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VULCAN, ACES AND BEYOND: PROVIDING LAUNCH SERVICES FOR TOMORROW'S SPACECRAFT

Rich S. DeRoy,[*] John G. Reed[†]

With the announcements of new developments, partners, products and services over the last year United Launch Alliance is transforming the path to space. We will discuss many of the steps along the revolutionary path bringing the Vulcan, Advanced Common Evolved Stage (ACES) and SMART Reuse. We then delve into the enabling technologies that are being investigated. We cover the capabilities each system will bring to the market and touch on the scalability they provide. Finally we touch on the redefinition of launch service that these systems accompany and the benefits to the spacecraft GN&C community.

INTRODUCTION

With 103 consecutive, successful launches by the end of 2015, United Launch Alliance continues along the path of transforming access to space, one launch at a time. Twelve missions flew last year on all three variants of ULA launch vehicles: Atlas V, Delta IV, and Delta II. These missions span the range of space launch markets, including national security, scientific exploration, human spaceflight support, and commercial communications. Morelos-3, a Mexican communications satellite, marked ULA's centennial launch and was the first in a string of three Atlas launches from two coasts within 30 days. The successful launch in mid-December of the Orbital ATK Cygnus spacecraft capped this busy year with ULA's entrance into the International Space Station cargo resupply market.

The year ahead is equally impressive as ULA executes another busy manifest while undergoing multiple development programs. The first flight of 2016 marks the last launch for the GPS block 2 constellation and the first launch of the common avionics system. Developed as a more affordable solution for vehicle control, common avionics is one step along the path towards revolutionizing space access. Development of the Vulcan booster, the Advanced Cryogenic Evolved Stage (ACES), and SMART Reuse evolve our current capabilities towards a single launch system that expands the potential for the nation's use of space. Together with next generation avionics and advancements in Guidance, Navigation & Control system capabilities, these evolutionary steps redefine the concept of launch service. This transformation benefits the spacecraft community with more capable, affordable, and flexible access to space.

[*] Engineer, Mission Design, United Launch Alliance, 7858 S. Chester St., Centennial, CO.
[†] Sr. Technical Fellow, Mission Design, United Launch Alliance, 7858 S. Chester St., Centennial, CO.

COMMON AVIONICS

ULA kicks off the first launch in 2016 with the cut in of the new common avionics system. The launch of GPS IIF-12 in February 2016 represents the culmination of several years of development work to update avionics hardware and flight software as well as simulation and test environment tools. Common avionics addresses the challenge of parts obsolescence any program with the longevity of EELV must face. ULA has taken advantage of this opportunity to design and produce a more affordable solution for vehicle control that will also expand the capability of our launcher fleet.

Figure 1. GPS IIF-12 is the inaugural flight of Common Avionics.

To manage schedule risk while maintaining high launch rates, we used a phased approach to implement the common avionics system. The successful launch of 12 missions in 2015 and 14 missions in 2014 is a testament of the benefits afforded by this approach. GPS IIF-12 includes the first roll out of common avionics hardware and flight software on the Atlas V launch vehicle. Late 2016 marks the phase-in for Atlas of the Inertial Navigation Control Assembly (INCA) flight computer and rate gyro systems. The common avionics suite will then fly on Delta IV Medium and finally the software and systems will be upgraded to operate the Delta IV Heavy.

Fundamentally, common avionics provides the basic functions of rocket control: from power to actuation, from data sensing to telemetry transmission.[1] The implementation of common avionics stretches beyond these essentials with the simultaneous development of common flight software and a common simulation suite.

Leveraging the heritage of both Atlas and Delta product lines, a single flight software program will be capable of operating the entire fleet. From a Guidance Navigation & Control perspective, this enables a cost effective and more rapid targeting and analysis approach as the Atlas Generalized Guidance algorithms are migrated to Delta. Flight software capability is also expanded to include additional targeted impulse opportunities. This allows the flight program to target and achieve compliant disposal orbits whenever sufficient additional impulse is available. More complex mission designs that require the launch vehicle to fly to multiple orbits can also be targeted. Mission designs with secondary payloads benefit directly, as deployment can occur in orbits fully separated from the primary mission. This capability is invaluable in supporting ULA's current expansion in the rideshare market as well as future growth as the delivery vehicle of choice for cis-lunar space.[2]

The new common simulation suite has been successfully exercised through flight software parameter development and validation during GPS IIF-12 mission integration. The suite consists of the Simulation Program for Advanced Rocket Trajectory Analysis (SPARTA) engineering simulation tool and the ULA Kommon Integrated Test Environment (KITE) real-time test bed environment. SPARTA is currently used for trajectory design, optimization, and flight software parameter development and validation on both Atlas V and Delta IV. KITE is currently used for real-time, hardware in the loop simulation for the common avionics fleet, and supports both Fault Tolerant Inertial Navigation Unit (FTINU) and next generation INCA flight computers.

Moving to a new simulation platform provides the opportunity to streamline processes and ensure the required capabilities, as well as flexibility for future growth, are present. Both SPARTA and KITE are designed to accommodate the fleet evolution to ULA's next generation launch system, the Vulcan rocket. With Centaur as the initial upper stage of Vulcan, and the bulk of the common avionics system tied to the upper stage, we can leverage the lessons learned from fielding on Atlas to enable a smooth transition to Vulcan. ULA's foresight to expand common avionics from solely addressing parts obsolescence to developing new flight software and simulation tools lays the foundation to seamlessly integrate Vulcan into the ULA fleet.

VULCAN DEVELOPMENT

Our on-going efforts to reduce cost and increase capability while maintaining the best value for our customers naturally leads ULA down the path to a next generation launch system. Newly introduced competition in national security space launch coupled with ULA's desire to expand market share beyond EELV provides the impetus to evolve our launcher fleet. The track record for reliably delivering payloads to space is remarkable for both the Atlas V and Delta IV launch systems. While keeping our heritage of reliable access to space, we are evaluating the entire booster system for cost and manufacturability to design an innovative solution that is more affordable, accessible, and commercialized.

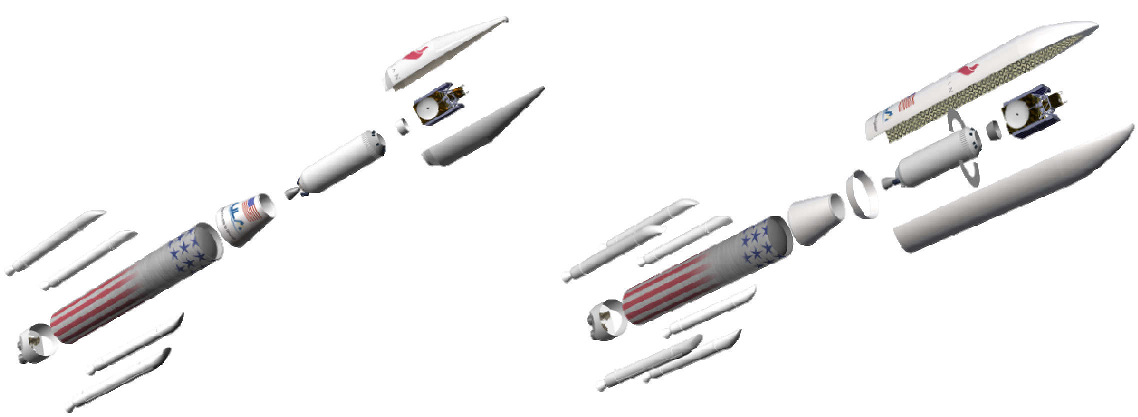

Figure 2. Vulcan 4 m and 5 m expanded views.

Focusing initially on the booster stage, Vulcan has the double benefit of increasing ULA's competitiveness in multiple space launch markets and eliminating our reliance on the Russian-built RD-180 engine. The later provides the leadoff for the booster design, as launch systems are designed around the engine. With the booster engines accounting for the bulk of the first stage cost, any design objective targeting affordability must address this component. Currently, two American-made engines are in consideration to fly on Vulcan: the methane-fueled BE-4 designed by Blue Origin, and the kerosene-fueled AR-1 designed by Aerojet Rocketdyne.

The high-performance, oxygen-rich staged combustion BE-4 is the primary candidate, with two engines attached to the booster generating a combined thrust of 5 million N (1.1 million lbf). Expanding the width of the booster tanks compared to Atlas increases the propellant capacity to accommodate the lower density methane fuel and deliver increased performance. Up to six solid rocket boosters (SRBs), developed by Orbital ATK, can be added to the Vulcan booster to generate the additional impulse necessary for heavy payloads or higher energy missions. The strategic partnerships with Blue Origin and Orbital ATK support ULA's commitment to improving efficiency and performance at lower costs.

The Vulcan booster successfully completed the preliminary design review prior to the end of 2015. Design continues on both Vulcan variants in support of a future down select to a single booster engine provider. Similar to the phased roll out of common avionics to the ULA fleet, we are fielding the next generation launch system over multiple steps.

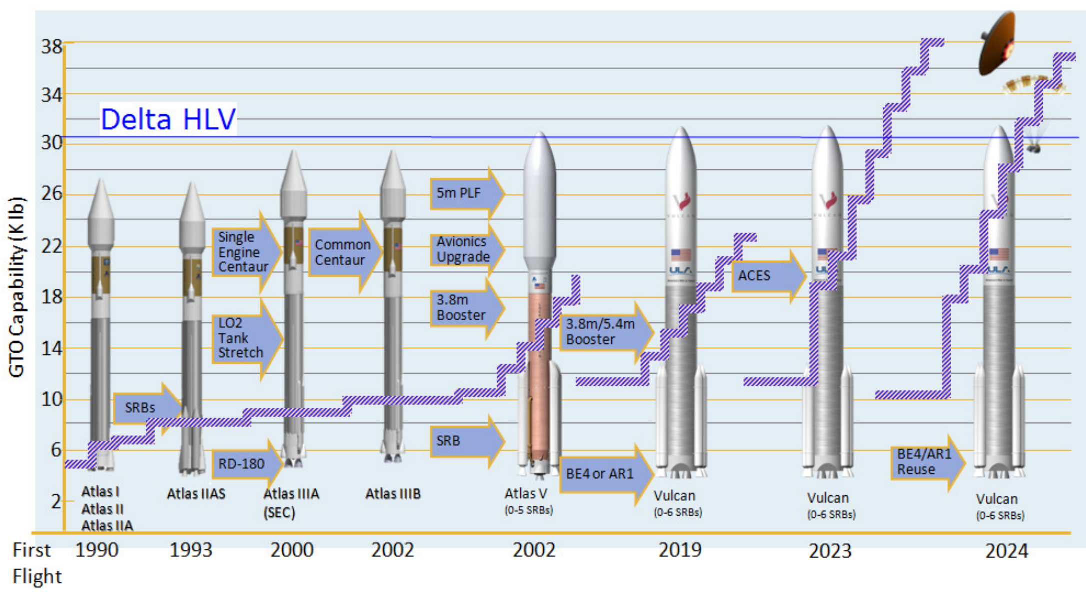

Figure 3. Atlas to Vulcan Vehicle Evolution.

Step one supports an initial launch capability in 2019, and sees the Vulcan booster matched with the Centaur second stage and either 4 meter or 5 meter payload fairings. To augment the total impulse of these configurations, up to four SRBs can be added to the 4 meter configuration and up to six SRBs can be added to the 5 meter. The Vulcan family exceeds the capability of Atlas V, allowing us to serve the vast majority of our customer's needs. Step two marks the replacement of the Centaur second stage with the more powerful Advanced Cryogenic Evolved Stage (ACES) in 2023. This combination will exceed the capability of our current Atlas and Delta families.

After fielding Vulcan in 2019, all three launcher families will coexist for a period of time as Atlas is ramped down and Vulcan is ramped up. The commonality in ULA mission design driven by common flight software, avionics, simulation suite, and processes allow for this seamless transition. We have already proven the ability to integrate three different launcher families with last year's mix of Atlas V, Delta IV, and Delta II launches. Atlas will continue to fly until Vulcan with Centaur is certified to launch missions for our government customers. The inclusion of ACES with the Vulcan booster and accompanying expansion in capability paves the way for retiring the Delta IV Heavy. Ultimately, ULA's transformation to a single, more affordable Vulcan launch system opens up brand new potential for the nation's use of space.

REVOLUTIONARY CHANGE – GROWING SPACE

The current space launch market has few profitable business sectors. National security, scientific exploration, human spaceflight, and communications make up the bulk of available business for launch providers. ULA is active in all of these markets. We launch national security payloads that provide critical support to the warfighter including weather, mapping, military communications, intelligence and surveillance. We launch NASA scientific missions to low Earth orbit, Pluto and beyond to further our knowledge of the universe. We support NASA human spaceflight activities on the International Space Station by partnering with Boeing to launch astronauts on the CST-100 Starliner, and Orbital ATK and Sierra Nevada to launch the Cygnus and DreamChaser cargo resupply spacecraft. Finally, we launch commercial communications satellites for both U.S. and international customers. Nevertheless, the challenge of high cost to orbit still remains. Vulcan addresses this in the near term, but it is evolutionary, not revolutionary. A self sustaining economy in cis-lunar space can significantly reduce transportation costs while growing the market and increasing launch rate.[2]

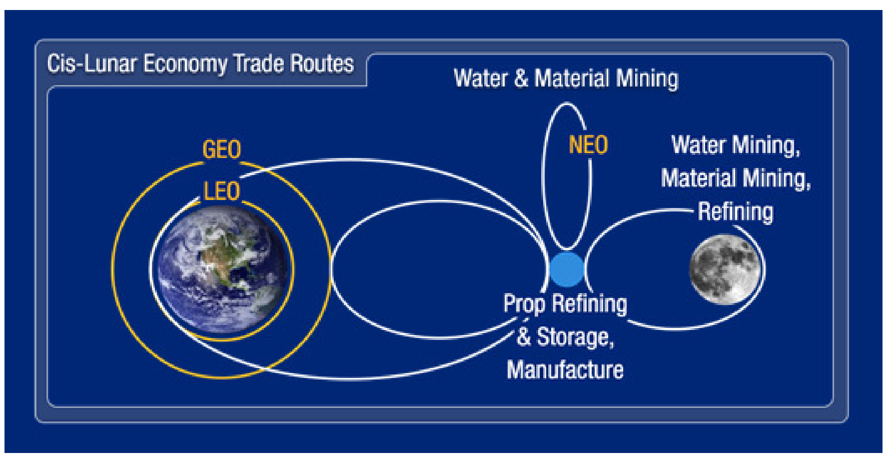

Figure 4. Cis-lunar Economy Trade Routes.

The cis-lunar econosphere includes trade routes between Earth LEO and GEO orbits, Lunar orbit, Earth/Moon Lagrange Points, and near Earth objects. These routes permit water and raw material mining, propellant refining and storage, and in-space manufacturing.[2] Transfer vehicles traveling along these routes can be self sustained by a near endless supply of high energy liquid oxygen (LO2) and liquid hydrogen (LH2) propellants, mined and refined from water on the Moon and asteroids. Outside of Earth's gravity well, goods and people can be transported with significantly less vehicle performance than transporting solely from Earth's surface. For example, traveling to geosynchronous Earth orbit from the moon takes less than 10% the energy as from Earth.

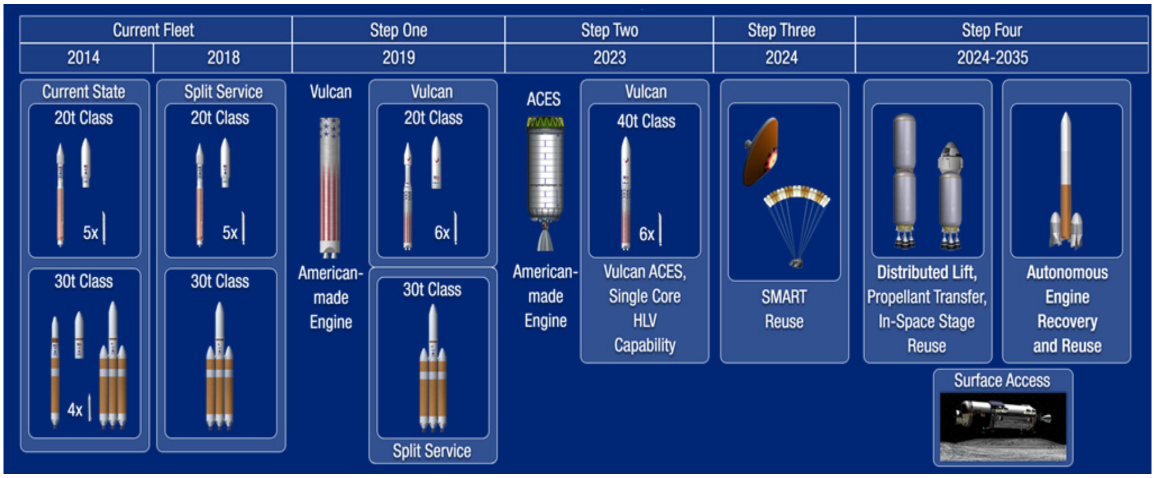

Figure 5. ULA's Evolution Roadmap.

ULA's roadmap for the future expands beyond Vulcan to include the enabling technologies for a cis-lunar space economy. The ACES second stage, next generation avionics, and reusability all support the path towards a growing economy in space transportation. Advanced upper stages with robust propulsion systems allow transfer vehicles to self sustain in space through in-situ re-fueling. This complex operation necessitates rendezvous capability and requires low cost avionics with advancements for long duration spaceflight. A self sustaining transfer vehicle implies reusability. This concept can extend to the booster engine systems to further collapse launch costs. The roadmap builds on ULA's strengths, benefiting customers with reduced cost and increased flexibility.

ACES and Integrated Vehicle Fluids

The ACES stage concept leverages our extensive experience in LO2/LH2 propulsion systems from decades of lessons learned with Centaur and the Delta Cryogenic Second Stage (DCSS). ACES will combine this experience with the resourceful Integrated Vehicle Fluids (IVF) concept to create a state-of-the-art LO2/LH2 upper stage.[3] When paired with the Vulcan booster, ACES exceeds the performance requirements of Delta IV Heavy, which provides the motivation to realize the concept as ULA evolves to a single launch system.

ACES is designed to carry 68,000 kg (150 klb) of propellant, 3 times the propellant load of Centaur. To minimize intrusion when mating the larger upper stage with the Vulcan booster, ACES structural dimensions are designed to match the length of Centaur and to match the diameter of Vulcan. Maintaining the same total vehicle height reduces changes to the ground support equipment at the Vehicle Integration Facility (VIF) and the launch pad. Maintaining the same vehicle diameter as the five meter Vulcan/Centaur configuration reduces aerodynamic differences while providing an efficient path for loads.

To deliver the impulse afforded by the larger propellant load, ACES will generate between 450 and 650 kN (100 and 150 klbf) of thrust. This is at least four times the thrust of Centaur. The Aerojet Rocketdyne RL-10, a Blue Origin BE-3 derivative, and the XCOR 8H21 engine are the three candidates for powering ACES.[3] Depending on the thrust provided by each engine, ACES is capable of supporting single, dual, and quad engine configurations with corresponding thrust structure and feedline designs.

Figure 6. ACES concept with multiple engines and innovative IVF technology.

A key differentiator for ACES is the innovative IVF system, a Hydrogen/Oxygen auxiliary power unit. IVF uses free boiloff hydrogen and oxygen to generate electricity, autogenously pressurize tanks, and feed GH2/GO2 reaction control system (RCS) thrusters. Inclusion of the technology on ACES eliminates several costly systems that traditionally limit the potential applications of an upper stage. Missions are currently designed within the constraints of vehicle battery power, Helium supply, and Hydrazine supply. By generating electricity, pressurizing tanks, and feeding an RCS system, IVF relieves these constraints on upper stage performance and replaces these costly systems with a single, more affordable solution.

IVF is an enabling technology for evolving ACES into a fully reusable, high-performing transporter in cis-lunar space. So long as gaseous Hydrogen and Oxygen remain in the tanks, the system can continuously generate power, pressurize tanks for engine starts, and provide attitude control thrust. This extends mission durations from hours to weeks. In-space refueling extends mission durations indefinitely. Helium and Hydrazine propellants are no longer needed in the supply chain. Upgrades present in common avionics allow for targeting the multiple orbital planes of cis-lunar space via propulsive burns using either the main engine(s) or GH2/GO2 RCS thrusters. Next generation avionics expand the capability to include complex on-orbit operations.

Next Generation Avionics

Though currently fielding common avionics, we are already evaluating designs for the next generation of low cost avionics. By using scalable technology upgrades, we will support the current customer base as well as long duration missions, integration of multiple state sources into a single navigation solution, two-way communications, and rendezvous proximity operations.

Continuing the theme of phased evolution, we are constantly looking for opportunities to leverage the upper stage as a space based test-bed for evaluating next generation avionics elements or expanding our knowledge of other systems.[4] ULA recognizes the growing demand for affordable access to space for small development, science and operation payloads. The rideshare capability uses the EELV Secondary Payload Adapter (ESPA), the C-Adapter Platform (CAP), and the Aft Bulkhead Carrier (ABC) to provide low cost options for space access without the need of a dedicated launch vehicle. Next generation avionics sensor packages can be integrated with these systems and fly on Centaur as technology demonstrators. Rapid development and fielding facilitates testing of multiple sensor suite and proximity computer combinations in a flight like environment. Mission profiles can be tailored after separation of the primary payload to characterize system performance in various space environments. Integrating sensor packages and avionics with existing Centaur upper stages expedites the development of Autonomous Rendezvous and Docking (AR&D) technology necessary for cis-lunar space operations.

SMART Reuse

Given our consistent focus on developing a more affordable launch system, ULA is pursuing recovery and reuse capabilities for Vulcan. Historically accounting for over half the cost of the first stage but a quarter of the mass, the engine is the highest value per unit mass for recovery and reuse. Our Sensible Modular Autonomous Return Technology (SMART) reuse concept aims to recover the booster engines after first stage burnout. The SMART reuse approach, including the economics of recovery and reuse, has been the topic of a separate paper.[5]

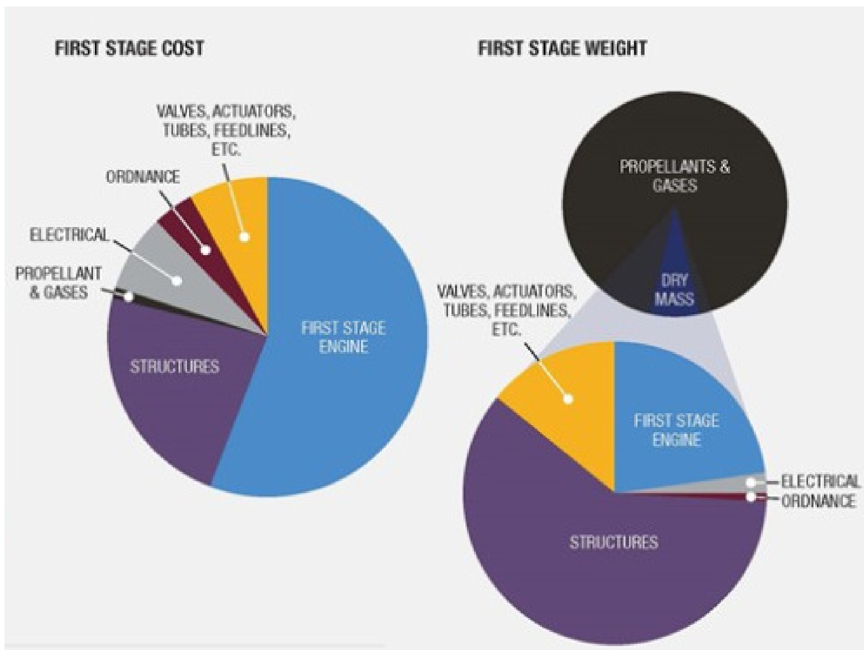

Figure 7. Historical First Stage Cost and Weight Breakdown.

In the SMART reuse concept of operations, a Hypersonic Inflatable Aerodynamic Decelerator (HIAD) decelerates the engine package jettisoned from the booster after first stage burnout. Aeroshells for atmospheric deceleration have historically been limited by the diameter of the launch vehicle shroud. The HIAD overcomes this constraint. It can be densely packed during flight and then inflated exo-atmospherically to cover an area exceeding launch vehicle geometric limits. After initial deceleration from the HIAD, a parafoil deploys to guide the payload for a precision mid-air recovery with a helicopter. The engine package is transported by the helicopter to a location on a land or sea platform for final recovery. Once recertified, the engines can be re-attached to a new booster stage for reuse.

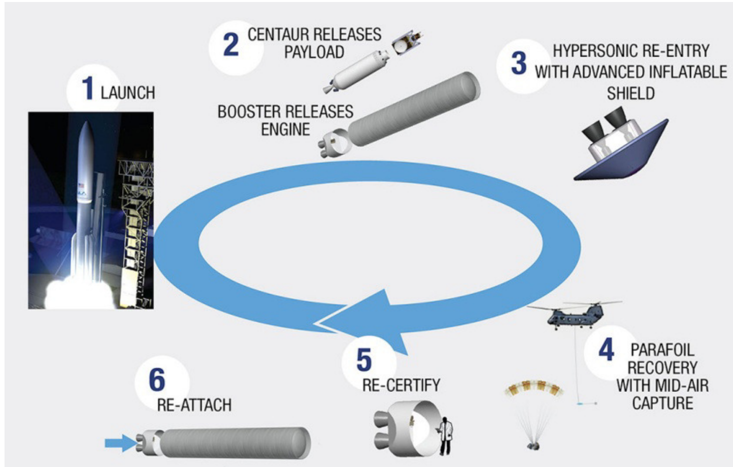

Figure 8. SMART Reuse Conops.

SMART reuse takes advantage of the reusability potential inherent to the BE-4 design. The engines are recovered without subjecting them, and the surrounding booster stage, to any unnecessary stressing flight environments caused by a boostback maneuver. Likewise, launch vehicle capability is not penalized by the significant performance holdback required to bend the velocity vector back towards the launch site and decelerate the stage for landing. Instead, with SMART reuse customers can benefit from near similar performance capability at a collapsing cost of lift.

Guidance, Navigation, and Control System Evolution

ULA's roadmap for this evolutionary change benefits from the scalability of current Guidance, Navigation & Control system capabilities. Our previous flight experience is built on demanding mission designs, often with multiple payloads separated into different target orbits on a single launch. This flight learning is the basis for maneuvers to efficiently guide vehicles along the trade routes of cis-lunar space.

From a Guidance and Navigation perspective there are exciting challenges ahead as we leverage the inherent robustness of Generalized Guidance algorithms to facilitate expansion of the capability to cover rendezvous and proximity operations. To cover the full cis-lunar environment we will develop a scalable architecture to allow inclusion of the requisite sensors and capabilities for each mission type. Blended navigation will integrate additional sensors to provide enhanced state knowledge. Relative navigation will aid rendezvous and proximity operations with knowledge relative to target objects. In the cis-lunar realm we will also be computing the more complex gravitational effects and using this information to better predict vehicle state. This enhanced state knowledge would be coupled with enhanced target calculations to allow the onboard Guidance system to determine the optimal placement for the various burns required. All in all, operating in cis-lunar space provides the opportunity for new and innovative approaches.

Recovering booster engines present additional Guidance and Navigation challenges. Mission design efforts are underway to characterize the booster flight environment under performance and guidance hardware/software dispersions. System capabilities within guidance are being explored to shape the booster flight profile to reduce state dispersions at burnout. Innovative targeting solutions and a guided parafoil descent ensure the first stage engines jettison within the flight envelope for mid-air recovery.

From a Controls aspect there are also interesting challenges. With the incorporation of IVF and its engine, we enter a new era with gimbaled RCS thrusters and continuous forces operating on the vehicle. Shifting to a gimbaled attitude control system while doing rotational and translational control opens a whole new area of investigation for us. Operating in cis-luanr space further expands the areas of investigation. The team is already engaged to understand and shape the options and implication of system scalability.

Evolution of the GN&C system opens up new possibilities in mission design and launch services. Distributing lift across multiple launches to carry propellant and payloads into space combined with the rendezvous capability to transfer propellants in LEO greatly increases lift capacity. This revolution in capability and cost can serve both the existing market space and emerging markets in cis-lunar space like commercial habitats, commercial asteroid mining, and space solar power. Launch service is redefined to cover a system that collapses the cost of lift while increasing flexibility for tomorrow's spacecraft.

CONCLUSION

ULA is embarking on an exciting course to redefine launch service for tomorrow's spacecraft. Steps towards a more affordable launch system are already happening with the inaugural launch of common avionics in 2016. The development of the Vulcan booster along with the announcement of strategic partnerships furthers ULA's commitment to reducing costs while increasing capability. ULA is expanding the space launch market with a pioneering vision of transportation within the cis-lunar econosphere. The development of ACES, next generation avionics, and SMART Reuse evolve our capability to support both current and emerging space launch markets. Evolution of GN&C capabilities in tandem with the overarching roadmap increase flexibility and facilitate innovative solutions for our customers.

REFERENCES

[1] J.G. Reed and B. Lathrop, "United Launch Alliance: Recent Experiences 2013", Guidance, Navigation, and Control 2014, Vol 151, Advances in the Astronautical Sciences, AAS-14-126, 2014.

[2] G. Sowers, "Transportation Architecture for Cislunar Space", Space Solar Power 2015, Orlando, FL, December 2015.

[3] J. Barr, "ACES Stage Concept: Higher Performance, New Capabilities, at a Lower Recurring Cost", Space 2015, Pasadena, CA, AIAA 2015-4495, August 2015.

[4] J.G. Reed, "Upperstage Extensibility for Testbed Applications", 2011 IEEE Aerospace Conference, Big Sky, MT, March 2011.

[5] M.M. Ragab, F.M. Cheatwood, S.J. Hughes, and A. Lowry, "Launch Vehicle Recovery and Reuse", Space 2015, Pasadena, CA, AIAA 2015-4490, August 2015.