System-of-Space Systems Architecture Utilizing Existing Space Assets to Complete and Re-Supply the International Space Station

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The United Launch Alliance (ULA) has been developing a low-risk cost-effective approach for delivering assembly elements, outfitting hardware, science payloads, and re-supply cargo to the International Space Station (ISS) in the post-Shuttle decade. Rather than developing new space vehicles, ULA's approach leverages existing space assets to create a practical systems-of-space systems architecture that satisfies the projected annual upmass requirements of ISS. This is a responsible approach because it ensures maximum utilization of the more than $5 billion of U.S. taxpayer and corporate investments in developing existing domestic space systems, launch vehicles, ground infrastructure and processes, and trained personnel. Further, utilizing existing, proven, and operational space assets minimizes development costs and risks associated with complex space systems, while improving safety, reliability and robustness of a system-of-space systems architecture capable of supporting the evolving launch needs through the life of the International Space Station in its fully operational phase after Assembly Complete.

Figure 1: International Space Station [2]

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I. Introduction

NASA expected to be able to utilize the U.S. Space Shuttle to fill the role as the primary crew and cargo delivery system throughout the life of ISS. However, after the Columbia disaster President Bush ordered that the Shuttle be permanently retired in 2010, and that NASA begin development on a new space vehicle to safely launch U.S. astronauts into orbit. With the impending retirement of the Shuttle, the NASA has been seeking alternate means to reliably deliver crew and cargo to ISS. Although many concepts are being considered, currently only the Russian Progress, European Automated Transfer Vehicle (ATV), and Japanese H-II Transfer Vehicle (HTV) are expected to be fully qualified and operational in time to begin delivering cargo to ISS before the Shuttle is retired. As the ATV and HTV become operational, they will begin carrying cargo to ISS according to agreements worked out between NASA and the European and Japanese space agencies. These agreements, however, were established when the Shuttle was assumed to be the primary cargo delivery system for NASA. As a result, the ATV and HTV missions, as currently planned, will not be able to fully meet the ISS post-Shuttle cargo delivery requirements, leaving a substantial 51.4 mT gap in the program.

NASA estimates more than 5000 kg of internal pressurized cargo and as much as 4000 kg of external unpressurized cargo will need to be delivered annually during the fully-assembled phase of ISS, post 2010. The actual number of ATVs and HTVs required to meet this requirement is dependant on the mix of pressurized and unpressurized cargo – not simply on the gross cargo mass. The variety, sizes, and shapes of pressurized internal cargo are extensive and include such things as clothing, foods and consumables, drinking water, avionics and other hardware, science experiments, and literally thousands of other items that range in sizes from tiny (e.g.; pens and nuts and bolts, etc.) to equipment racks more than 40" wide and six feet tall - which as about as large as will fit through the hatch. Based on current estimates, at least two additional ATVs and/or HTVs (combined) would be needed to transport the annual internal cargo requirements of ISS. Unpressurized external cargo is typically much more massive and includes replacement hardware, called Orbital Replacement Units (ORUs), such as the Control Moment Gyros (CMG) that stabilize the station, batteries, avionics such as computers and controllers for the many systems that support ISS, parts for the dexterous robotic arm, radiators, and many other items. Unpressurized cargo also includes external science payloads which can range in sizes as small as a 1 cubic meter experiment packages weighing a few kilograms (kg) to massive research facilities such as the Alpha Magnetic Spectrometer (AMS) which at more than 52 cubic meters and weighing almost 8,000 kg is as large as a semi-tractor. Since the ATV is capable of handling only pressurized cargo, only the HTV will be able to carry external cargo. However, the HTV is limited to cargo that can fit on the approximately 2 m x 2 m x 3.7 m External Pallet, which excludes many of the larger logistics ORUs and payloads.

This potential disparity between what *needs* to be delivered to ISS and what the HTV and ATV *can* carry is a direct consequence of the new post-Shuttle reality. Recognizing and responding to this paradigm shift was a critical requirement in the development of the ULA cargo transportation system approach.

Since virtually all of the as-built ISS infrastructure (e.g.; trusses, modules, logistics carriers, international elements, ORUs, science and research experiments, etc.) were designed to fly on – and *only* on – the Space Shuttle; and, since the Space Shuttle system is scheduled to be retired in 2010; the ISS program must either: (a) be completed and fully outfitted by 2010 and every large hardware ORU that doesn't fit on the HTV must operate through the life if ISS; or, (b) an alternative architecture(s) must be implemented to augment the Shuttle for ISS assembly, while also meeting the continuing operational and logistical requirements of the ISS throughout its expected on-orbit life from 2010 through 2020 (and perhaps longer). To further compound the issue, the finite and limited number of flights between now and the Shuttle's scheduled retirement indicated to many in the space community that the impending gap in our U.S. space capability should be immediately addressed.

Based on an inquiry from the NASA ISS program management in 2004, the ULA has been developing space systems architectures to assure continued U.S. access to and support of the ISS from retirement of the Shuttle in 2010 through the expected ISS end of life in 2020. With this premise, the United Launch Alliance Advanced Programs team has invested significant R&D resources developing a realistic and cost-effective systems-of-space systems architecture capable of supporting the ISS both before and after Shuttle retirement. The objective of the ULA advanced programs team was to use existing domestic space assets to the greatest extent possible to develop a responsive ISS cargo delivery system that met NASA's post-Shuttle ISS re-supply requirements. Using our current space resources is responsible stewardship of current and past investments in vehicles, technology, infrastructure, processes, and, most importantly, the trained and experienced personnel who manage, manufacture, launch, and operate our existing space systems.

This paper summarizes the results of a multi-year study which sought to develop a system-of-space systems architecture based on existing space assets that could effectively either augment or replace the Shuttle within three years.

II. Identifying the Needs

As with any systems architecture design, one must first identify the overarching needs for the system. In this case, the primary need identified by NASA was to "replace the Space Shuttle." However, when examining this stated need a common heuristic in systems architecting came to mind:

"Don't assume that the original statement of the problem is necessarily the best, or even the right, one." [3]

In this case the identified problem oversimplified the real needs and overcomplicated the desired end-state. A new space transportation system designed to deliver cargo to ISS would <u>not</u> necessarily be required to perform many of the functions or have the unique capabilities for which the Space Shuttle system has become famous. Examples of what the new system was *not* required to perform include:

- Launching humans to orbit (ULA assumed this will be performed by the new Orion space vehicle)
- Supporting humans in a shirt-sleeve environment on-orbit
- Transporting humans to the ISS
- Rescuing and/or repairing worn or damaged assets in orbit (e.g.; Hubble Space Telescope)
- Returning to Earth and landing on a runway
- Re-useability; and many others.

In fact only four primary needs were identified for an ISS cargo delivery architecture:

1. Launch already built ISS assembly elements not launched before the Shuttle is retired;
2. Transport already built outfitting hardware and equipment (e.g.; racks of avionics and science equipment);
3. Provide regular delivery of re-supply consumables, logistical cargo, and replacement hardware; and,
4. Dispose of waste from ISS.

Though launch and transport of humans and return of high value cargo to Earth *are* needed services, it is not necessary – nor responsible – to require one system to "do it all." As with most cases in systems engineering, whenever competing and conflicting multi-use capabilities are levied on an architecture, compromises must be made resulting in reduced efficacy and robustness of the system. In fact the Space Shuttle system for all it technical prowess, is held up as a cautionary example of levying too many requirements onto a single vehicle. As operational flexibility increases, so does system complexity, cost, and risk, which can – and often does – lead to tragic results. Therefore, the desired capabilities for return cargo and transport of humans were deemed to be outside the scope of this ISS cargo re-supply architecture.

In support of the first need, ULA identified (at the time the study was completed in late 2007) at least nine more assembly element flights would be required to complete the ISS (primarily trusses and modules). Should the unthinkable happen and another safety incident occur which causes the Shuttle be permanently grounded prior to completion of ISS, the ULA system would be required to launch and deliver any remaining elements to the ISS. This need then scoped the scale of the system in that it must be capable of launching large ISS assembly elements such as the pressurized modules. This first need also dictated that the system under consideration must accommodate even the largest existing ISS hardware (e.g.; modules) and already built science payloads (e.g.; AMS), leading to the conclusion that Shuttle-like interfaces must be inherent in the system to ensure that transition of ISS hardware to the new system would not require costly modification or re-qualification of existing ISS hardware.

Needs number two and three are very similar, and if the system was able to meet the first need, these needs would also be met. For instance, most outfitting hardware and re-supply cargo is designed to be stowed in a pressurized cargo carrier such as the Multi-Purpose Logistics Module (MPLM) or on an unpressurized cargo carrier such as the Express Logistics Carrier (ELC), which are illustrated in Figure 2.

These logistics carriers are designed to meet the same Shuttle interface requirements as the ISS elements, therefore if the system architecture accommodates the first need, then the second and third needs would be enveloped by those requirements.

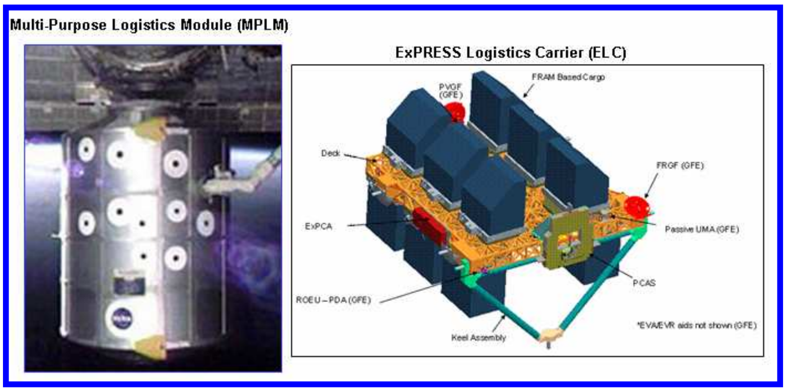

Figure 2: ISS Logistics Carriers [4]

The fourth need identified was to dispose of ISS waste. This dictated that the system architecture be designed to accommodate waste materials from the ISS, safely depart the ISS vicinity, and then perform a controlled destructive re-entry into Earth's atmosphere.

Some additional parameters of the system desired by the ULA architecture team included low-risk, low per unit cost, an IOC starting as early as 2010, as well as being reliable, safe, robust, and flexible. The overarching design philosophy adopted by the ULA architecture team was to maximize utilization of existing U.S. space assets – which, if successful, would support many of the other parameters identified.

III. Maximizing Existing Space Assets to Develop the System Architecture

After identifying the true needs for the system architecture under study, careful review was undertaken to determine what existing space assets were both available and applicable to meet the goals of the system. Since ULA has significant existing resources, the team desired to maximize the use of heritage Delta and Atlas hardware, infrastructure, facilities, processes, and operations. However, the architecture search space was opened to include all existing U.S. and International space assets that might be applicable to address the goals. The team first reviewed the available space vehicles that are and/or soon to be operational.

Currently, only three space vehicles have traveled to and docked with the International Space Station (ISS): the Soyuz and Progress spacecraft – both Russian – and the U.S. Space Shuttle. Beginning in 2008 the European Automated Transfer Vehicle (ATV) is scheduled to begin limited cargo re-supply flights to the ISS; while the Japanese H-II Transfer Vehicle (HTV) is not expected to make its first visit to ISS until sometime in 2010. The only other space vehicle on the relatively near-term horizon that is expected to travel to ISS is the Crew Exploration Vehicle (CEV), which is currently in a NASA preliminary systems design phase. The CEV is not expected to begin operations until 2015 and possibly much later depending on Congressional support, budgetary funding, and the upcoming presidential election. Further, the CEV has extremely limited cargo capability, thereby making it unsuitable for anything other than transport of crew to the ISS.

With limited qualified space vehicles available, and in expectation of the impending Shuttle retirement, NASA initiated the Commercial Orbital Transportation Services (COTS)[5] program to encourage industry to develop innovative, low-cost commercial orbital transportation solutions to meet the ISS re-supply requirements in the post-Shuttle timeframe. The COTS phase I demonstration program is scheduled to run through 2010, with the COTS Phase II support contract expected to be awarded in 2008. This limits the timeline for development and demonstration of any new commercial space system to less than three years. However, history has shown that space systems, especially man-rated space systems such as those that are required to dock to the ISS, routinely experience difficult development and test programs, escalating costs, and slipping schedules. Although there has been considerable press coverage of several entrepreneurial companies developing new commercial cargo delivery systems, at this point few of the commercial space ventures have working hardware, fewer have operational space experience, and almost none have experienced the Byzantine world of NASA's manned space program in general or the ISS program in particular. Based on publicly available data there appears to be no conclusive indications that such systems will materialize, be fully qualified, and become operational in time to support the ISS prior to retirement of the Space Shuttle, and perhaps not for years after.

Independent of the COTS program, ULA has been working on a cost-effective and low-risk approach for implementing an ISS cargo transportation system based almost entirely on existing, flight proven ULA launch system technologies. If begun in 2008, this system could have an Initial Operational Capability (IOC) as early as late 2010, and would be capable of providing complete end-to-end cargo transportation to the ISS using flight proven domestic and international space assets. Full operational capability (FOC), with an annual internal and external cargo upmass capability exceeding projected NASA requirements, could be phased in as early as 2011. This additional capability could be used to deliver government and commercial utilization payloads and science hardware not currently manifested on any planned flight to ISS, as well as to deliver assembly elements and outfitting hardware not launched prior to the Shuttle's retirement.

Figure 3: ULA's flight-proven launch vehicles[6]

In this proposed architecture, ULA's flight proven and fully certified Delta IV (DIV) and Atlas V launch vehicles (Figure 3) would be utilized to deliver assembly elements and cargo to low Earth orbit (LEO). The DIV and Atlas are the only operational U.S. launchers capable of lifting up to 25mt (55,000lbs) to the ISS LEO transfer orbit (nominally 300 km circular at 51 degrees inclination). The only other U.S. space vehicle that has this capability is the Space Shuttle, which will be retired in less than three years.

The ULA approach was based on maximizing utilization of U.S. space and infrastructure assets in launch vehicles, ground infrastructure, and trained personnel. Cargo transportation would be provided by derivatives of existing U.S. EELV's. By utilizing these existing, proven, and fully operational U.S. launch systems, the ULA approach avoids the considerable operational impacts and development costs and risks associated with embarking on the creation of completely new launch systems to meet ISS requirements.

A review of the United States aerospace and launch industrial base indicates that we already have the capability to supply the International Space Station following the retirement of the Space Shuttle in 2010. The transition of the ISS Cargo re-supply services to existing launch vehicle providers is extremely beneficial for the U.S. space industry, NASA, the Air Force, and the Department of Defense
as it will serve to increase launch vehicle production, assembly, and launch thereby increasing reliability of EELVs and lowering costs to all government customers over time. Current ULA launch vehicle operations includes all the activities needed to support ISS cargo missions including manifesting, packaging, integration, and both launch and on-orbit operations. Utilizing existing assets would also provide high technology, good paying jobs to US workers, further U.S. space innovation, lessen U.S. reliance on foreign launch service providers, and increase national security.

Therefore, ULA believes that U.S. produced launch vehicles launched from U.S. launch sites be a primary requirement for any proposed system architecture that seeks to support ISS post-Shuttle. The use of domestic launch for ISS transportation services should also be in accordance with current U.S. Space Transportation Policy and NASA ELV Policy Directives. This will serve to sustain and maintain the U.S. launch industrial base and enable further economics of scale and cost savings for not only launch vehicle Prime contractors, but also for critical suppliers of the launch and aerospace industry, reducing U.S. government launch costs.

The Commercial Space Launch Act provides the framework for NASA to procure domestic launch services, while honoring the basic agreements to the ISS partners to supply the already agreed-upon launches of ATV and HTV. In short, further reliance on foreign launch providers is *not* needed. While an operational domestic capability for ISS cargo end-to-end services does not currently exist, operational domestic capabilities do exist for launching that can be modified to successfully integrate and perform the full range of ISS Cargo missions. ULA stands ready to offer our Delta IV and Atlas V launch vehicle families that are not only available, but are fully operational and proven systems that have achieved the necessary NASA flight certification to perform this critical mission.

Existing U.S. ground infrastructure space assets (Figure 4) include ULA's extensive manufacturing, production, integration and launch facilities at Decatur (AL), Harlingen (TX), San Diego (CA), Denver (CO), Cape Canaveral Air Force Station (CCAFS), and the Kennedy Space Center (KSC). Leveraging the more than $5 billion of government and commercial investments in existing U.S. space assets for delivery of cargo to the ISS is financially responsible and good stewardship of our country's infrastructure resources.

Figure 4: ULA Ground Infrastructure Assets[6]

ULA's substantial launch vehicle production capability at its state of the art launch vehicle production facility in Decatur, Alabama should be more than sufficient to meet both anticipated national security space launch requirements as well as NASA's future launch needs. Currently, Delta IV production takes up less than 50% of the Decatur manufacturing facility's capacity, and a larger footprint would not be necessary even if the rate were to go to 20 boosters per year. Decatur is currently staffed and tooled to build 7 Delta IV boosters annually in a 1-shift operation, and up to14 in a 2-shift operation. Decatur is also currently staffed and tooled to build 5 Delta IV upper stages in a 1-shift operation, and 10 in a 2 shift operation.

ULA is in the process of moving segments of the Atlas V manufacturing to Decatur in the near future. Once the move is complete Atlas V production is expected to use ~25% of Decatur's capacity to deliver a 6 LV per year capability. ULA plans to maintain the LV manufacturing capacity in Decatur to deliver a mixed fleet totaling 12 boosters plus 12 upper stages annually in support of the existing EELV contracts. With our extensive manufacturing capability, production limitations are not expected to be an issue in Decatur, regardless of the quantities of additional launch vehicles necessary to support ISS. Increasing capacity up to 20 boosters a year – much more than would be needed to support ISS re-supply – would only require a minimal capital influx for tooling modifications, and the plans and processes are in place to execute should that become reality.

ULA's operational launch site infrastructure at Cape Canaveral Air Force Station (CCAFS) includes Launch Complex 37 for Delta IV and Launch Complex 41 for Atlas V, both of which would be used to support ISS Cargo Delivery mission requirements. These existing, flight-proven complexes are capable of launching up to 10-12 times per year *each*, providing maximum manifest and schedule assurance for ISS Cargo needs. The cargo and payload processing requirements in support of ISS re-supply missions are compatible with the numerous payload processing facilities available at CCAFS for the pre-launch servicing and integration with payload carriers. Depending on customer requirements, ISS support missions could be processed at the existing ISS and Shuttle-related facilities at NASA Kennedy Space Center (KSC) or at commercial facilities such as Astrotech Space Operations (ASO) at the SPACEHAB Payload Processing Facility (SPPF). ASO, located in Titusville, Florida, is capable of processing spacecraft and has facilities capable of integrating 5-m Payload Fairing (PLF) encapsulations. The processing and integration timeline for cargo missions to ISS would be similar to processing flows provided in the Delta IV and Atlas V Payload Planner's Guides,[7] which are available to the public.

Once the cargo is integrated with the LV, the Atlas and Delta rockets can accurately deliver payloads to just about any location required by the customer. With the demonstrated ability of our upper stages to provide 1, 2 or 3 burns with short or long coast periods, the Atlas and Delta vehicles have delivered payloads to LEO, MEO, sun synchronous, GTO, GSO, various Earth escape velocities and any orbit in between. This flexibility allows NASA to customize their launch to the orbital requirements. ULA's upper stages, with their demonstrated mission design flexibility and proven unparalleled injection accuracy can directly deliver the cargo carrier to just outside of the ISS visiting vehicle stay out zone. Direct delivery would reduce time from launch to ISS rendezvous. This flexibility is enabled by the advanced avionics, flight software and mission design capabilities developed over decades of support to NASA and other customers.

Many of these capabilities can be combined to provide significant launch window duration while minimizing the imparted velocity requirements for an ISS re-supply mission. This combination, as an example, can be used to maximize the likelihood of launching by providing a longer window, while minimizing the extra analysis effort necessary for the current earth-relative ascent trajectory designs. All of these capabilities are flight proven with demonstrated accuracies well within ISS mission requirements.

ULA's Atlas and Delta launch systems are both fully operational which provides NASA with mutual backup capability to space via reliable U.S. based launch systems and experienced launch teams. Further, by using our existing fully operational and qualified Atlas and Delta launch systems, NASA is provided with the flexibility of independent launch systems that can launch virtually any proposed mission, any combination of cargo types and quantity, and with immediate capability to utilize either launch system as appropriate.

The architecture team baselined the use of existing Atlas and Delta space manufacturing, production, integration, launch, and mission operations facilities and personnel, for the ISS cargo re-supply system. This approach minimized the costs and risks inherent in the development, certification, and operational verification of new and unproven space transportation systems. With all of the "big bones" in place, the architecture team next identified the only significant missing pieces of an end-to-end cargo transportation system: the cargo carrier and a means of rendezvous and docking or berthing with the ISS.

IV. The Payload Bay Fairing©

Existing operational vehicles capable of transporting cargo to the ISS include the Progress, which carries only limited pressurized cargo, and the Shuttle Orbiter which can be configured to carry substantial amounts of both pressurized and unpressurized cargo. Once it becomes operational, the European ATV will be capable of carrying only pressurized cargo. Although the Japanese HTV is being designed to carry both pressurized and unpressurized cargo, its external cargo transport capabilities are limited to those ORUs that weigh less than 1500 kg and can fit on the approximately 2 m x 2 m x 3.7 m External Pallet. Several cargo carriers have been proposed by various participants as part of the COTS initiative, although few of the designs have progressed much farther than the concept or viewgraph stage, and none of the participants have developed flight proven hardware or an operational launch vehicle. This leaves NASA in an unenviable position – either purchase additional HTVs and ATVs to meet their approximately 10 mT annual cargo shortfall after the Shuttle stops flying, or *hope* that one of the COTS participants actually succeeds in developing, qualifying, launching, and certifying an ISS cargo re-supply system in less than three years.

ULA has been working independent of the COTS program to develop a cost-effective and low-risk approach for implementing an ISS cargo transportation system based almost entirely on existing, flight proven ULA launch system technologies. If begun in 2008 and an aggressive schedule was implemented, this system could have an Initial Operational Capability (IOC) as early as late 2010 and would be capable of providing complete end-to-end cargo transportation to the ISS using flight proven domestic and international space assets. Full operational capability (FOC), with an annual internal and external cargo upmass capability exceeding projected NASA requirements, could be phased in as early as 2011. Therefore, if implemented immediately, the ULA cargo system *could* be ready to support ISS before the Space Shuttle is retired. This would close the gap for ISS re-supply, and ensure NASA has a viable and reliable approach to supporting ISS in the post-Shuttle era.

In order to complete the end-to-end cargo transportation system architecture, the ULA team had to develop a cargo carrier capable of meeting the requirements identified for ISS cargo. Dozens of possible concepts that might fulfill the cargo carrier element of the architecture were considered, but most of the concepts were abandoned for technical or feasibility reasons. After considerable analysis and design, one rather elegant solution evolved that efficiently met all of the requirements of an ISS cargo carrier element. The ULA advanced programs team dubbed the cargo carrier the "Payload Bay Fairing©" or PBF© (Figure 5) because it was essentially an EELV payload fairing modified to emulate

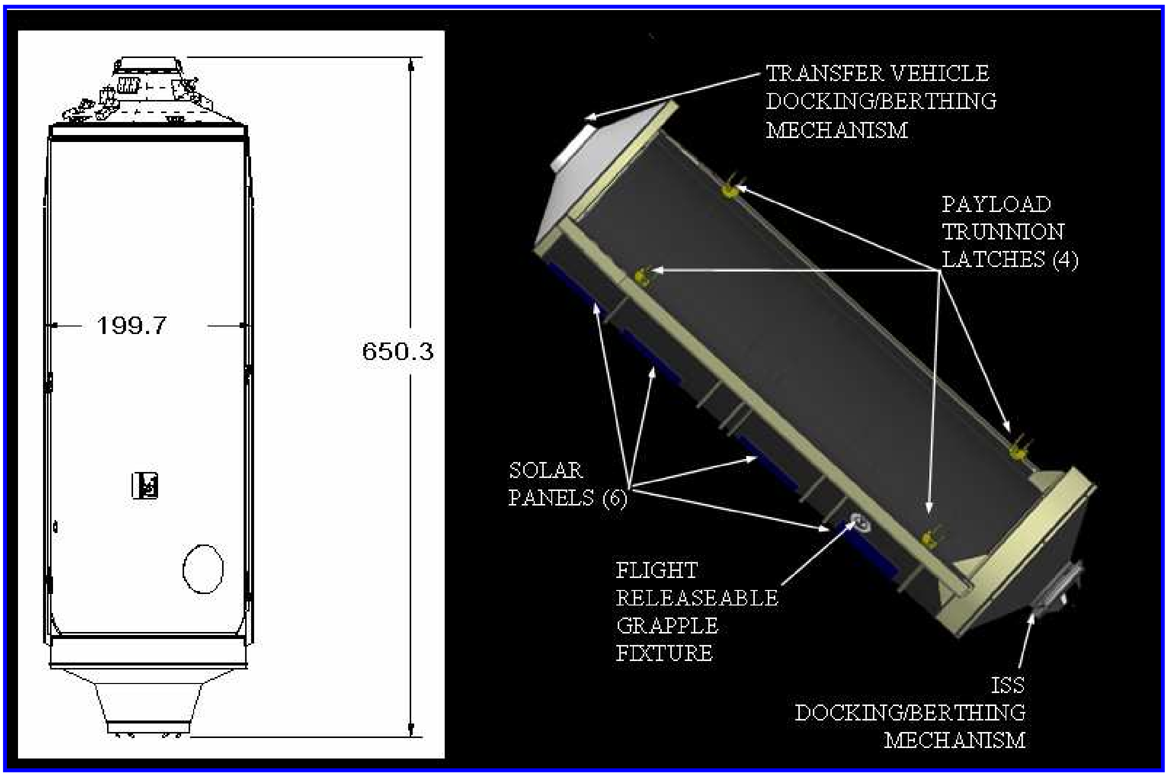

Figure 5: Payload Bay Fairing©[8]

the Shuttle Orbiter cargo bay. As designed, the PBF has approximately the same cargo volume as the Orbiter payload bay (Figure 6), and employs latches and payload/cargo interfaces designed to emulate those currently used in the Space Shuttle cargo bay (Figure 7). This design philosophy ensures existing ISS elements and other ISS and Shuttle hardware can be utilized with no modification or re-qualification. Further, in order to support ISS assembly, the ULA PBF was specifically designed to accommodate ISS elements as large as the Japanese Experiment Module (JEM) – the largest of the pressurized ISS elements. This feature enables the ULA PBF system to augment the Shuttle to support ISS assembly, if needed, or to deliver un-launched elements such as the Centrifuge Module and/or science payloads such as the Alpha Magnetic Spectrometer (AMS) after ISS assembly is complete. The primary mission of the PBF, however, would be to deliver outfitting hardware, cargo, and logistics in support of the long term needs of ISS.

The launch environments were then analyzed to ensure that the ISS elements and cargo would not be subjected to shock events, loads, or other environments exceeding their design margins. After several months of analysis the team concluded that all PBF environments were within limits and, in some cases even more benign than Shuttle environments, which would potentially eliminate the need to re-qualify or modify existing ISS hardware.

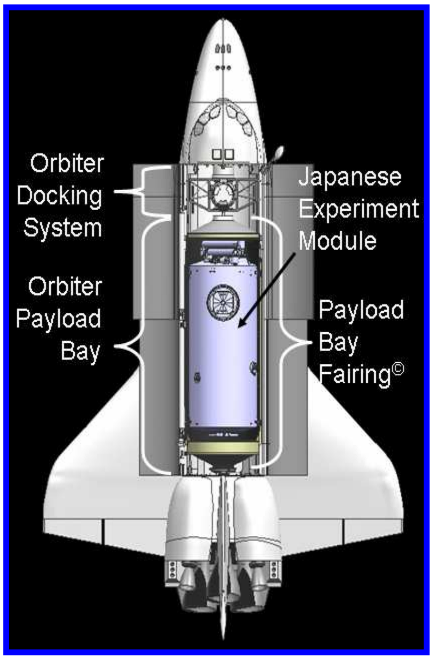

Figure 6: Shuttle Payload Latches[9]

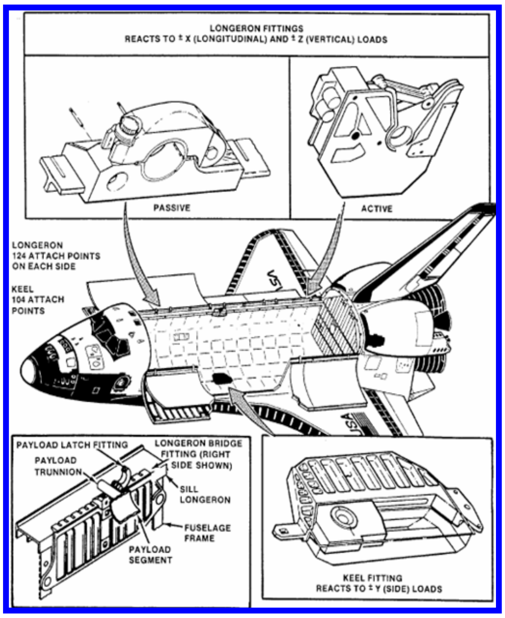

Figure 7: Orbiter vs. PBF Comparison[8]

PBF mission integration would be performed in much the same way that ISS missions are currently integrated into the Shuttle payload bay. A typical PBF re-supply mission, such as the MPLM would be encapsulated in a 5.4-m Atlas payload fairing (Figure 8) and mounted to a Delta V launch vehicle (Figure 9). The PBF would then be launched into an insertion orbit compatible with the ISS standard 51.6 degree, 220 nautical mile low Earth orbit. Finally, since most of the new hardware and systems needed to complete the architecture are relatively simple derivatives of existing Delta IV and Atlas V technology, the ULA cargo transportation system could be developed relatively quickly. In fact, initial indications are that the first flight units of the cargo carrier could be completed within the standard EELV build schedule, so potentially both the carrier and launch vehicle could be shipped to KSC before the Shuttle is retired.

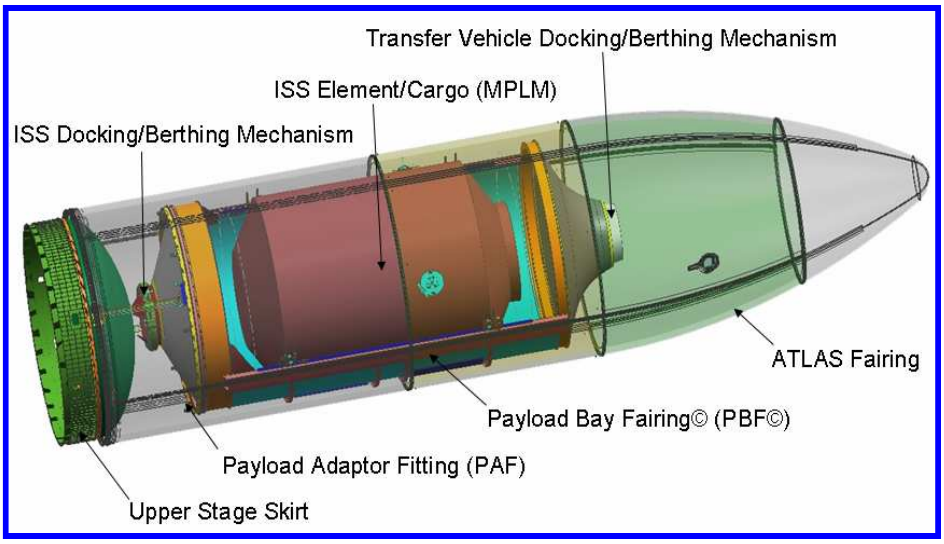

Figure 8: PBF with MPLM Payload Encapsulated in Atlas Fairing[8]

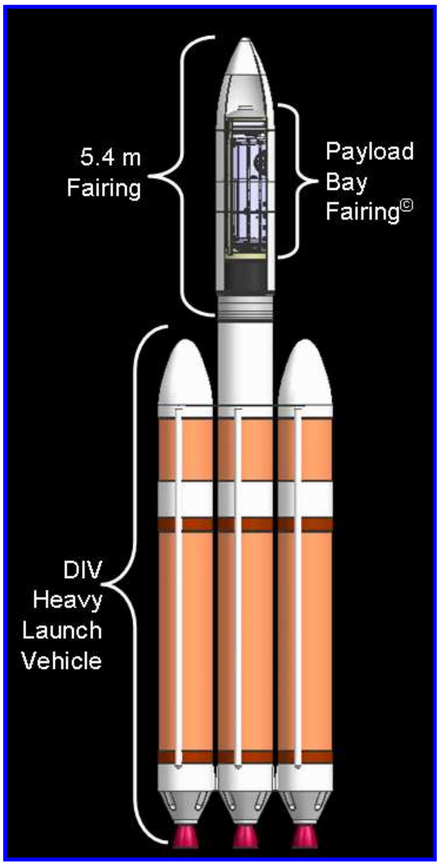

Figure 9: PBF Launch Configuration[8]

V. The "Last Mile"

Nicknamed "the last mile," the last remaining major architectural element needed to complete the ULA cargo transportation system was a means of rendezvous and docking (or berthing) the cargo carrier to the ISS, which was perhaps the most difficult operational element the architecture team had to solve. Although ULA's upper stages, with their demonstrated mission design flexibility and proven unparalleled injection accuracy, can directly deliver the cargo carrier to just outside of the ISS visiting vehicle stay out zone, the upper stages are *not* designed to rendezvous and dock or berth with another satellite such as the ISS. Further, the ISS Visiting Vehicle Requirements are extremely stringent, which is necessary to protect the safety of the Space Station and on-board crew, making the problem more difficult.

The architecture team considered dozens of possible concepts that might solve the "last mile" problem, but most of the concepts were abandoned due to feasibility, schedule, cost, and/or risk issues. After trade studies were conducted on transfer systems, the architecture team realized that the best way to meet the cost and schedule constraints was to follow the team's overarching philosophy to utilize existing space assets to the greatest extent possible. This architecture philosophy not only ensured the lowest cost and operational risk, it also provided the architecture the ability to rely on proven systems, thereby minimizing the considerable cost and risk associated with a "clean sheet" design approach to the problem.

The team established top-level requirements for an in-space "tug" capable of rendezvousing with the PBF, either by direct docking or capturing (e.g.; grappling) the PBF, and then transporting the PBF and/or the payload back to ISS. Since the list of existing space vehicles certified to dock or berth with the ISS was very small, the architecture search space narrowed down to five existing operational or soon-to-be operational space vehicles:

(1) Space Shuttle Orbiter;

(2) Progress;

(3) Soyuz;

(4) HTV; and,

(5) ATV.

After careful review of each vehicle, the Progress and Soyuz were eliminated due to International Traffic in Arms Regulations (ITAR) issues with U.S. providers utilizing Russian vehicles to service the ISS. The HTV was eliminated because it had neither the necessary delta V nor any capability that would enable it to operate as an in-space tug. Therefore, the only two vehicles that remained as likely candidates capable of performing the "last mile" for the ULA system were the Space Shuttle Orbiter and the European ATV.

A. Shuttle Orbiter

The Shuttle Orbiter has had a long and successful career performing missions similar to that desired for the ULA architecture. Past Shuttle missions have set a precedent allowing the Orbiter to perform "space tug" missions including changing orbital altitude, performing multiple orbital parameters per mission, rendezvous and retrieval of satellites and spacecraft in orbit, and capture and re-boost of satellites into higher orbits. Example missions include:

- STS-32 deployed SYNCOM IV-05 and retrieved LDEF for return to Earth
- STS 41-C captured the Solar Max satellite – which had been launched on a Delta launch vehicle
- STS 51-A deployed TELESAT-H & SYNCOM IV-1, and captured and returned to Earth with PALAPA-B-2 & WESTAR-6, a mission requiring three different orbital altitudes and two separate rendezvous and capture operations

- STS 51-I deployed AUSSAT-1, ASC-1, & SYNCOM IV-4, then rendezvous and salvaged SYNCOM IV-3 which involved capture of the satellite without using grapple fixtures
- Hubble Space Telescope (HST) Servicing missions (four separate missions) where the Orbiter rendezvoused with HST, captured the telescope with the SRMS, berthed the HST into the payload bay for servicing, and then reboosted and released the 12-ton HST into a higher orbit
- STS-88 the first ISS mission that launched ISS Node 1, which rendezvoused with the Russian-launched FGB, captured the FGB with the SRMS, docked ISS Node 1 to the FGB, and reboosted and released the fledgling ISS into a higher orbit

Thus, the Shuttle is not only capable of performing in-space tug operations similar to what is needed for the PBF, it is a proven system with decades of experience performing successful in-space tug missions. With the help of Boeing's Shuttle operations team in Houston, TX, we performed a top level feasibility study and concluded that there were no technical show-stoppers preventing utilization the Shuttle as an in-space tug. The architecture team then developed a concept of operations for the combined ULA PBF and Space Transportation System (STS) architecture, and identified the requirements and capabilities of such a systems-of-space systems architecture.

B. Automated Transfer Vehicle [10]

The Automated Transfer Vehicle (ATV), illustrated in Figure 10, is a 20-metric-ton unmanned expendable space cargo transport vehicle, which has been in development since 1994 by the European Space Agency (ESA). The ATV docks at the rear ISS Russian port and is capable of delivering up to 7700 kg of a variable mix of pressurized cargo, refueling propellants for the Russian Segment of the ISS, as well as additional fuel required by the ATV to reboost the ISS.

The general architecture of the ATV is simple, modular, and designed for easy manufacturing, testing and assembly. The ATV upper section, or Integrated Cargo Carrier (ICC), is the portion directly docked to ISS and carries the dry and fluid cargo (e.g.; gasses, propellant, and water) for the mission. The ICC is an ISS human-rated, pressurized volume, allowing astronauts shirt-sleeve access, and its interior is fully compatible with the NASA manned vehicles specifications. The ICC also carries on its front cone all the hardware, sensors and ranging cues needed for the final approach and docking to space station, as well as eight attitude control thrusters.

The lower section of the ATV comprises all the services needed to support and execute the mission, including eight main propellant tanks, two large helium tanks, the propulsion tank pressurization system, propulsion and attitude control command system, four main thrusters, twenty attitude thrusters, power generation and storage, navigation, control, command, and telecommunications systems, and the launch vehicle payload adapter containing the separation system.

The expensive and high risk development effort associated with creating a transfer vehicle capable of visiting the ISS has largely been completed for the ATV, with the first flight spacecraft ("Jules Verne") scheduled to perform an ISS cargo mission in early 2008. This working flight will provide full checkout of all ATV ground and flight operations, including all aspects of cargo processing, integration, launch, orbit rendezvous and docking with ISS, ISS crew cargo loading and unloading, ISS departure, and destructive re-entry. The Jules Verne will also demonstrate the new ATV laser docking system, which will replace the antiquated Russian docking system, and will perform several safe escape modes from ISS.

While current ATV mission requirements dictate a long docking period, the ATV is also capable of docking durations as short as one week, and can perform multiple docking, undocking, maneuvering away from the space station, loitering and re-docking operations. This short-duration docking and loiter capability could be utilized by the ULA cargo transportation system to perform in-space tug operations with the PBF©.


Figure 10: Automated Transfer Vehicle [8]

The ULA cargo transportation system approach would seek to work with the Europeans to adapt the ATV to more fully utilize the existing built-in spacecraft capabilities to enable the transfer vehicle to operate as an in-space tug. Preliminary discussions with the ATV development contractor and ULA indicated that such modifications could be achieved, and were in fact already under consideration. These design modifications would primarily be limited to enhancing the on-orbit proximity operations software to interact with a United States Operational Segment (USOS) docking/berthing port and adjust vehicle maneuverability to compensate for the larger combined ATV/PBF, and so would have minimal impacts to the qualification status of the ATV and its certification to operate as an ISS visiting vehicle. Therefore, limited technical and programmatic risk would be introduced by the adaptation of the ATV to support the ULA cargo transportation system.

The ATV is not only capable of performing in-space tug operations similar to what is needed for the PBF, it will soon be a proven system and will have performed at least two and possibly three re-supply missions to the ISS, verifying its safety, reliability, and capabilities. With the help of the ATV design and operations team in Europe, ULA intends to perform a top level feasibility study and to ensure that there are no show-stoppers to utilizing the ATV as an in-space tug that can capture the PBF, transfer back to ISS, and dock/berth to a USOS port. With the assumption that the ATV *can* be used as an in-space tug, the ULA team developed a concept of operations (Figure 11) for the combined ULA PBF and ATV architecture, and identified the requirements and capabilities of such a systems-of-space systems architecture.

VI. Concept of Operation

The ULA cargo transportation system concept of operations (CONOPS) is naturally divided into three phases: mission requirements analysis, ground operations, and flight operations. In each phase, the ULA cargo transportation system would rely on processes, facilities, equipment and personnel with experience on related missions, thereby reducing or eliminating additional critical verification and certification requirements. The ULA cargo transportation system would also benefit from existing systems, operations, personnel and infrastructure already qualified and in-place for the Atlas V and Delta IV launch vehicles.

A. Mission Requirements Analysis

In support of Mission Requirements Analysis, a range of pre-mission planning activities are performed well in advance of the mission. Typical pre-mission planning activities include launch vehicle and cargo carrier production; mission requirements and cargo manifest definition, and analytical integration of the cargo being manifested.

In support of the ISS re-supply missions, once pre-mission planning was complete, ULA would work with NASA to sequence the mission into the annual ISS traffic model to ensure the mission does not overlap another ISS mission to prevent multiple vehicles performing visiting operations at the same time. In support of the cargo missions, ULA would work directly with the NASA ISS Program Office, drawing on extensive resources currently supporting both ISS and Shuttle cargo operations. Our ULA payload processing experts would work closely with their NASA counterparts to provide complete ISS cargo mission support, traffic modeling, cargo analysis, and related activities. ULA and NASA experts would finalize the mission traffic model, develop detailed processes and schedules, and complete preparations for handling of the ISS cargo.

B. Ground Operations

ULA launch site ground operations would commence when the Delta IV or Atlas V launch vehicle and the PBF are delivered “on dock” at KSC. Once on site, the LV and the PBF would be transported to one of the ULA integration facilities and prepared for launch. As soon as the ISS element or cargo is transferred to ULA from NASA, both the PBF and ISS element/cargo would be transported to an existing integration facility (candidates include Astrotech and the NASA KSC Space Station Processing Facility [SSPF]), where PBF and element/cargo integration and final assembly would be conducted. The integrated PBF and element/cargo would be checked out and final verification completed. Assembly, cargo loading, processing, integration, and checkout of the PBF would be performed by experienced launch site personnel from ULA. PBF and ISS element/cargo launch site processing would rely on existing ULA, NASA, and KSC procedures to the maximum extent possible, further reducing operational costs.

The ULA launch vehicle team would prepare a launch vehicle (either Delta IV or Atlas V depending on the needs of the mission) for launch of the PBF and ISS element/cargo using existing, proven processes and infrastructure. The LV first and second stages would be integrated and tested, then transported to one of ULA’s Launch Complexes at CCAFS, where the launch vehicle is erected into launch configuration.

Once the PBF and ISS element/cargo complete integration processing, they would be handed over to the ULA launch team, who would mate the PBF to the Payload Adapter Fitting (PAF), and encapsulate the PBF in an Atlas 5.4-m composite fairing. The encapsulated PBF would be lifted to the top of the vertical integration facility, and integrated with the launch vehicle, where final checkout would be conducted and any late access operations would be performed prior to launch.

C. Flight Operations

Flight operations would encompass launch, on-orbit operations, ISS Activities, ISS departure operations, and destructive re-entry. Launch operations would use the mature capabilities of the ULA launch vehicles for successful deployment of the PBF in the ISS LEO transfer orbit (nominally 300 km circular at 51 deg inclination). Once the PBF is deployed to orbit, in-space operations would rely on established facilities, procedures, and personnel at NASA's JSC Control Center, who would serve as the mission control center for PBF on-orbit operations from launch vehicle deployment up to PBF arrival at the ISS approach ellipsoid.

In developing the ULA PBF Concept of Operations (CONOPS) a system-level overview of ISS assembly and re-supply and operations identified the PBF system conceptual design drivers. The process utilized by the ULA team involved

developing a top-level list of mission sequences, followed by a detailed mission timelines. The timelines developed contain information not just on time, but on delta-V and propellant consumption for each phase of the mission. Three different mission timelines were developed: a nominal timeline illustrating a typical mission, a maximum-case timeline using three-sigma dispersions and worst-case parameters, and a sizing timeline using a root-sum-square of the dispersions. For individual mission segments, different worst-case parameters were used. As an example, for de-orbit propellant calculations, ISS was assumed to be at its highest altitude (460 km), because that is where the propellant consumption for de-orbit is greatest. However, for PBF orbit lifetime calculations, ISS was assumed to be at its lowest altitude (278 km) because that is where it may take the longest to phase the PBF orbit to that of ISS (i.e.; least difference of altitudes between PBF insertion orbit and ISS). Obviously, these two events cannot practically happen on the same mission, yet our sizing analyses used both events to envelope the "worst-on-worst" case analysis for fuel, phasing, and operational timelines.

As discussed previously, the PBF would rely on either the Shuttle Orbiter or ATV to complete the "last mile" transfer from its insertion orbit, so separate CONOPS were developed for each approach.

Orbiter/PBF CONOPS

For Orbiter/PBF on-orbit perations, the (Figure 11), the PBF would be launched weeks or months prior to the Shuttle launch, and remain in a loiter orbit near the ISS. After the Shuttle's primary mission was complete, the Orbiter would undock from the ISS, translate to the PBF loiter orbit, rendezvous and capture the PBF, remove the ISS element/cargo from the PBF and stow it in the Orbiter cargo bay, and return to the ISS where standard Shuttle/ISS element/cargo would be performed. Since the element/cargo would be removed from the PBF, after the Orbiter returns to ISS the PBF would perform a disposal operation, and destructively re-enter Earth's atmosphere.

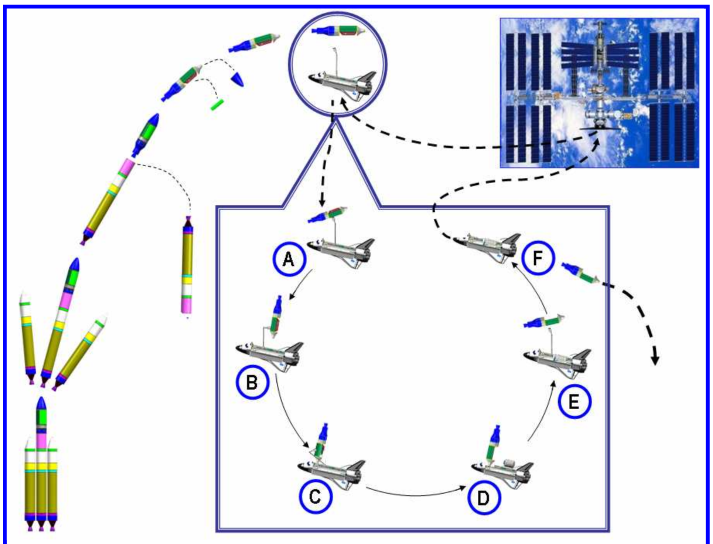

Figure 11: Orbiter and PBF© CONOPS [8]

ATF/PBF CONOPS

For ATV/PBF on-orbit operations (Figure 12), considerably more flexibility would be possible as to when the PBF would be launched. The ATV/PBF could be been launched more or less concurrently, the PBF could be launched weeks or months prior to the ATV mission and remain in a loiter orbit near the ISS, or the PBF could be launched weeks or months after the ATV mission and the ATV could either remain docked to ISS or wait in a loiter orbit near the ISS. Regardless of when the PBF was launched, after the ATV's primary mission was complete, the ATV would undock from the ISS, translate to the PBF loiter orbit, rendezvous and dock with the PBF, and return to the ISS and dock or berth at one of the USOS Nodes. Once docked/berthed to the ISS, the element/cargo would be removed from the PBF by the SSRMS and transferred to the appropriate location on the ISS. Trash and failed ISS hardware would be stowed in the now-empty PBF cargo bay, and the ATV/PBF would undock from ISS. Once safely out of the ISS departure ellipsoid, the ATV/PBF would perform a disposal operation, and the PBF would destructively re-enter Earth's atmosphere. Preliminary calculations by the ULA architecture team indicated that the ATV could be capable of at least two, and possibly three PBF rendezvous and transfer operations, before its fuel was depleted.

The ATV Control Center located in Toulouse, France would serve as the mission control center for ATV on-orbit operations from launch vehicle deployment up to ATV arrival at the ISS approach ellipsoid, where NASA's JSC Mission Control would assume control. The ULA cargo transportation system would rely on the same TV departure operations as worked out directly between NASA and the ESA for their national missions. This commonality of operations essentially minimizes new on-orbit operational risks with the ULA cargo transportation system.

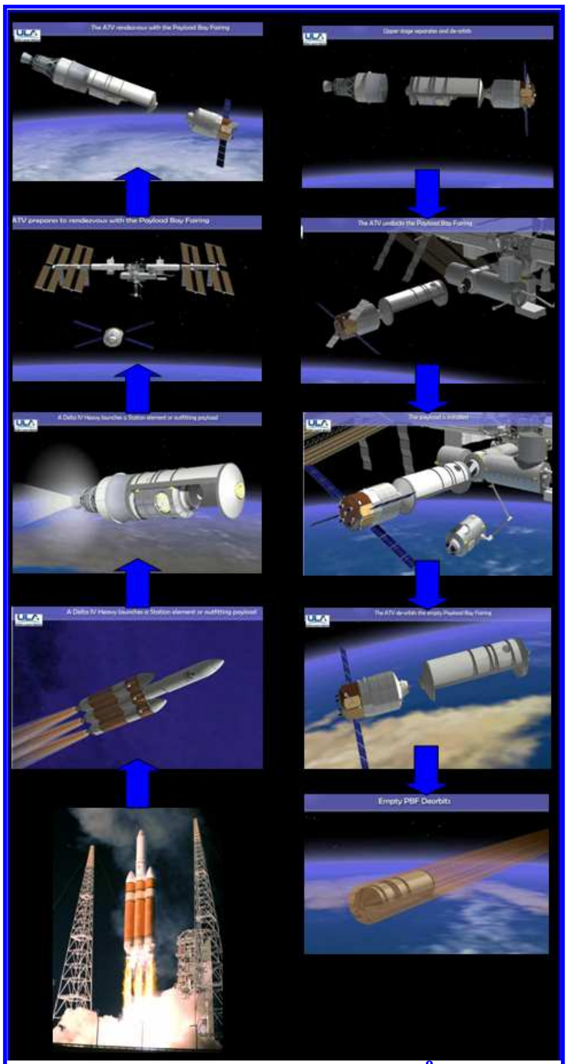

Figure 10: ATV and PBF© CONOPS [8]

VII. Conclusion

ULA has developed a low-risk, cost-effective integrated systems-of-space systems architecture to meet NASA's requirements for ISS cargo delivery in the post-Shuttle era. The ULA cargo transportation system team has devised a cost-effective cargo delivery approach utilizing space assets that are either in operation or nearing completion – the Space Shuttle, the European ATV, and ULA's Delta IV and Atlas V families of launch vehicles – avoiding substantial cost and risk inherent in development of new space systems.

These assets – plus ground support equipment, infrastructure, operations and support personnel – have been developed over the past two decades with more than $5 billion (U.S. dollars) invested by both the aerospace industry and the U.S. government. The ULA cargo transportation system is a unique system-of-space systems solution that stands ready to meet the large and demanding cargo delivery requirements of the ISS.

After careful review of the results of more than two years of R&D, we concluded that ULA could implement a low-risk, cost-effective cargo space transportation system capable of providing complete end-to-end cargo transportation to the ISS using flight proven domestic and international space assets. If begun in 2008 and aggressively managed, this system could have an Initial Operational Capability (IOC) as early as late 2010, and would be ready in time to close the impending gap resulting from Shuttle retirement, relieving pressure on NASA during the final years of the STS program, and providing reliable and robust cargo re-supply for the ISS through the next decade and beyond.

Acknowledgments

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Nomenclature

AMS	Alpha Magnetic Spectrometer
ASO	Astrotech Space Operations
ATV	Automated Transfer Vehicle
CCAFS	Cape Canaveral Air Force Station
CEV	Crew Exploration Vehicle
CONOPS	Concept of Operations
COTS	Commercial Orbital Transportation Services
DIV	Delta IV
EELV	Evolved Expendable Launch Vehicle
ELC	Express Logistics Carrier
ESA	European Space Agency
GSO	Geosynchronous Orbit
GTO	Geosynchronous Transfer Orbit
HTV	H-II Transfer Vehicle
HST	Hubble Space Telescope
IOC	Initial Operational Capability
ICC	Integrated Cargo Carrier
ISS	International Space Station
ITAR	International Traffic in Arms Regulations
Kg	Kilograms (1000 grams)
KSC	Kennedy Space Center
LDEF	Long Duration Exposure Facility
LEO	Low Earth Orbit
LV	Launch Vehicle
m	meters
mT	metric Ton (1000 kg)
MEO	Medium Earth Orbit
MPLM	Multi-Purpose Logistics Module
NASA	National Aeronautics and Space Administration
PAF	Payload Adapter Fitting
PBF©	Payload Bay Fairing©
PLF	Payload Fairing
R&D	Research and Development
SPPF	SPACEHAB Payload Processing Facility
SRMS	Shuttle Remote Manipulator System
SSRMS	Space Station Remote Manipulator System
STS	Space Transportation System
ULA	United Launch Alliance
USOS	United States On-orbit Segment