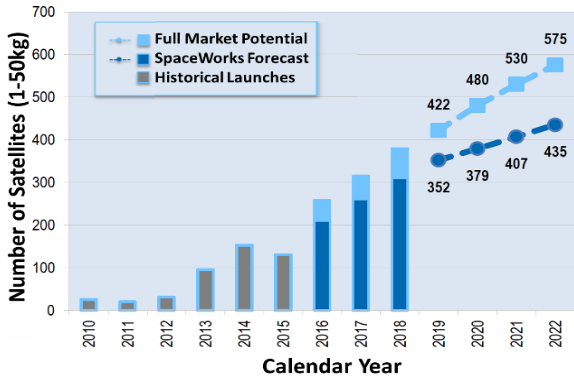

Figure 2: SpaceWorks's 2016 SmallSat forecast showing substantial growth of the industry [4]

In the early 1990s, the steady growth of orbital debris warranted the creation of the Inter-Agency Space Debris Coordination Committee (IADC). This inter-governmental forum of spacefaring nations provides recommendations for best practices to enable the overall reduction of space debris, including spacecraft design methods, on-orbit operations and asset removal timelines at end-of-life. The recent in-space debris producing events coupled with the explosive growth of the small satellite community has caused increased focus on the debris experts and the IADC. In many cases, recommendations put forth by the group have been adopted by regulating bodies to ensure resources are dedicated to combating this problem.

In this paper, we discuss the development and flight integration of the ROC-FALL de-orbit device for a specific small satellite mission. This program had to meet a 25-year de-orbit requirement enforced by the United States Federal Communications Commission prior to receiving a license to operate on-orbit, which it was able to do with the addition of two ROC-FALL systems. This paper starts by providing an overview of existing de-orbit techniques with a focus on systems that rely on aerodynamic drag and discusses advantages of the various approaches. The subject then focuses on the design and flight build of the ROC-FALL system, delivered in Q2 of 2018. This paper concludes with lessons learned for this rapid 6-month, design-to-flight installation schedule.

EXISTING DE-ORBIT SOLUTIONS

To lower a spacecraft's orbit, thrust must be exerted on the body to change the orbital velocity. There are three known methods to enable this: the **first** and perhaps best recognized is the rocket thruster. Here mass from the spacecraft is expelled away from the vehicle at high velocity to utilize Sir Issac Newton's third law of motion whereas *equal and opposite reactions* provides a net force on the body. This can be performed with short-term high thrust chemical propulsion or long-term low thrust electric propulsion technologies. The **second** method utilizes a long electrodynamic tether that couples electrical charges with the Earth's magnetic field to generate a braking force on the orbiting spacecraft. The **third** method, which is of interest to the present satellite customer, is to deflect fast-moving atoms (primarily dissociated oxygen and nitrogen) that are already present in the ionosphere to provide drag. This method is sometimes referred to as aerodynamic drag although the effect is calculated using rarified gas dynamics due to the extremely low densities of gas atoms. Similar to one's experience holding an umbrella on windy day, the spacecraft's aerodynamic drag efficiency is directly related to the projected surface area of the system.

Multiple groups have developed aerodynamic decelerators that change the projected surface area of the spacecraft on-orbit. Below are a few examples of prominent technologies under development or demonstrated on-orbit. It should be noted that in some cases, solar sails are used for inter-planetary travel, relying solely on solar wind; however, the technology may also be applicable to the aerodynamic decelerator problem.

Planar Sail Technologies

Numerous deployable sails have been demonstrated on-orbit with the primary architecture consisting of a folded thin-film (i.e. Mylar or polyimide) sail that deploys via four radial booms on a central hub. During nominal deployment, a motor slowly unwinds the hub, driving the radial booms outward, and pulling out the deployable sail one-fold at a time, until the finalized, square-like cross section is tensioned. Flight heritage of this architecture include *NASA's NanoSail-D* in 2010 ($10m^2$) [5], *The Planetary Society / Ecliptic Lightsail* in 2015 ($32m^2$) [6], and the *University of Surrey, Surrey Space Center InflateSAIL* in 2017 ($10m^2$) [7]. The latter uses an inflatable mast to offset the sail from the spacecraft body to increase stability. A significantly larger version of this architecture is currently under development by NASA for the *NEA Scout mission* ($86m^2$) [8] and is scheduled for launch in 2020. A $1200m^2$ solar sail was ground tested by *L'Garde* in 2013 however was not flown. Advantages of this architecture focus on the packaging efficiency, the utilization of a rigid structural member to support the sail and a controlled, methodical deployment. Challenges present are the use of a thin tensioned membrane that is challenging to fold and susceptible to tearing and the need to incorporate a motor with sensory feedback to control deployment, all of which lead to higher production and qualification costs.

In efforts to simplify the four-boom sail architecture, some organizations utilized stored strain energy within the furled booms to deploy, hence enabling a rotating hub while eliminating the need for a motor. Examples of this technology include *The University of Toronto Space Flight Laboratory's CanX-7* (4m^2 /0.75 U) [9] launched in 2016, and *The University of Glasgow / Clyde Space AEOLDOS* (1.5m^2 /0.4 U), [10]. While this approach eliminates the motor and hence mass and mechanism complexity, the release of strain energy and dynamics during deployment must be considered in the design. In addition, the finite stored strain energy must be properly characterized to balance deployment speed in the thermal worst-case environment. Another variant of this system is *MMA's dragNet* (14m^2) [11] launched in 2013. Here in place of the deformable booms are a series of interconnecting articulating rigid beams, otherwise known as a pantograph structure. Here the strain energy is more characteristically controlled via torsional springs; however, this system has many moving parts, which inherently can increase cost and complexity.

Taking another engineering approach, the architecture identified above can be modified to eliminate the rotating hub all together. Here a strained or rigid articulating boom may be co-wrapped with the sail around a central structure. An example of this is the *Cranfield University / Surrey Satellite Technology's TechDemoSat-1* [12], launched in 2014. This system used articulating booms wrapped around the square shaped perimeter of the spacecraft and deployed via springs. Another example of this approach is *Space Mind's ARTICA* (1m^2) [13], currently under development. Here four booms are co-wrapped within a thin 1U cross section. Overall, this architecture has many advantages including deployment simplicity, leading to low-cost mechanisms as well as packaging efficiency. Challenges remain in the need to protect the sail during a dynamic deployment and the effective utilization of the volume available in the central hub.

Another notable architecture is to deploy and maintain in-plane stiffness via angular momentum. This was demonstrated on an impressive scale by *JAXA's IKAROS* mission (200m^2) [14] in 2010 and is currently recognized as the first solar sail to travel between planets. Advantages of this system are the extreme packaging efficiency and lack of need for booms, shedding considerable mechanism challenges. This architecture however relies on an active spacecraft control system to spin-up prior to the deployment as well as to maintain a constant spin rate during operations.

Other Drag Based De-orbit Technologies

Spacefaring inflatable systems are another area of intrigue; in fact, they date back to the pioneering days of spaceflight with *NASA's Echo* [15] program. Here the newly formed agency inflated a 30m diameter sphere in 1960 to conduct atmospheric sounding experiments and to act as a communication relay. The packaging efficiency and the absence of stiff elements makes this technology conducive for a wide range of mission architectures. Configurations such as large spherical balloons, flat planes and even conical aeroshell shapes for atmospheric re-entry protection have been considered. Inflation is usually via the sublimation of a solid material when exposed to heat or vacuum. Specific to deorbit devices, a 1.2m cone-shaped drag-system has been studied by *Andrews Space* [16] as well as a 2m diameter spherical balloon for CubeSats called *GOLD*, by the *Global Aerospace Corporation* [17]. Advantages include the high packaging efficiency, utility of forming various shapes and in the case of spheres, the elimination of the need for pointing to maximize cross sectional area. The challenges however remain significant with concerns focusing on maintaining pressure and susceptibility to punctures during deployment or from orbital debris.

Tether Based De-Orbit Technologies

Electrodynamic tethers can provide de-orbit capability via interaction with the ionosphere. *The Tethers Unlimited Terminator Tape* [18] unspools a 250m long conductive tape at the spacecraft's end-of-life. The tether provides a gravity gradient attitude stabilization and increased drag due to the electro-magnetic interaction with the ionosphere. The advantages of this technology are the dramatic packaging efficiency and theoretical performance. Challenges however stem from the limited on-orbit heritage and concern of entanglement or susceptibility to damage due to other space debris.

ROC-FALL TECHNOLOGY

In Q4 of 2017, Roccor of Longmont, Colorado was approached by an ESPA class spacecraft provider with the request to deliver a de-orbit sail within a six-month period. The 140kg spacecraft will be placed in a ~750km, high inclination orbit and, in order to meet the 25-year deorbit requirement, needed to deploy a drag device at the end-of-life with a surface area greater than 4m^2. After a series of concept iterations with the customer, two rectangular tip-roll sails were selected, each offset by 45º from the spacecraft's structure to maximize the cross-

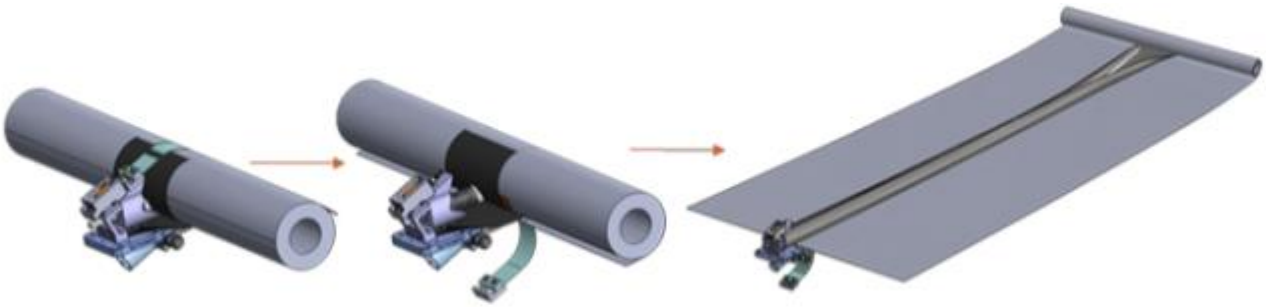

Figure 3: ROC-FALL System Deployment stowed (left) and deployed (right)

sectional area and aerodynamic stability. The rectangular sails, each measuring 4m x 0.5m, are named the Roll-Out Composite, FCC Approved Life Limiting De-orbit Device, otherwise known as **ROC-FALL**.

Deployment Architecture Overview

The ROC-FALL De-orbit Device consists of a rectangular sail supported by a High Strain Composite (HSC) boom that is co-wrapped on a spool and restrained with a strap for stowage. An image of the system in a furled state is shown on the left side of Figure 3. During launch and throughout the spacecraft's mission lifetime, the steel strap secures the system in the stowed configuration. To initiate deployment, an actuator is triggered which releases the strap and allows the strain energy of the thin walled boom to rollout the composite boom and sail. To start the motion, a compression spring kicks the boom away from the chassis allowing the boom to regain its natural cross section and stiffness. Stored strain energy within the boom continues to propel the sail and boom until the system is fully deployed. To avoid a chaotic, uncontrolled deployment, the laminate architecture of the composite boom is specifically tailored for this application. This enables the slow release of strain energy allowing the spool to roll out smoothly without risk of ballooning or kinking that would be experienced with a metallic substitute [19].

The ROC-FALL system is unique to other de-orbiting technologies because the system uses a fiber-reinforced sail that is structural in nature. Where most de-orbit sails utilize thin polymer films requiring four radial booms for deployment and tensioning, the ROC-FALL system requires only a single boom to deploy and support the sail, like a mast on a ship. The integral stiffness of the sail provides enough rigidity to keep the sheet from collapsing and deforming, removing the need for batons or other supporting structures. However, the sail has enough flexibility so that it can be co-rolled with the HSC boom. The fiber reinforced composite materials used in the sail are also robust and tear-resistant, which protect against impacts from micrometeoroid and orbital debris.

Architecture Flexibility

ROC-FALL provides mission-to-mission flexibility by allowing the customer to specify the required sail area. The length, width, and stowed diameter can be changed to meet varying satellite requirements.

This system is currently tailored for ESPA class satellites where available drag surface area is limited, and deployment of the sail needs to avoid other components protruding from the satellite. Multiple ROC-FALL deorbit devices can mount to a satellite face, as shown in Figure 4, where the sail is shown deploying away from the satellite at a 45° angle.

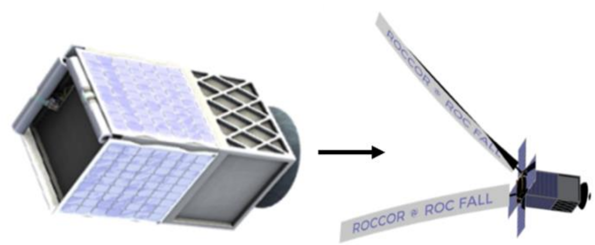

Figure 4: ROC-FALL's unique design allows for improved flexibility for S/C mounting consideration

System Description

The ROC-FALL system can be broken into two main sub-systems: the sail, and chassis as shown in Figure 5. The sail subsystem consists of the sail, boom, and center hub while the chassis contains the machined and COTS hardware used to support the sail and boom during launch and after deployment. The sail stows into a Ø6.3cm × 50cm cylindrical envelope, while the chassis is 8.5cm tall × 6.0cm wide and located in the center region of the system. The full system weighs less than 1.0kg, and when deployed the ROC-FALL sail area is $2m^2$ (4m × 0.5m rectangle).

The sail and HSC boom are supported kinematically during launch by the chassis root and the strap. The strap tension is controlled via a compression spring in the base, providing flexibility for variations in assembly and

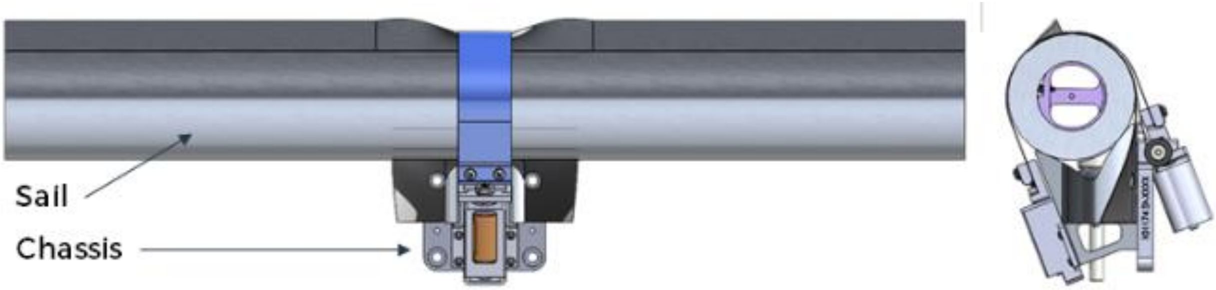

Figure 5: ROC-FALL stowed for launch, depicting a top and side view

thermal effects on orbit. Above the root, a TiNi Frangibolt actuator constrains the strap. Once the bolt is released, the tension strap swings away from the stowed sail, allowing for a quick and clean deployment. As the HSC boom begins to deploy, it recovers its original tubular cross-sectional geometry and closes around the root plug, providing a stiff and stable root boundary condition and controlling the orientation of the deployed sail.

The base of the sail is tensioned through constant force springs attached at the chassis. These springs allow for shear compliance between the sail and boom during the co-wrapping process. The distal ends of the sail and boom are mechanically fastened to a metallic hub, which is keyed. Tooling is used to rotate the hub allowing the sail to wrap consistently during the stowage process. Once the sail and boom are fully rolled against the chassis, the mechanism is reset by fastening the retention strap to the Frangibolt restraint and applying a torque to the hub ensuring the system is properly preloaded.

FLIGHT SYSTEM

The ROC-FALL effort went from concept to flight delivery within six months. To accomplish this, three principals were applied: 1) design for simplicity and robustness, 2) vertically integrate the team and allow for rapid R&D efforts supporting a "test early and fast" mentality, and 3) apply an "agile" quality process that allows for efficient documentation and quality control while providing a smooth transition between prototype and flight manufacturing.

Technical Approach

Achieving a simple, robust design required leveraging existing technologies. The strain-energy-driven tip-roll boom allowed for a reliable, low-part count approach with limited interfaces. A laminate architecture was selected that was tunable, allowing the team to tailor the strain energy throughout the development process and testing. The absence of a motor and supporting electronics further eliminated interfaces and testing while the use of a COTS actuator with extensive flight heritage enabled a rapid mechanical design. Finally, a previous sounding rocket mission, partnered with the Colorado Space Grant Consortium (COSGC) at the University of Colorado Boulder, provided a testing platform for the tip-rolled boom technology.

For the second approach, the sail and chassis subsystems were developed and tested in tandem during the R&D stage of the program. Creep (i.e., stress relaxation within the composite) and its relationship to the deployment energy of the boom were concerns early on, and multiple laminates were manufactured and tested. This took advantage of a vertically integrated team with constant feedback from the composite fabrication and quality teams early during the design process. New techniques were established in-house for full-length composite boom manufacturing, and new sail architectures were explored. An engineering prototype of the ROC-FALL system was manufactured within 2.5 months of kick-off and was instrumental in working through assembly, system-level performance and risk assessment. This is shown in Figure 6 below.

Figure 6: Early engineering prototype development

Qualification vibration testing was performed on the prototype to validate system design and FEA model predictions. In addition, the analysis team elected to test-to-failure, revealing further limitations in the design resulting in better characterization of system margins and small design tweaks. Finally, the prototype was used to develop acceptance criteria to ensure the sail and boom are stowed consistently from one deployment to another.

Quality processes and practices were adopted early that allowed for efficient documentation and quality control.

These provided unrestricted creative design and testing of prototypes and enabled an efficient transition to flight manufacturing. The quality team was present during the design stage of the program, helping the team to define the framework and expectations for the eventual flight build. This enabled a seamless transition to a stricter and more controlled flight assembly and testing process.

Flight Build

The flight hardware was fabricated in Q1 of 2018 with two units assembled in early April. Due to the lessons learned with the engineering prototype and coupled with system simplicity, the full assembly was completed in less than two days. Follow-on acceptance testing included a series of deployments performed both prior to and after vibration (Figure 7) and thermal cycling. One final deployment test was performed utilizing spacecraft power prior to the flight stowage (Figure 8) and integration onto the spacecraft.

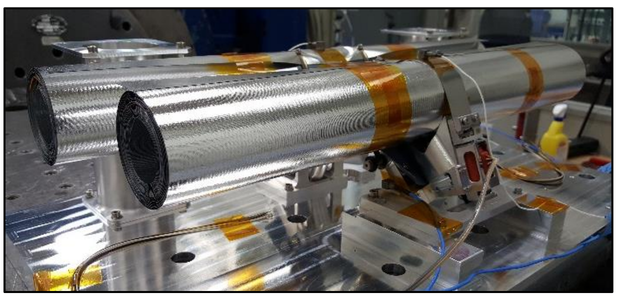

Figure 7: ROC-FALL flight hardware during acceptance vibration testing

Figure 8: ROC-FALL final stowage prior to spacecraft integration.

LESSONS LEARNED

During the ROC-FALL development, a combination of former lessons learned influenced the execution of the program while were documented for future efforts. This section describes a few prominent examples.

While high strain composite laminates are designed to be compliant and deformable to natural handling, they remain susceptible to accidental degradation during installation. This ranges throughout the full life cycle of the thin walled composite structure from mandrel extraction to the installation into the ROC-FALL chassis. While this issue was known by the Roccor team early on, there were a few occurrences during testing where the system underperformance was directly tied to damage during unintended composite handling. This was resolved by minimizing the hands-on processing of the booms and incorporating tooling to ensure a controlled load was imparted on the boom during each phase of integration.

High strain composites are susceptible to stress relaxation, whereas after large sustained strains, energy is bleed out of the system, lowering the material's overall flexural recovery forces. In the case of the ROC-FALL system, this creep effect had the potential to reduce the deployment authority of the composite boom. This induced the risk of the system stalling out during deployment, leaving the sail only partially exposed. One of the larger hurdles of this program was developing a boom laminate that would deploy with the proper authority after being stowed for the lifetime of the mission. Multiple tests were performed to determine the effects of creep at various storage periods and temperatures. The laminate architecture was specifically designed to combat the worst-case environment. While this issue was well understood at program kickoff and incorporated into the design, the verification criteria for ensuring this performance was not well defined during the development phase. This was further compounded by the difficulty of performing long duration testing during a rapid program. As a result, several early tests performed provided a false sense of requirement verification, leading to surprises on EDU hardware testing discovered after the CDR milestone. This was easily rectified with tweaks to the laminate architecture, however scrapped a series of fabricated booms originally intended for flight.

Given that this program was schedule and cost driven, a full engineering unit prototype was fabricated and tested to mitigate risk early on. As a result, several limitations within the system design were discovered early in the program development, the majority of which focused on the mechanism chassis. Examples relate to potential catch points on the strap preload spring or the interfacing between the strap and root chassis. Identification of these issues early on provided ample time to incorporate changes in the flight design. The insistence of this prototype cycle was the result of lessons learned from previous programs and enabled a flight build, test and delivery campaign void of surprises.

Finally, the ROC-FALL engineering development unit provided an excellent testbed to understand the deployment mechanics and process to ensure proper stowage from one deployment to the next. The stowed mechanics (wrapped consolidation force, strap preload, centering within the chassis) of this system are highly non-linear with multiple boundary conditions, friction forces, and materials all effecting the stowed dynamics of the system. As such, the presence of the EDU hardware enabled the engineering to loosely handle the system and better understand the processes needed to be imparted into the build/stowage instructions.

CONCLUSIONS

In Q4 of 2017, Roccor was asked to provide an end-of-life deployable drag sail for an ESPA class spacecraft to ensure compliance with the FCC 25-year de-orbit regulations. Over the course of a six-month period, Roccor designed, fabricated and delivered two customized rollout sails, each providing 2m^2 of deployed surface area. This deployable system is unique to current state of the art systems in that the sail is deployed via a tip-roll. In addition, the sail diverges from traditional ultra-thin Mylar based materials and utilizes a thicker, fiber reinforced sail that is structural in nature and resistant to tearing. In addition, the architecture enables a simplistic deployment mechanism utilizing few machined parts and ultimately yielding a low-cost system. The flight build was completed in Q2 of 2018 and the delivered units are currently installed on the spacecraft with an expected launch date in Q4 of 2018.

REFERENCES

1. Levin, E., Pearson, J., and Carroll, J., "Wholesale debris removal from LEO,"*Acta Astronautica*, Vol. 73, Dec. 2011, pp. 100-108
2. Liou, J.-C., "Active Debris Removal – A Grand Engineering Challenge for The Twenty-First Century," presented at 21st AAS/AIAA Space Flight Mechanics Meeting; 13-17 Feb. 2011; New Orleans, LA, AAS Paper No 11-254
3. Anz-Meador, P., "Orbital Debris Quarterly News" *The Orbital Debris Program Office*, NASA Johnson Space Center, Vol. 22, Issue 1, (Feb 2018) *https://www.orbitaldebris.jsc.nasa.gov*
4. Doncaster, B., "SpaceWorks' 2016 Nano/ Microsatellite Market Forecast", *Proceedings of the AIAA/USU Conference on Small Satellites, Launch* (2016) SSC16-II-01
5. Johnson, L., et. al., "NanoSail-D: A Solar Sail Demonstration Mission", *Acta Astronautica*, Vol 68, (2011), 571-575
6. Ridenoure, R., et. al., "LightSail Program Status: One Down, One to Go", *Proceedings of the AIAA/USU Conference on Small Satellites, Year in Review* (2015) SSC15-V-03
7. Viquerat, A., et. al., "Functional and Qualification Testing of the InflateSail Technology Demonstrator", *Proceedings of the 2nd AIAA Spacecraft Structures Conference, 2015 AIAA SciTech Conference*, AIAA 2015-1627, Kissimmee, FL.
8. Few, A., et. al., "Testing and Development of the NEA Scout Solar Sail Deployer Mechanism", *Proceedings of the 44th Aerospace Mechanism Symposium, NASA Glenn Research Center, (2018)*
9. Cotten, B., et. al., "On-Orbit Results from the CanX-7 Drag Sail Deorbit Mission", *Proceedings of the AIAA/USU Conference on Small Satellites, Year in Review* (2017) SSC17-X-06
10. Harkness, P., et. al., "Development Status of AEOLDOS – A deorbit module for small satellites", *Advances in Space Research*, 54 (2014) 82-91
11. MMA Design LLC, dragNET^{TM} De-Orbit System, http://mmadesignllc.com/products/dragnet-de-orbit-system/
12. Hobbs, S., et. al., "De-orbit Sail Design for TechDemoSat-1", *Proc. of the 6th European Conference on Space Debris,* (2013), 22-25
13. Space Mind, ARTICA https://www.npcspacemind.com/in-space-now/
14. Tsuda, Y., et. al., "Flight Status of IKAROS deep space solar sail demonstrator", *Acta Astronautica*, (2011), Vol. 69, p 833-840
15. D'Alto N,. et. al., "The Inflatable Satellite", *Invention and Technology Summer* (2007), Vol. 23, Num. 1 pp. 38–43.
16. Andews, J., et. al., "Nanosat Deorbit and Recovery System to Enable New Missions", *Proceedings of the AIAA/USU Conference on Small Satellites, Mission Enabling Technologies II* (2011) SSC11-X-03
17. Sarzi-Amade, N., et. al., "Gossamer Orbit Lowering Device (GOLD) for Safe and Efficient CubeSat Deorbit", *Proceedings of the AIAA/USU Conference on Small Satellites, Pre-Conference Workshop* (2015)
18. Forward, R., et. al., "Terminator Tether: A Spacecraft Deorbit Device", *Journal of Spacecraft and Rockets*, Vol. 31, No. 2, (2000).
19. Murphey, T., et. al., "High Strain Composites", *Proceedings of the 2nd AIAA Spacecraft Structures Conference, 2015 AIAA SciTech Conference, Session on Composite Materials for Spacecraft Structures*, AIAA 2015-0942, Kissimmee, FL.