Pathfinding USSF MOSA Adoption Utilizing Ring-based and Small Spacecraft

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ABSTRACT

The U.S. Space Force's Space and Missile Systems Center's (SMC) Directorate of Innovation and Prototyping is evolving the concept of medium and small class combat bus to provide on-orbit warfighter and systems support and advance the open systems architecture. We begin with a Long-Duration Propulsive ESPA ring with six ports for multiple small hosted and/or separable satellites and prototypes (aka SMC's "Freight Train to Space"). By adding communication, open processing, maneuverability, and refueling options, a ring that was once "just hardware" becomes an outpost in GEO and an integral part of a hybrid architecture. Envision adding more outposts along the GEO belt and the result is a robust architecture for cross-linking satellite systems and extending warfighting missions worldwide. Tetra, our small-class combat bus program, fits on one of these ESPA ports and provides additional options to host smaller prototypes and a key training capability. These programs mark the beginning of a new USSF architecture, and will deliver capabilities to orbit faster, smarter, and more affordably than ever before.

INTRODUCTION

The United States Space Force is moving swiftly toward a more resilient architecture, delivering smaller satellites more rapidly to orbit and enabling greater resiliency in numerous mission areas. The Space and Missile Systems Center's (SMC) Directorate of Innovation and Prototyping is evolving the concept of medium and small class satellites to provide on-orbit warfighter and systems support, and advance the open systems architecture. Modular Open Systems Approach (MOSA) and Digital Engineering initiatives are facilitating this shift toward fielding capabilities faster and smarter than ever before. The title "combat bus" refers to the ability to design a bus that will enable the benefits of MOSA and Digital Engineering to bring more effective combat capability to the USSF architecture. This paper will explore two such USSF bus programs, the Long Duration Propulsive ESPA – Evolved Expendable Launch Vehicle Secondary Payload Adapter (LDPE) program and the small satellite Tetra program. These programs are pathfinding the adoption of MOSA and Digital Engineering and already realizing both the benefits and challenges of each. Additionally, it will explore the future of the LDPE spacecraft called the ROOSTER program and how it will enable the pivot towards a new USSF architecture.

MODULAR OPEN SYSTEMS APPROACH (MOSA)

Modular Open Systems Approach (MOSA) is now a requirement in US law, **10 USC 2446**, for all major defense acquisition programs to allow for the development of affordable and adaptable systems. Foundationally, it encourages modular designs with standard interfaces between major system components and platforms. This enables parts or systems to be swapped out during assembly when those parts become obsolete or unsustainable, effectively allowing the evolution of the production line of major defense systems.

Applying MOSA to the USSF architecture is critical for building resiliency to our mission sets and allowing faster fielding of capabilities. SMC is looking across its organizations to find the best ways to implement MOSA standards to enable faster production. The Innovation and Prototyping Directorate is the first stop for developing and testing standards before entering into a higher rate of production. The Department of

Defense has advocated the benefits of MOSA, as listed below.

Benefits of MOSA[1]

"**Enhance competition** – open architecture with severable modules, allowing elements to be openly competed.

Facilitate technology refresh – delivery of new capabilities or replacement technology without requiring change to all elements in the entire system.

Incorporate innovation – operational flexibility to configure and reconfigure available assets to meet rapidly changing operational requirements.

Enable cost savings/cost avoidance – reuse of technology, modules, and/or elements from any supplier across the acquisition life cycle.

Improve interoperability – severable software and hardware modules that can be changed independently"[1]

Each of these benefits are being realized by the LDPE and Tetra programs. These benefits are also complemented by implementing Digital Engineering techniques which will allow the USSF to fully realize the rewards of MOSA.

DIGITAL ENGINEERING

Digital Engineering employs a variety of tools to develop space systems prior to bending metal. Programs use these practices to assess future performance of spacecraft which is used heavily in coupled loads analysis for launch, risk reduction, and mission assurance. While contractors have used these practices in the past, there is a desire to do more by building "digital twins" of every spacecraft. These twins can be inserted into a digital sphere of the USSF architecture to better understand architecture gaps and help make investment decisions for USSF priorities.

One of the earliest Digital Engineering pathfinders at SMC is the LDPE follow-on, Rapid On-orbit Space Technology Evaluation Ring (ROOSTER), which will develop a digital model of the ring's interface to the payloads. By handing models to the payload program offices, the modular approach can be evaluated in digital space, thereby reducing risks to the development and final integration with each individual system. Additionally, we will be able to better 'fly' the system in digital space. One critical lesson learned from implementation of the LDPE series has been the effect of different payload requirements on system resources such as pointing, power, thermal management, launch loads management, and overall communications downlink bandwidth. While the focus on the LDPE series has been the benefits of a standard interface, significant integration and test costs are also being realized.

LDPE/ROOSTER

The Long Duration Propulsive ESPA (LDPE) program and its follow-on, Rapid On-orbit Space Technology Evaluation Ring (ROOSTER), are both run by the Rapid Development Division at the Space and Missile Systems Center. LDPE is a medium class bus that hosts six ports for connecting a wide array of ESPA-class prototype payloads. Lovingly called "the Freight Train to Space," it boasts the ability to hold prototypes for various mission areas and classification levels. LDPE can insert separable space vehicles into geosynchronous (GEO) orbit or host dedicated payloads on the ring itself until test completion.

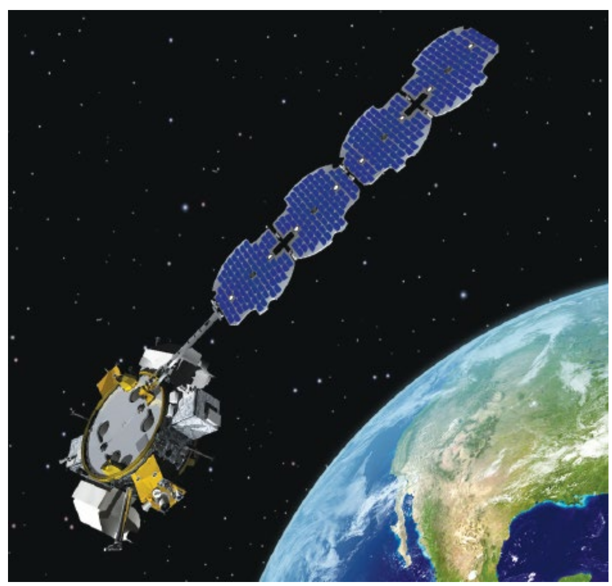

Figure 1: LDPE as based upon the Northrop Grumman ESPAStar Bus

SMC is investing in the LDPE capability because it is a great way for mission partners to increase the technical readiness levels of a particular piece of technology for a relatively low price. This approach has realized significant cost savings as opposed to paying for a dedicated launch. The mission partner technology is manifested as a rideshare on a launch vehicle with an anchor program, essentially sharing launch costs. The costs for manufacturing the ring are also shared amongst mission partners. In addition to the payload, partners are responsible for mission-unique costs such as specific integration needs, ground software unique items, and tests that are above and beyond standard integration tests.

Hosting six or more unique payloads comes with many challenges. Integration activities are not standard, thus costs may vary to accomplish appropriate activities and tests. Additionally, the coupled loads analysis of the integrated payload stacks can be at risk, often because payloads are being developed until just before integration and models do not have fidelity until closer to launch. We expect the adoption of Digital Engineering techniques will reduce these integration risks and associated costs, and will improve speed to development and launch.

LDPE use of MOSA

The implementation of MOSA techniques would further complement LDPE's Digital Engineering initiatives. Payloads with a common size, weight, and power (SWAP) could result in a more precise assessment of coupled loads of the integrated payload stack during launch. It would enable late manifesting/de-manifesting of payloads that may or may not be ready for launch. It would also decrease risk to launch by enabling a more predictable model of loads leading into a launch. The LDPE series is currently based upon Northrop Grumman's ESPAStar bus, which can provide significant capabilities as shown below in Table 1.

Table 1: Northrop Grumman ESPAStar specifications[2]

Capability	Parameters
Orbit:	Optimized for GEO, adaptable for LEO and MEO missions
Design Life:	Multi-year mission life, single string
Dry Mass (no P/Ls):	430-470 kg (orbit dependent)
Dimensions (no P/Ls):	62" dia. x 24" ht.
Fuel Capacity:	310 kg
Payload Mass:	> 1,920 kg (> 320 kg per port)
Total Power (BOL):	1,200 W via four-panel solar array
Payload Peak Power:	Tailorable based on mission profile
Battery:	96 A-hr Li-ion
Downlink Rate:	256 kbps/1.6 Mbps via AFSCN higher downlink rates available upon request
Uplink Rate:	2.0 kbps via AFSC higher uplink rates available upon request
Payload Data Storage:	36 Gbytes non-TMR, non-volatile, 500 kbytes/day/ payload SOH
Pointing Control:	< 50 μrad (1σ) via 3-Axis RWA control
Attitude Knowledge:	< 10 μrad (1σ)
Jitter at Payload Interface:	< 20 μrad, (σ), >0.1 Hz
Slew Rate:	≥ 1.2 deg/sec
Position Control:	12x .9 N and 4x22 N REAs, 6 DoF control
Position Knowledge:	< 100 m
Avionics:	IAU, BRE440 processor, Virtex 5 FPGA, 40 GB memory

The development of cubesat dispensers, such as the P-POD[3], provides a good analogy that illustrates the power of the standard interface for both hosted and separable payloads. The cubesat dispenser was central to an explosion of diversity of missions across the space enterprise. The dispenser effectively created a constrained volume and interface, and virtually eliminated critical launch vehicle review except for safety considerations. This simplification of launch access created the fundamental opportunity to innovate at a much lower cost. It also created an open competition space where even a few college students could compete with major corporations and government agencies at a minor cost. This is the heart of MOSA.

The LDPE program has observed initial benefits by extending the cubesat dispenser approach to much more complex systems and payloads. There are several aspects that are analogous to the dispenser example. First, the authors have performed and collaborated on AFRL's Evolved Expendable Launch Vehicle Secondary Payload Adapter Augmented GEO Laboratory Experiment (EAGLE) program's approach for 'Do No Harm' criteria certification with the launch vehicle and other stakeholders sharing the launch. EAGLE was successfully launched 14 Apr 2018 to a near-GEO orbit. This set of criteria creates a significant simplification of the launch coordination, as demonstrated by the cubesat dispensers, by mitigating risks and therefore analysis requirements with the overall launch stack. However, this approach leaves significant room for improvement which we will explain below.

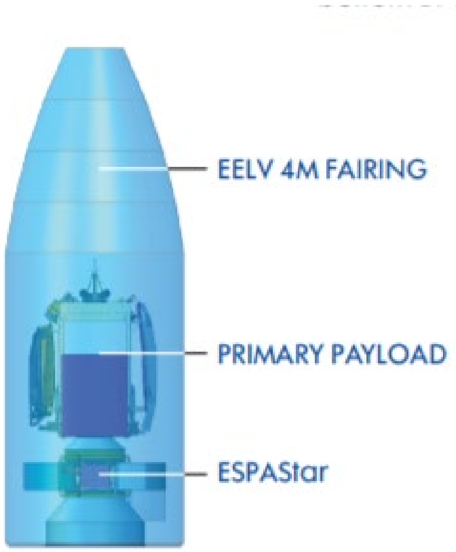

Figure 2: ESPAStar bus illustrates the interfaces between a 'primary' payload and the need for 'Do No Harm' requirements[2]

Another parallel to the cubesat dispenser is the creation of a standard envelope and a standard interface, depending upon which canister is chosen. This standard interface envelope is shown in Figure 3. By creating this interface and envelope, the Tetra series (explained in a later section) of spacecraft was able to develop an open competition space, which allowed the small satellite community to expand beyond canisterized volume and constraints. While there are costs incurred with this approach, it is significantly cheaper and more flexible than the traditional canisterized option. By accomplishing the 'Do No Harm' analysis as a consolidated vehicle within the LDPE, the Tetras are able to cost share this approach thereby significantly reducing cost and complexity while taking advantage of the power of the modular interface.

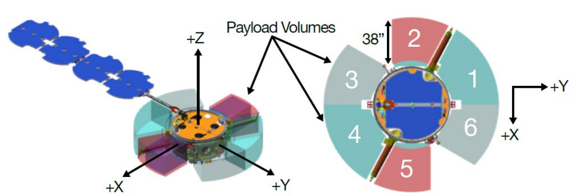

Figure 3: LDPE accommodation wedges establishing virtual canister boundaries

LDPE use of Digital Engineering

Digital Engineering will form the foundation of further extending the 'Do No Harm' and containerized approaches in order to increase access to space. The Aerospace Corporation is using a tool called Coupled Loads Analysis Sensitivity Program (CLASP) to help predict the best SWAP for the ESPA-class vehicles. The LDPE program office will then fund the acquisition of the flight worthy mass model, which will incentivize the payload providers to use the common SWAP. To start, three out of six ports will use common SWAP, while the other ports will be for other missions. Those missions will be obligated to provide flight models one year in advance of launch to enable the coupled load analysis.

Rideshare or "multi-manifest" missions – where several smaller "auxiliary" spacecraft are launched together, usually with a larger spacecraft – are becoming increasingly common. In many such cases, the properties of the rideshare spacecraft are not well-known during initial launch manifesting. Launch coupled loads analysis is used to predict the structural loads on the launch vehicle and the larger spacecraft, and traditionally relies on detailed dynamic models of all spacecraft in their final launch configuration. For cubesats, the launch community has run these models on the containers and the permutations of all systems within the container. However, models are often unavailable for smaller, non-containerized, spacecraft until close to launch, which limits the ability to flexibly manifest auxiliary payloads or swap them late in the launch integration process.

SMC and The Aerospace Corporation are developing a process by which uncertainty in the loads and related structural verification of a spacecraft can be reduced prior to final definition of the rideshare manifest. The process is based on a series of analytical studies performed with the CLASP tool, which utilizes cluster computing for the calculation of full-fidelity coupled loads analysis; resulting in thousands of potential rideshare configurations. The process works by calculating an envelope of primary spacecraft loads for a wide range of potential launch configurations, including various auxiliary spacecraft attached to ESPA-like adapters. The auxiliary spacecraft are represented in the analysis using dynamic simulator models as opposed to full-fidelity models of the spacecraft. The dynamic simulator models allow the sensitivity study to account for a wide range of potential configurations when actual models of the auxiliary payloads are not available. The envelope of loads across all configurations is then examined to identify areas of the primary spacecraft structure that are sensitive to rideshare manifest changes. This information is utilized to improve the design of the primary spacecraft, or to define requirements on auxiliary spacecraft to improve the potential for compatibility of the entire manifest. If this process is applied early in the launch integration of a mission, it will significantly increase the flexibly to manifest auxiliary payloads or swap them closer to launch.

Digital Engineering also enables streamlined and efficient manufacturing and integration processes. These practices were used to manufacture parts critical to the interfaces for the payloads. During the pandemic when travel was limited, digital models assisted in the creation of 3D representations that allowed for "fit checks" to be accomplished remotely.

Another primary area for development by SMC is the problem of thermal management, especially during the coast phase of the launch. The current LDPE approach is to require a near-adiabatic thermal interface. This approach certainly creates a standard, but significantly limits the payload design or requires significant additional thermal design on the side of the payloads, especially for higher power payloads. The opportunity to apply Digital Engineering techniques to expand MOSA standards is a key area of investigation. Models and standards can be much more easily shared and manipulated. While this may seem to break the 'standard' part of MOSA, it allows models to integrate more seamlessly between the bus and the payload. By establishing the standard or thermal model exchange, we hope to drive a more capable system at lower cost and faster speed. For example, an ESPA-class bus could have a lot more heat acceptance and heater power capability as potential service to its payloads. Currently, the bus design is inherently limited in the power capacity of the LDPE ring in the coast phase. This drives considerable complexity and cost, negating the benefits of MOSA to maintain mission capability. By allowing model standards, additional digital trade space is opened up to allow for heat transfer within limits of the existing modular ring design. The limits of this approach will be investigated, and the ability to share and communicate models across multiple agencies and industry partners remains a key challenge to overcome.

Several payload providers have acknowledged the adiabatic interface approach as a key design bottleneck for payloads with varying levels of impact. Many solutions have been investigated, such as power from the launch vehicle or additional batteries to support additional heater power. The solutions drive cost, complexity, and time at the altar of the adiabatic interface. The MOSA framework has the opportunity to manage trade space much more readily in the digital model environment, and to find nearer to optimum solutions using CONOPS, heat transfer, and other model verification techniques at the whole system level. Payload developers tend to favor a host-as-a-service-provider approach, but the thermal interfaces between bus and payload need to be co-developed and managed at the system level in order for the host to enable the MOSA framework. The host-as-a-service-provider approach also tends to drive systems to point solutions that negate the MOSA benefits. These point solutions tend to propagate further design analyses, more time, and further complexity while reducing the modularity.

Again, we propose to utilize heat transfer limits within the combined thermal modeling analysis to allow limits of heat transfer between payload and ring, rather than a carte blanche adiabatic definition. Managing the modularity in digital space allows for limits of the standard to be explored within the established system constraints. Those constraints can be driven by the modularity of the system, but allow for better sub-optimization; thus expanding MOSA benefits rather than limiting them.

Future of the Rings

The success of the ring concept across DoD has started a number of conversations on how we can all work together to benefit both the government and industry. Efficiencies in cost, schedule, performance, modeling, risk analysis, mission assurance, and production can be gained from utilizing one program office to manage all of these items. Currently, program offices are purchasing rings one or two at a time and are seeing varied production and integration costs across contracts. Making these rings in a production-like manner, and developing the associated digital twins to these rings, will enable modeling that provides predictable coupled loads analysis prior to launch. This burns down risk for the integrated stack of rideshare space vehicles assigned to any rocket. It also enables the late change out of payloads that would be integrated onto the ring.

An additional opportunity for the rings is to move the satellite from a short mission duration to providing a residual capability on orbit. Currently, LDPE's role is to demonstrate the technical feasibility of prototypes. These demonstrations last up to 18 months, but can go longer if there is a desire to sustain operations to continue gathering data, and if the prototype is still able to perform. Once the demonstrations on the payloads are complete, the mission of the ring is also complete and the ring will proceed to a disposal orbit.

Rather than sun setting these rings, they could remain on orbit and provide services that enable the USSF enterprise architecture. Acting as modular nodes in GEO, they can enable communication through cross-links, open processing platforms, expanded maneuverability, and on-orbit servicing/refueling for other spacecraft. SMC's Innovation and Prototyping Directorate is pursuing many concepts, which tackle these possibilities. In order to make the rings more integral in the future architecture, SMC is looking for opportunities to extend the ring service life to help further the USSF architecture gaps. By using both MOSA standards and Digital Engineering practices, rings across the architecture from various program offices could host these capabilities, effectively creating its own "ring-based modular architecture." Current concepts are also looking to expand this idea into cis-lunar space. This expansion opens up possibilities even more to establish a foundational architecture that enables mission success for deeper space missions.

This brings the foundation of a total integrated MOSA framework within the USSF architecture. Each ring becomes a modular component of the total architecture that can be cost-effectively introduced and modified as the architecture develops. Along with complementary operations and development of the Tetra class of vehicles, the opportunity for capability evolution should create a whole new approach to providing critical capabilities. Working as complementary as well as additive elements of the architecture, SMC has developed a specific class of small satellite companions to the LDPEs called the Tetra program.

TETRA

In a similar manner, Tetra is a "small class" bus that allows different prototypes to be placed on orbit. Tetra has three primary differences than LDPE.

First, Tetra is a separable payload attached to a ring. This enables a different kind of mission for Tetra. While LDPE is the "Freight Train to Space," Tetra was developed to prove maneuverability that could be used during on-orbit test of a variety of satellites. These performance characteristics can also be used in a variety of training scenarios by both new and experienced operators, providing an on-orbit resource to develop tactics, techniques, and procedures.

Second, Tetra is considerably smaller that LDPE, therefore allowing only smaller payloads to be manifested. This is ideal for new technologies that aren't ready to be hosted on a standalone bus, but need an ability to get to GEO and a way to transmit data back to its owners.

Finally, Tetras are built by three different vendors, which increases the variety of performance characteristics of these satellites and additional industrial base building small satellites. All Tetra spacecraft are procured through the Space Enterprise Consortium (SpEC) to enable competition amongst a wide set of vendors. Tetra-1 is built by Millennium and will be focused on GEO operations. Tetra-2 is built by Blue Canyon Technologies and is proving out some interesting maneuverability options. Tetra-3 and -4 were purchased as a "two for one" deal and are being built by York, with missions still in definition.

Figure 4: Tetra-1 being assembled by Millennium Space Systems personnel[4]

Tetra Leverages MOSA

MOSA standards have not yet been implemented within the payload accommodation for the Tetra. This was done initially to demonstrate the capacity and cost effectiveness of a wide variety of vendors. Furthermore, a key acquisition goal was to increase the small satellite market in the GEO environment. The success of the Tetra program has borne out the utility and power of the MOSA framework as applied to the LDPEs, as discussed above. There is a requirement for Tetra to be assigned to a LDPE port, so they are beholden to the interface standards established by the ring. Once MOSA standards have been expanded to include multiple vendors for all rings (through the program office running the ring buys), then future Tetras will be able to attach to any port on any ring in any orbit configuration.

The benefit of competition with the LDPE MOSA interface approach has allowed for three completely different vendors to compete and provide unique capabilities to the USSF.

CONCLUSION

MOSA and Digital Engineering are fundamental to our ability to provide a dynamic and cost effective USSF architecture. The initial benefits of these approaches have been clearly proven by the LDPE and Tetra programs. As we consider the future of the MOSA construct, further development of Digital Engineering capabilities are critical to implementing within the space community and the USSF architecture. It is clear there is a demand across the government for smaller payloads to have a platform that gets these prototypes to orbit quickly, and can share on-board resources for operations.

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