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CONTINUOUS PRODUCTION AGILITY (CPA): ADAPTING AT THE SPEED OF RELEVANCE

A PROJECT THOR PUBLICATION

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WHY WE WROTE THIS REPORT

While the DOD adapts to a new national security space paradigm, The Aerospace Corporation, as operator of the only federally funded research and development center (FFRDC) dedicated to the space enterprise, is working aggressively to address all aspects of this critical challenge. As a trusted advisor and liaison among DOD, intelligence, civil, and commercial space, Aerospace offers an informed perspective, which we holistically call Project Thor, on the changing landscape and necessary course of action. Decades of experience working with government customers and industry partners, coupled with technical depth and domain breadth, uniquely provide Aerospace with the insight needed to help the government make this crucial transformation.

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Summary

The Department of Defense (DOD) is transforming the way it does business to outpace rapidly evolving threats. The traditional risk averse approach for space development favors high performance satellite systems, based on optimized designs and a slow pace of constellation refresh. This typically produces only enough for replacement of long-life spacecraft, with periodic adjustments as spacecraft outlive initial projections. This approach limits opportunities for technology insertion, disincentivizes capital investment in long-term production efficiencies, and fails to account for the attrition that would occur during an active conflict. To avoid these limitations, the national security space enterprise should consider a Continuous Production Agility (CPA) approach, which focuses on delivering an *entire constellation* over a short period (e.g., *five* years) and immediately begins the replenishment process on a schedule-certain basis.

Introduction

In March 2018, then Deputy Secretary of Defense Patrick Shanahan asked The Aerospace Corporation (Aerospace) to look at the space enterprise and recommend what should be done to build a more resilient space architecture capable of outpacing the emerging threat. In response, Aerospace undertook a study, referred to as *Project Thor*. Thor's recommendations were presented to the DOD senior leadership and are summarized in a recent Aerospace paper, *Outpacing the Threat with an Agile Defense Space Enterprise*.[1] The proposed Continuous Production Agility (CPA) procurement strategy was a key element of Thor's recommendations.

The CPA strategy realigns space acquisition for speed, adaptability, and resilience using increased production, a modular open systems architecture design and contracting approach, and enhanced competition. By shifting to a continuous production approach and opening the space system architecture, the DOD can more readily field new capabilities or respond to counter-space efforts.

Maintain Production Cadence

CPA focuses on delivering an *entire constellation* over a short period (e.g., five years) and immediately beginning the replenishment process on a schedule-certain basis. This is an operational

The fundamental insight behind the CPA approach is that resiliency does not come from picking one optimal future architecture now. Instead, it comes from the ability to adapt the architecture and scale to future needs in an affordable way. Adaptability and scalability are themselves key architectural design features, along with the more traditional performance goals.

and cultural shift from the traditional high reliability mindset where current programs typically build long-life satellites in quantities only sufficient to maintain a small constellation with high functional availability. For high profile mission areas like protected communications and missile warning, the traditional strategy, coupled with fiscal constraints, results in satellite production rates of just 4 or 5 units every 15 to 20 years. By contrast, CPA's high quantity and high production rate strategy drives a predictable manufacturing cadence and incentivizes industry to invest for efficiency and speed. Increased spacecraft production diminishes dependence on individual satellite reliability. Constellations are more robust against threats and single-point failures. In some cases, shorter design lives may enable simpler designs with less redundancy, reducing per-unit costs and partially offsetting the increased costs from production and launch quantities.

Adopt Open Standards, Modularity, and Higher Volume Production to Motivate Industry Innovation

Many commercial industries have already demonstrated how to improve flexibility and agility by adopting modular methods to establish production quickly and then scale up production rates in a cost-effective manner to meet demand. The secretaries of the Army, Navy, and Air Force have directed the application of modular open systems architectures (MOSA) to the maximum extent possible.[2] CPA applies this approach to satellite development and procurement, focusing on the acquisition of modular elements rather than buying whole satellites or systems. In this approach, the U.S. government (USG) contracts with multiple providers for satellite buses and payloads in support of multiple programs. Modular, nonproprietary interfaces using open standards defined in consultation with industry allows rapid integration of compatible elements while enabling each element to develop at an appropriate pace, as changing threats and technologies dictate. To encourage innovation, competition, and schedule confidence, multiple parallel contracts may be established where economically viable, with each delivering a portion of the needed units. This allows major components to be competed throughout the program's life, giving the industrial base multiple opportunities to participate. A key first step will be development of modular bus/payload interface standards to shape future acquisitions. To this end, the USAF Space and Missile Systems Center (SMC) has already started an effort with a working group of 10 prospective contractors for its strategic space systems.

The Changing Space Paradigm

How the United States responds to the combined strategic and economic challenges, coupled with how it seizes opportunities afforded by rapid technology progress and the commercial space revolution, will determine whether the United States maintains its advantage in national security space.

U.S. Lead in Space is Narrowing as Foreign Competition and Capabilities Grow

Leadership in the space domain has historically provided the United States with key advantages for defense and economic growth. Today, substantial foreign, military, and commercial investment has also blunted the U.S. competitive edge. The numbers of foreign reconnaissance and remote sensing satellites has tripled (from 100 to 300) in the last 10 years. And within areas where the United States still leads, China and, to a lesser extent, Russia, are gaining. The National Air and Space Intelligence Center concluded that new technology deployed by these potential adversaries was unprecedented.[3] While striving to catch up to U.S. space capabilities in areas such as communications, reconnaissance, and positioning, China and Russia are also aggressively pursuing new electronic warfare, directed energy, kinetic weapons, and cyber-attack capabilities that threaten U.S. space capabilities. This dynamic threat environment is

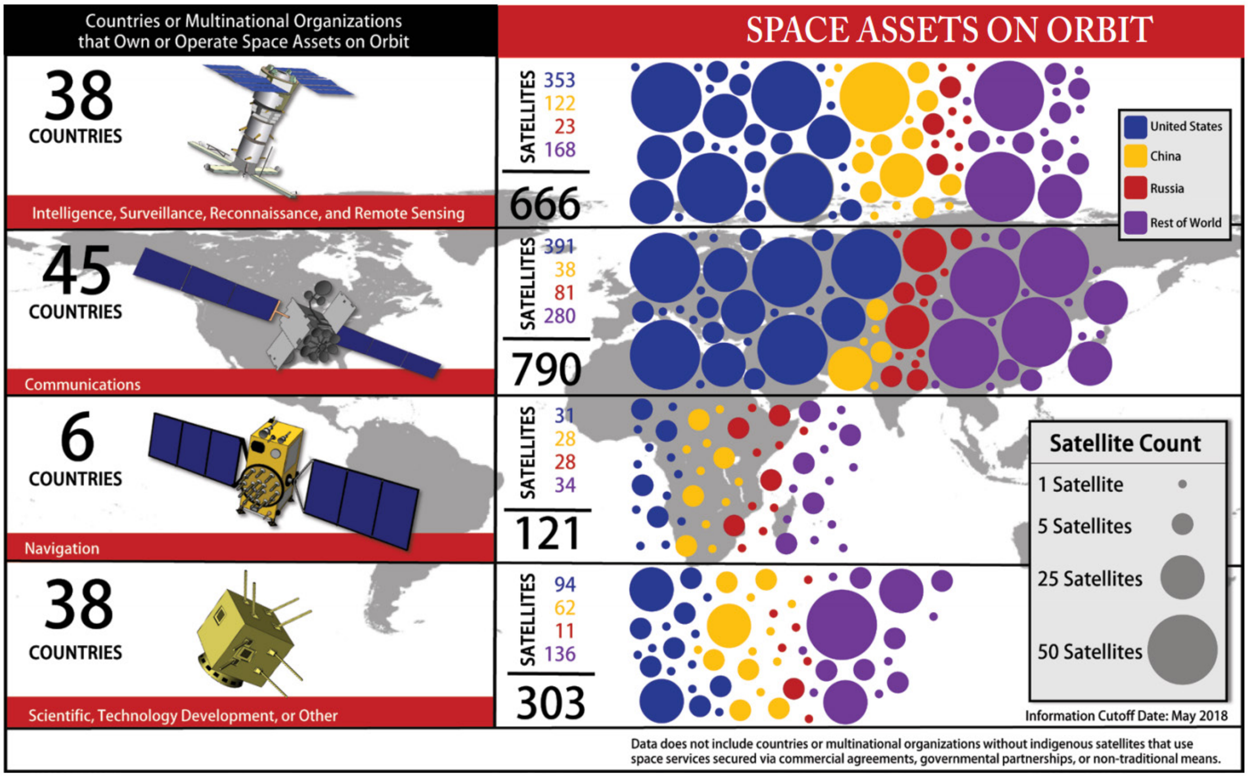


Figure 1: Space Assets on Orbit for Intelligence, Surveillance, Reconnaissance, and Remote Sensing (ISRR). *Based on an assessment of 38 countries that own or operate ISSR satellites. (Source: National Air and Space Intelligence Center, "Competing in Space," December 2018)*

driving the need to rapidly respond, adapt, and enhance our space enterprise technology posture.

National Security Space Systems Currently Rely on a Fragile Space Industrial Base

The U.S. military and intelligence community's space capabilities depend on a strong domestic aerospace industry at a time when the space club is becoming less exclusive. During the last few years, total global satellite manufacturing revenues have increased—last year increasing 26 percent to \$19.5 billion. While total U.S. satellite manufacturing continues to grow, the U.S. share of global satellite manufacturing revenues has declined from 75 percent in 1995 to 59 percent in 2018.[4] This rapid global growth means that the Pentagon and intelligence community rely on an evolving global satellite manufacturing ecosystem. In this ecosystem, several single points of failure exist, mostly in highly specialized and capital-intensive Tier 2 (space assemblies) and Tier 3 (components and parts) businesses that supply Tier 1 contractors (primes). DOD and USG-wide studies and analyses have identified at-risk capabilities, fragile suppliers, and stress in the lower tiers of the U.S. space industrial base, including aerospace structures, radiation-hardened microelectronics, radiation test and qualification facilities, and various satellite components and assemblies.[5]

According to the Office of the Deputy Assistant Secretary of Defense for Manufacturing and Industrial Base Policy, National Security Space (NSS) "leverages the commercial sector; however, there are certain performance requirements and capabilities that are more demanding or unique to NSS and are not supported by the growing commercial/civilian space ecosystem."[6] Companies that supply these unique capabilities to NSS are hurt by low production quantities and severe fluctuations in demand—caused by a production strategy driven by replenishment, funding uncertainty, programmatic peaks and valleys, and by major vendors' efforts to cut costs through consolidated buys of components. Fluctuations in satellite systems procurement (see Figure 2) have created a "bullwhip effect," which forces inefficiencies across the supply chain.[7] The bullwhip effect, sometimes referred to as *demand amplification*, is the escalated response to demand signals as one moves up the supply chain from satellite operators to Tier 1 (satellite primes) and to Tier 2 (satellite component) providers.

High Volume "New Space" Opportunities

The Space Critical Technologies Working Group (CTWG), the executing body for the Space Industrial Base Capability Investment Program, recognized that, to be effective, risk mitigation for the space industrial base is best shared among enterprise partners through a shared effort to maximize efficiency of investments.[8] The CPA modular architecture is one such approach that could apply a long-term acquisition strategy that increases demand and reduces demand uncertainty across the NSS enterprise.

Executive Order (EO) 13806: Assessing and Strengthening the Manufacturing and Defense Industrial Base and Supply Chain Resiliency of the United States

On July 21, 2017, the White House issued EO 13806, which aims to expand the use of the Defense Production Act Title III and the Industrial Base Analysis and Sustainment programs to address critical bottlenecks, support fragile suppliers, and mitigate single points of failure across multiple industrial base sectors. CPA supports the intent of EO 13806 by introducing a launch-on-schedule approach, which smooths out demand, creating market stability for upstream supply chain participants.

Shifting from a project or batch manufacturing to a steady flow production line is one way to gain

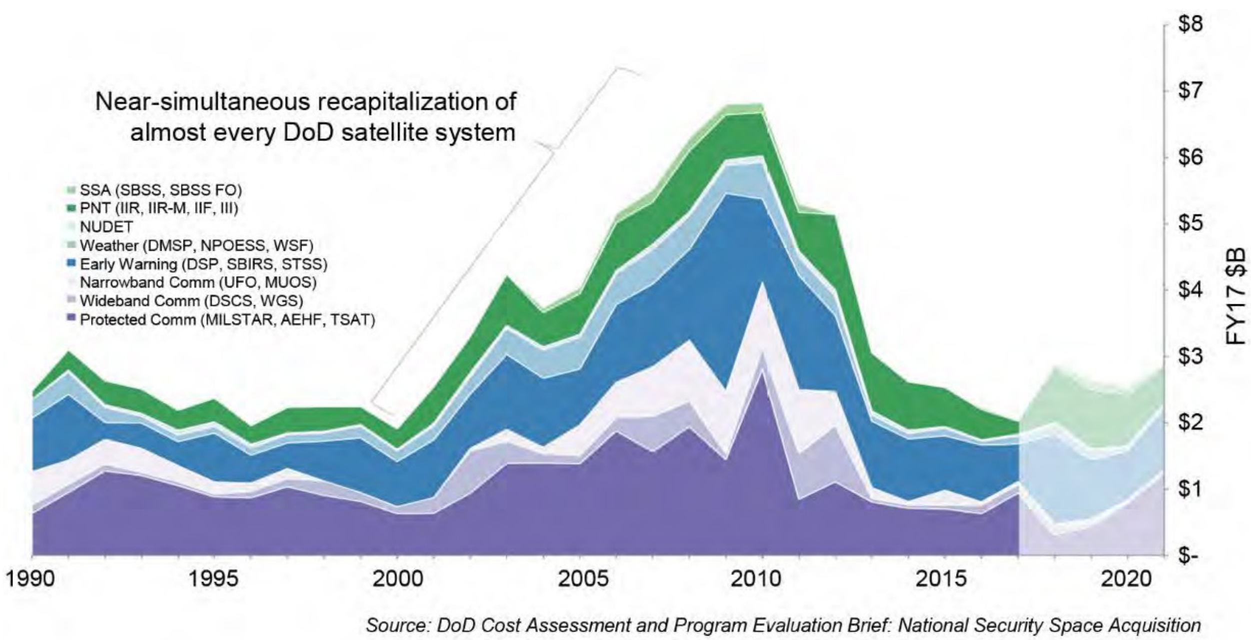


Figure 2: The Bullwhip Effect – Space Recapitalization. *The spike of recapitalization and overruns in space programs from 2000 to 2010 was followed by a dramatic decline, leaving suppliers with excess capacity. (Source: Interagency Task Force in Fulfillment of Executive Order 13806, "Assessing and Strengthening the Manufacturing and Defense Industrial Base and Supply Chain Resiliency of the United States," September 2018)*

efficiencies. Initial capital investment in production capacity is typically justified by increased gross revenues from increased volumes.

The space industry is beginning to move to high-volume production for large constellations (e.g., OneWeb and SpaceX Starlink) and elements of the DOD are looking to build off these high-volume production lines. The Space Development Agency (SDA), for instance, has stated that it will lean heavily on proliferated low Earth orbit (pLEO) constellations to serve multiple missions, from missile defense to providing positioning, navigation, and timing data.[9] Recognizing the pLEO potential for its high degree of connectedness, resiliency, and coverage, the Defense Advanced Research Projects Agency's (DARPA's) Project Blackjack aims to demonstrate the value for a variety of military uses. And for those national security constellations that cannot build off these high-volume lines, an enterprise acquisition strategy can still realize flow production opportunities (albeit at lower rates) for common modules, leveraging an open architecture for mission-specific needs.

The Time Is Right to Make a Shift to Continuous Production Agility

The DOD is currently undertaking significant recapitalization of space systems to replenish its missile warning, protected communications, navigation, and weather satellites. The DOD is also acquiring several constellations of new satellites and ground processing capabilities, including for missile warning, protected communications, space-based environmental monitoring, and space command and control. GAO Report 19-482T, "DOD Faces Significant Challenges as it Seeks to Address Threats and Accelerate Space Programs" provides a more detailed description of these space programs.[10] Concurrently, the DOD is also boosting efforts to increase space domain awareness and protect space assets.

As many of these recapitalization programs are still in their early stages, much of the non-recurring engineering (NRE) that would otherwise be spent on designing recapitalized systems using legacy concepts could instead be applied to designing CPA-informed systems. The time is right to leverage the one-time investments associated with recapitalization to establish a stable, efficient, and agile production process.

Why Is Our Pace of Change So Slow?

A replenishment-focused approach to fielding new systems involves lengthy decisionmaking processes. In many cases, we only consider fielding new, or replacement, systems on 15- to 20-year cycles.

Decisionmaking and design/production processes alone can take, on average, 5 years to mature a concept, gain stakeholder validated requirements, and establish an acquisition program;[11] and another 7.5 years, on average, to reach first launch.[12] This extended time frame highlights the increasingly difficult task of gaining consensus across disparate stakeholder needs, the difficulty of securing funding on which to base a program of record, and the investment challenges of NRE. There are several reasons for this:

- ***Infrequent Opportunities.*** Given the many competing defense budget priorities, funds are typically only appropriated for space systems acquisition when a predicted need can demonstrate that a capability gap is imminent. These periodic predictions are based on functional availability projections. Because space systems that survive launches and first year of operations typically outlive initial life projections, the analysis consistently results in shifting acquisition need dates several years into the future. The approach ignores risk that on-orbit assets can become operationally irrelevant due to growing threats long before they run out of fuel or fail due to the natural environment. Functional availability does not account for potential attrition during an active conflict.

✓ ***CPA solution:*** *transition from infrequent "launch on need" to frequent "launch on schedule," creating regular opportunities for change and on-orbit reserve for unanticipated attrition, including hostile actions and on-orbit failures.*

- ***Difficult to Decide.*** Infrequent opportunities for fielding new systems, coupled with diverse interests among multiple stakeholders, result in long decision cycles. Heterogenous stakeholder input has sometimes resulted in multiple rounds of analyses of alternatives based on divergent assumptions. Infrequent opportunities also drive an "everything but the kitchen sink" mentality on requirements since the user might not get another opportunity to articulate needs for 10 years or more.

✓ ***CPA solution:*** *create a process for regular requirements updates, continuous innovation, and frequent technology insertion.*

- ***Closed Architectures.*** Today's DOD space systems were developed in stovepipes and have proven costly to evolve. Partly because of the infrequent opportunities and exacerbated by the difficulty in obtaining stakeholder buy in, recent space systems have not been designed for frequent product improvements. The acquisition system, focused on each program element and yearly budgets, inherently favors closed architectures (reduced individual element cost) and one-off development.

✓ ***CPA solution:*** *develop architectures based on an enterprise acquisition view, incentivizing open and upgradable solutions.*

Shift from Launch-on-Need to Launch-on-Schedule

The single most critical step to move to CPA and enhance resilience of the NSS architecture is to shift to a launch-on-schedule paradigm. One might view CPA as a space military corollary to what the commercial sector refers to as *future-proofing*. For instance, traditional commercial low-volume/highly complex (LV/HC) manufacturers must consider how to remain competitive and profitable during an ever-changing business environment. Solutions typically include investing in production line capital assets to gain production flow efficiencies and creating flexibility through modularity. Regular line upgrades are carefully scheduled to ensure return on investment while anticipating evolving needs.

Space system launch tempo is influenced by three independent variables:

1. ***Satellite life*** – determined by empirical satellite data.

2. ***Risk*** – determined by the level of risk tolerance, including failed launch, failure on orbit, and the ability to respond to a threat. Program managers focus on reducing these risks, fielding the number of spares required at any point in time to mitigate risk and the level of ability to replace the loss due to failure or hostile action.

3. ***Capacity*** – the output of work that labor and equipment can perform within a given period.

In an uncontested market, high weight is given to return on investment, resulting in long-life satellites and point optimization. By contrast, a contested environment places a premium on opportunities to counter the increased risks: long design life becomes less favorable.

An uncontested market favors a *launch-on-need* approach (see Figure 3A). This has historically resulted in an irregular tempo that depends on variable satellite life expectations and creates industrial base instability due to fluctuations in satellite systems, which forces inefficiencies across the supply chain. CPA applies a *launch-on-schedule* strategy (Figure 3B), presuming the value of more frequent opportunities. A launch-on-schedule approach would result in regularly scheduled launches and would be less influenced by unexpected satellite failures.

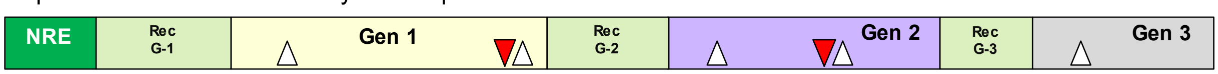
CPA Strategy Enablers

Five elements are critical to the CPA strategy:

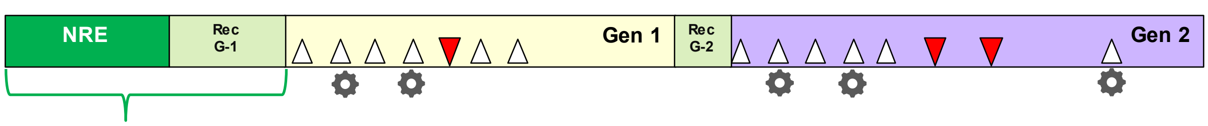
1. Streamline acquisition, efficient production quantities and commitment
2. System interoperability and modularity
3. Space enterprise integration
4. Digital engineering and "Industry 4.0" integration
5. Enterprise ground services (EGS) architecture

Comparing Launch Tempo Alternatives for Fixed Performance

3A: Current Approach – Launch-on-Need: Less frequent technology insertion. Launches are based on replacing failures or expiring satellites. New technologies are typically introduced with new satellite generations. Satellites are often designed as long life "Class A" satellites and experience fewer failures. They also require more time to manufacture.



3B: CPA Approach – Launch-on-Schedule: A modular open systems architecture allows for continuous production improvement and frequent technology insertion. Higher upfront NRE costs and reduced recurring costs associated with later generations are due to greater investment in modular architecture and capital infrastructure needed to produce high satellite volumes. A high degree of modularity also allows for rapid production.



Initial costs are higher compared to launch-on-need because launch-on-schedule strategy must initially invest in modular architecture and high production capital infrastructure. Recurring costs are less for future generations.

This modular open system approach allows for architecture extensibility whereby each generation can extend its relevance.

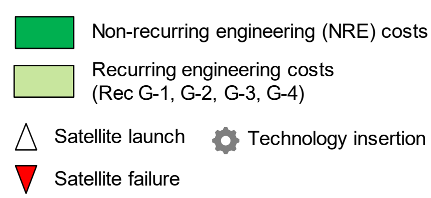


Figure 3: Launch Tempo Alternatives. *Both launch-on-need (3A) and launch-on-schedule (3B) can meet similar mission performance requirements. However, launch-on-schedule results in increased technology insertions and development cycles and requires greater upfront capital investment. Longer term, the payback is greater agility and decreased recurring costs due to modular architecture design benefits.*

Enabler: Streamline Acquisition, Efficient Production Quantities and Commitment

Outpacing the threat requires getting capability to the warfighter in a more responsive manner. The DOD currently captures warfighter needs, analyzes alternatives, programs the necessary resources, and develops or procures capabilities to meet the needs using three major decision support processes:

1. Joint Capabilities Integration and Development System (JCIDS) requirement process
2. Planning, Programming, Budgeting and Execution (PPBE) resource allocation process
3. Federal Acquisition Regulation (FAR) and DOD 5000-series instructions process for management of acquisition programs

CPA focuses on improving the agility for developing and procuring the capability. However, simplifying and reforming the top-level requirements analysis process for the space enterprise and simplifying the appropriations and programming structure for space systems can help compress the timeline from identifying the need to delivery. Building confidence among overseers within the DOD, the Office of Management and Budget (OMB), and Congress through transparency and successful pathfinders will be essential to secure support for these reforms. Shifting to the new CPA model will also require multiyear procurement (MYP) commitments to efficiently produce and field satellites at a higher rate, even though the modular approach and deliberately incremental additions of new technologies run counter to traditional MYP design stability requirements.

If long-term, higher-quantity, contracting arrangements can be made, likely efficiencies associated with continuous production will include reduced "start-up and ramp down" costs and increased manufacturing productivity associated with higher quantities. CPA's goal will be to drive down unit costs by maximizing the return on NRE and reducing the recurring engineering (RE) of future bus procurements.

The quantity commitments can be further increased, for additional cost savings, if procurement of similar components used across mission areas are consolidated into single contracts or a small number of competitive contracts. For example, consolidating multiple payloads or peripherals into a single production contract supports reduced NRE and efficient production. This benefit may be most pronounced when applied to spacecraft buses. To maximize the cost benefit associated with increased quantity, the contract strategy must encourage spacecraft bus manufacturers to invest and improve the bus design and its producibility. The early investment in process qualification simplifies mission assurance during production, leading to per-unit cost and schedule savings. As discussed earlier, a launch-on-schedule program is critical for efficient manufacturing production. Manufacturers can avoid frictional inefficiencies from starting and stopping production.

When to Consider Multiyear Procurement (MYP)?

Multiyear contracting is a special authority and an exception to the full-funding policy that requires the entire procurement cost of a weapon or piece of equipment to be funded in the year in which the item is procured. Using MYP allows procurement under a single contract award without the need to exercise an option for each program the year after the first. Under a MYP, DOD can contract for up to five years of quantities and is liable for termination costs if it fails to buy the systems contracted. Funding is appropriated on an annual basis for the next production lot. Termination liabilities budgeted up front are drawn down as production lots are acquired. A 2008 Government Accountability Office (GAO) report[13] notes that multiyear procurement can enhance the industrial base by providing defense contractors a more stable time horizon for planning and investing in production and by attracting subcontractors, vendors, and suppliers.

The consolidation of production for multiple bus types, supporting multiple different missions, into contracts that extend across mission areas is anticipated to enable cost efficiency. Satellite buses provide structure, pointing, position and attitude knowledge, power, propulsion, and basic command and telemetry with ground systems. The traditional customized and tightly integrated model for payloads and buses was rationally developed for performance optimization. However, the evolving threats require optimization for flexibility and agility. The CPA approach allows for both a modular satellite design and modular acquisition approach that can "mix and match" satellite buses, payloads, and group contracts.

To help understand the potential benefits of design similarities between missions and the potential for applying internal design modularity within the bus, concept designs for many future NSS missions were developed. Figure 4 illustrates the results of these studies.

In addition to reaping the benefits of long-term stability and higher-quantity production, the CPA approach could also seek to preserve competition to drive reduced cost and schedule risk. Where overall quantity permits, a dual-source contracting model is recommended. By splitting production quantity for functionally equivalent elements across multiple contractors, incentives can be established to

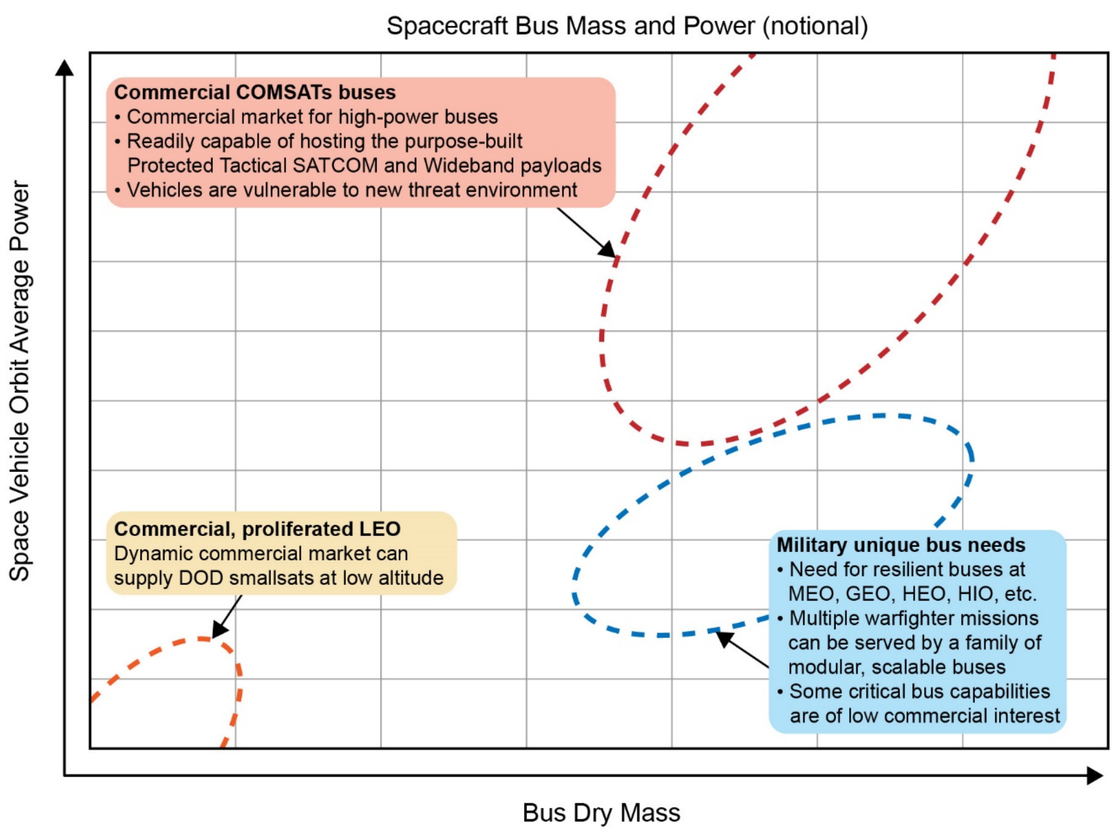


Figure 4: Space Vehicle, Average Power, and Bus Dry Mass (kg). *Satellite bus concept designs indicate a potential for a high degree of scalability and modularity for military-unique buses. While the specific values for each system or concept are not publicly releasable, blue, orange, and outlines represent multiple actual, in development, and conceived space vehicle designs: blue = family of buses for mid-size applications that address future U.S. Air Force mission needs; red = family of buses for large geostationary Earth orbit (GEO) applications (commercial); orange = family of buses for small low Earth orbit (LEO) (commercial)*

promote cost and schedule objectives and spur new capabilities through continuous innovation. With the goal of obtaining multiple, functionally equivalent bus, payload, and ground elements from different contractors, a modular approach based on open interface standards will be critical. Moreover, open standards and regular procurements will reduce the barriers to future competition.

Enabler: System Interoperability and Modularity

CPA is closely aligned with the DOD's MOSA efforts, which encourage employing interfaces that share common, widely accepted standards. The *Defense Acquisition Guidebook* (DAG) discusses the benefits of open systems architecture (OSA) to accelerate and simplify the incremental delivery of new capabilities into weapon systems. CPA is consistent with the five fundamental elements of the DOD's OSA, as presented in Table 1.

The introduction of a modular open interface between the spacecraft bus and payload (see Figure 5) will modify the current acquisition structure by separating spacecraft bus designs from payload designs. This modular and open approach will break down program stovepipes to achieve efficiencies through higher volume production. The higher production quantity lowers the per-unit spacecraft bus production cost, including NRE. In addition, standard and open government-controlled spacecraft bus-to-payload interfaces will yield a greater variety of bus–payload pairings and enable regular technology insertion opportunities to outpace the threat, regardless of which direction it evolves. Importantly, standard interfaces enable the government to own the technical baseline and minimize the potential for technology or vendor lock-in.

Table 1: CPA Meets the Fundamental Elements of Open System Architecture

Five Fundamental Elements of OSA[14]	How CPA Compares
1. ***Modular designs based on open standards*** with loose coupling and high cohesion, which allow for independent acquisition of system components.	CPA calls for standardized open interfaces for independent acquisition of satellite buses, payloads, ground systems, and user equipment.
2. ***Enterprise investment strategies*** based on collaboration and trust, which maximize reuse of proven system designs and ensure we spend the least to get the best.	CPA anticipates the need for increased spacecraft production, which will require increased resources. By taking an enterprise look at common production elements, the expectation is that the NRE required for the traditional approach will offset the NRE investment required to kick-start CPA.
3. Aggressively transform our ***lifecycle sustainment strategies*** for software-intensive systems through proven technology insertion and product upgrade techniques.	CPA creates frequent opportunities for continuous technology development and insertion for *both* software and hardware.
4. ***Dramatically lower development risk through transparency of system designs; continuous design disclosure***; and government, academia, and industry peer reviews.	CPA is enabled by the DOD's *digital engineering strategy*, which encourages model-centric interaction between industry and government (including model-based reviews, audits, and trust based on validation and verification).
5. ***Strategic use of data rights*** to ensure a level competitive playing field and access to alternative solutions and sources across the lifecycle.	CPA is based on modular standards developed through selected vendor consensus but facilitated by government, encouraging competitive introduction of alternate sources.

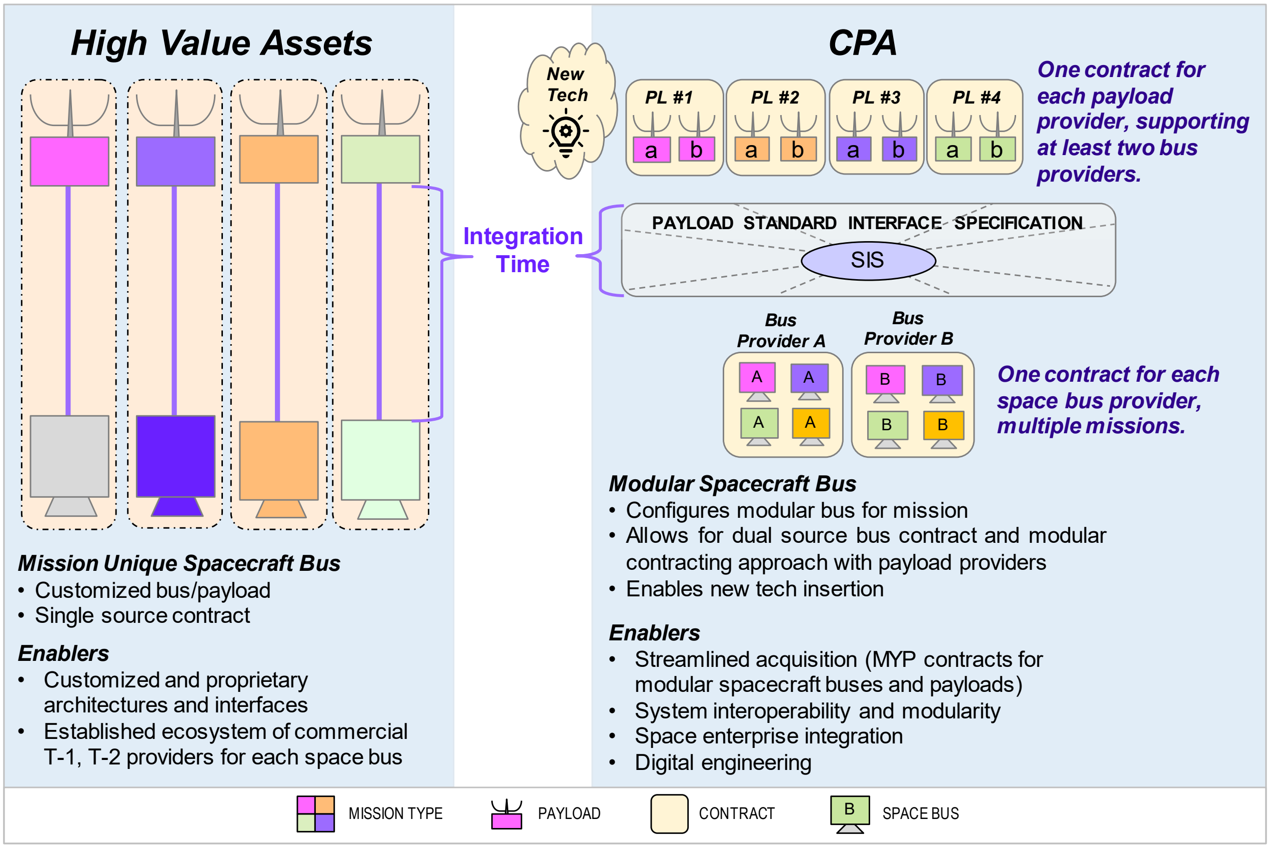


Figure 5: CPA concept overview.

What Areas of Modularity Will CPA Focus On? By standardizing the interfaces among buses, payloads, and ground elements, innovation can be worked on both sides of the interfaces. Although design changes for the spacecraft and payload still need to be qualified, isolating the impact of design changes will mitigate the amount of work required to qualify and integrate the new design. Similar to bus families that are available today from prime contractors, modular bus production lines can be reconfigured to support payloads for diverse missions. Development and establishment of a government-owned open standard payload interface will be accomplished through a working group partnership between government and industry.

What Is the Path to Open Standard Nonproprietary Interfaces? Interoperability standards allow an industry to advance without each company needing to design and build a ground-up implementation. Through a collaboration between government and industry teams, the payload standard interface specification (SIS) will become an open standard to address interoperability between the bus and payload across physical, mechanical, electrical, power, thermal, electromagnetic compatibility, and software and data interfaces. Aerospace has already identified approximately 650 legacy interface specifications used in NSS missions, including both proprietary and nonproprietary interface specifications. For those specifications that are already common, modular open standards offer the shortest transition time. However, the goal is to transition both nonstandard proprietary and nonproprietary interfaces to open standard non-proprietary interfaces. Aerospace provided SMC with a template for a SIS in

June 2019 and is now facilitating an industry working group to mature the document into a usable contractual specification. [15]

***How to Manage an Open Systems Architecture Across Multiple Stakeholders*?** To implement an open systems architecture, the government could develop an open systems management plan (OSMP) to meet the specific objective for an open systems strategy. This plan will clearly define and document all component and system interfaces and all subsystem and configuration item level interfaces.[16] To realize the benefits of open architecture, for instance, the Air Force's open architecture management (OAM) activity, sustains and evolves the Open Mission System (OMS) standard.

Encourage a Platform-Centric Ecosystem of Innovators. The DOD will also need to nurture an ecosystem of payload innovators by ensuring that their platform is understood and friendly enough for industry to iteratively apply ongoing and agile innovation. Although Apple's platform may not technically be an "open platform," in February 2008, it opened the iPhone to third-party software developers. Today, there are 1.8 million apps on iOS. Similarly, Google's Android users can choose between 2.7 million apps.[17]

Enabler: Space Enterprise Integration

Future space system planning must focus on the enterprise architecture capability as opposed to the capability of individual space vehicles. Enterprise architecture capability is increasingly distributed among multiple space vehicles, ground systems, user equipment and other architectural elements, which must be integrated to function as an enterprise. Use of modern enterprise systems engineering, development, operations, and cybersecurity methodologies across the space, launch, ground, and user equipment areas can help manage the growing integration complexity. It is important to emphasize that modernizing the enterprise architecture also requires the replacement of aging, proliferated user equipment that has prevented full use of on-orbit capabilities.

CPA focuses the scope of work on individual procurements and assigns the enterprise architecting and integration responsibility to the government. In turn, the government may delegate portions of the effort to a qualified systems integrator. Ultimately, the government must work as an "orchestra conductor" to oversee the architecting and integration of payloads and spacecraft buses since mission payload development and procurement contracts are separated from the spacecraft buses needed to host those payloads. Once developed, modular spacecraft buses can be produced under a stable, recurring contract with regular opportunities for process and product improvements. Multiple contractors may be able to provide spacecraft buses or payloads with functionally equivalent capabilities, creating design diversity and improved industrial base robustness.

Lessons Learned:
Encouraging Agile Innovation

Mobile electronic devices, such as cell phones, operate in a highly competitive environment where rapid evolution is necessary to stay ahead of competitive threats. Apple and Android, for instance, displaced the market leader, Nokia, and became market leaders by encouraging an ecosystem of developers to innovate on top of their scalable platforms.

The "once mighty" Nokia tried to come back with its own platform, but it was essentially too late, and the company's open source platform was not transparent or open enough for developers. According to INSEAD, despite Nokia's early advantage, it remained "a device-centric system in what was becoming a platform- and application-centric world." (Source: *Yves Doz,* INSEAD, "The Strategic Decisions That Caused Nokia's Failure," November 23, 2017.)

Enabler: Digital Engineering and "Industry 4.0" Integration

In June 2018, the Office of the Deputy Assistant Secretary of Defense for Systems Engineering released the guidance document, "Digital Engineering Strategy." The strategy calls for the incorporation of digital computing, analytical capabilities, and new technologies to conduct engineering in a more integrated virtual environment to "increase customer and vendor engagement, improve threat response timelines, foster infusion of technology, reduce cost of documentation, and impact sustainment affordability."[18] The idea is to allow the DOD and its ecosystem of partners to evolve designs and reduce the need for expensive mockups, premature design lock, and physical testing. This strategy fits well with the goals of CPA. Digital engineering benefits extend beyond the design phase. SpaceX, for instance, has introduced fully digitized operations for its Starlink satellites and Falcon rockets. From concept through manufacturing, this "digital lifecycle" is considered a competitive advantage over traditional manufacturing methods.

CPA-based acquisitions will benefit from best practices and guidance from the DOD's "Digital Engineering Strategy" to securely and safely connect spacecraft and payload manufacturers with other stakeholders, including government customers, SETA contractors, FFRDCs, standards bodies, and regulatory authorities to ensure an end-to-end digital enterprise. Use of models across this end-to-end system will establish a greater understanding of the entire satellite ecosystem as well as the ability to conduct digital prototyping for novel elements, which can initially be digitally integrated into the overall DOD space enterprise.

Digital models will allow payload innovators to prototype, experiment and test decisions and solutions in a virtual environment before they are realized physically and integrated into the modular bus.

Manufacturers across many industries are learning how to transform by optimizing their operations. The *fourth industrial revolution*, a term coined by Professor Klaus Schwab, founder of the World Economic Forum, enables manufacturers to evolve from machine-based mass production to digitally enabled production. Industry 4.0 factories can visualize the entire production line, including the supply chain. Space Manufacturing Industry 4.0 will harness the capabilities of distributed sensors, Industrial Internet of Things (IIoT), cloud computing, cognitive computing, machine learning, artificial intelligence, and automated inspection. The commercial space sector is already embarking upon this path. For instance, OneWeb's "Factory 4.0" factories in Toulouse, France, and Florida include smart tools, automated guided vehicles, big data, and deep learning on test results. Airbus is also building a Factory 4.0 to automate and digitalize the production of solar arrays for satellites, including a robotic assembly line.

Enabler: DevSecOps Strategy

Current software development takes too long, is expensive, and exposes warfighters to unacceptable risk by delaying access to tools needed to ensure mission success. For software-intensive ground systems like Enterprise Ground Services (EGS) or Enterprise Space Battle Management, Command and Control (BMC2), the CPA approach integrates security end to end, as a shared responsibility. This approach is referred to as a "DevSecOps" strategy. In August 2019, the DOD chief information officer released the first reference design document for DevSecOps.[19]

DevSecOps offers a way to field on-orbit solutions to ever-changing requirements. Adoption of DevSecOps into a secure, open architecture also strengthens the DOD space enterprise's ability to work with our allies. This agile development strategy is already a recognized best practice within the commercial sector. Moreover, China, Russia, and North Korea are already "massively implementing DevOps."[20]

Benefits

Economies of Scale: Launch on Schedule and Streamlined Processes

High production volume drives acquisition tempo and can enable efficiencies throughout the space value chain. CPA benefits include:

- ***Greater Agility and Responsiveness.*** CPA is designed to reduce time from decision to delivery. By launching on schedule, there will always be a near-term opportunity to deliver a new capability or insert a new technology. For example, a more capable auxiliary payload can be inserted on the next spacecraft vehicle to be launched to counter a newly emergent threat; and a proven new technology can be on-ramped to a bus or payload at the next near-term opportunity—without waiting for a series of decisions on a new acquisition program or delaying a system already in production.
- ***Mission Assurance for Producibility.*** CPA will also change how programs conduct mission assurance. A stable industrial output fosters

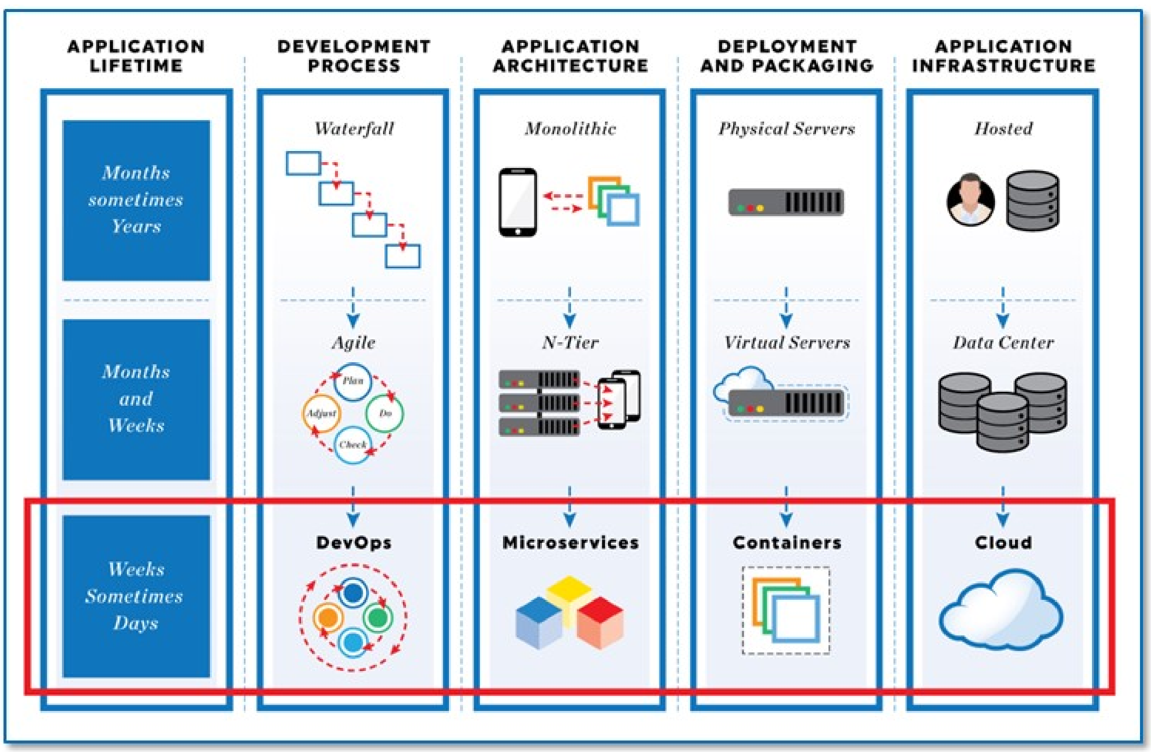


Figure 6: From Waterfall to DevSecOps. *DevOps disrupts the traditional acquisition model. The waterfall software development process is segregated into predefined phases (e.g., feasibility, planning, design, build, test, production, and support). By contrast, agile development DevOps can avoid complex requests for proposals (RFPs) and long planning phases with deliverables, milestones, and fixed budgets, while still providing flexibility for changing project requirements. (Source: DOD Chief Information Officer; "DoD Enterprise DevSecOps Reference Design," Version 1.0; August 12, 2019.)*

ongoing production learning and innovation and assures availability and readiness for manufacturing facilities and skilled employees. Reliability at the unit level should increase over time, based on ongoing learning made possible by continuous production. As a result, government mission assurance resources may shift from product-focus to process-focus once the design is qualified to ensure in-process controls minimize or eliminate workmanship escapes. The government can reap the benefits of a production program, with resiliency gained at the system level.[21]

- ***Safety in Numbers.*** A launch-on-schedule tempo can be selected specifically to create on-orbit reserves. This contributes to higher levels of resilience and provides residual resources that could potentially be made available for foreign military sales (FMS) or cooperative agreements.

- ***Overall Efficiencies.*** Increased production rates and the consolidation of similar unit types onto a product line will create "resource sharing" opportunities within the supply chain and across the government. The extension of these product lines to additional similar items can benefit sister departments and agencies with greater opportunity to share contracts, production lines, and designs.

- ***Innovation, Innovation, and Innovation.*** CPA will focus and foster innovation. The defense community can rapidly insert and operate new technologies, and, with a stable open interface, payload manufacturers can focus their design capabilities on creating unique sensors and new capabilities. To further drive innovation, these modular open standards will also encourage competition among spacecraft bus and payload providers when multiple vendors exist.

Costs

Increased production and launch rates will be necessary to outpace the threats posed to U.S. national security space systems. Upfront investments are necessary to break the vicious cycle in which current DOD high-value assets are stuck. Still, average unit costs can be lower due to the following:

- ***Flow Production Efficiencies.*** Although the establishment of high-volume production lines may initially increase both NRE and total costs, CPA and modular design can increase value-efficiency by reducing overall production and unit costs over time due to efficiency gains when manufacturers migrate from project-based or batch-based production to flow manufacturing. In other industries, such as aircraft and automobiles, flow manufacturing has proven to lower unit costs over time.[22]

- ***Planned Build Quantity.*** Planned production build quantity drives design and development engineering. As a space program plans to build more units, it must invest more in upfront costs. This is measured relative to the theoretical first unit (T1) cost. A space program typically invests more upfront for larger production runs. Return on capital investment will depend on the number of units produced (see Figure 7).

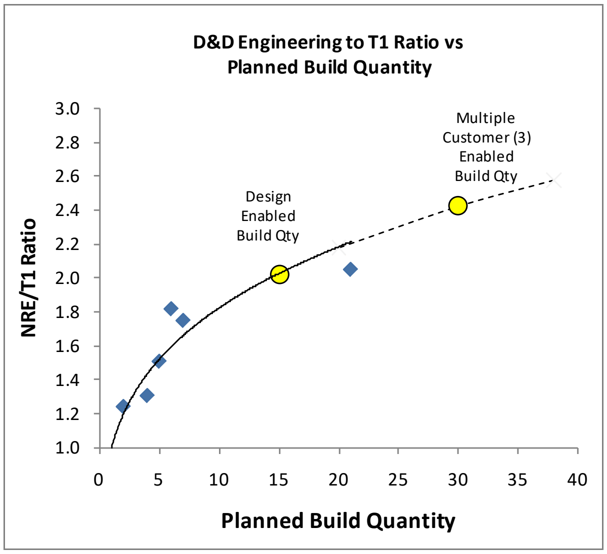


Figure 7: Planned Build Quantity. *Based on a NASA headquarters study from 2007, which looked at 44 programs and down-selected to 6 (to allow for an "apples-to-apples" comparison). The study examined different production design and processes across various space programs and the required associated manufacturing and management for cost-efficient large production runs.*

- ***Shorter Design Lives.*** Costs can decrease as manufacturers shift from Class A long life to Class C long life to Class C short life satellite designs. Figure 8 illustrates mission class cost comparisons showing that costs decrease with lower mission class and shorter satellite design life. This figure is based on a study where Aerospace applied three global positioning system (GPS) configurations using standard cost models to develop the representative mission class cost comparisons. For instance, the NRE cost for a Class C short life mission is about 32 percent of a Class A mission. The recurring engineering costs for the first unit (REC T1) for a Class C short life design is 57 percent of the Class A design. A Class C short life satellite will be 42 percent of the total NRE and REC T1 combined as compared to a Class A long life mission satellite.[23]

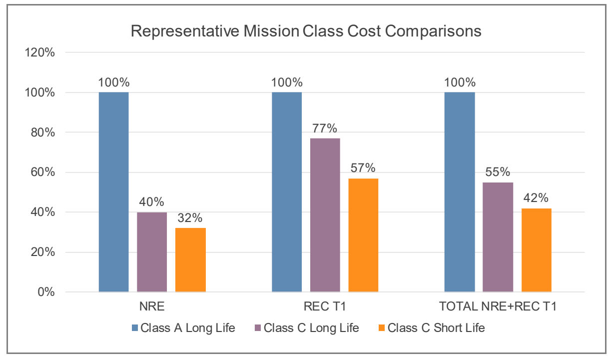


Figure 8: Representative Mission Class Cost Comparisons. *Based on a study by The Aerospace Corporation.*

- ***Learning Curve Efficiencies.*** Experience is a significant unit cost reduction driver. Proliferated LEO constellations are already banking on the benefits of high-volume production infrastructure. They can also benefit from learning-curve efficiencies as modularity will introduce established and repetitive procedures for building satellites (see Figure 9).

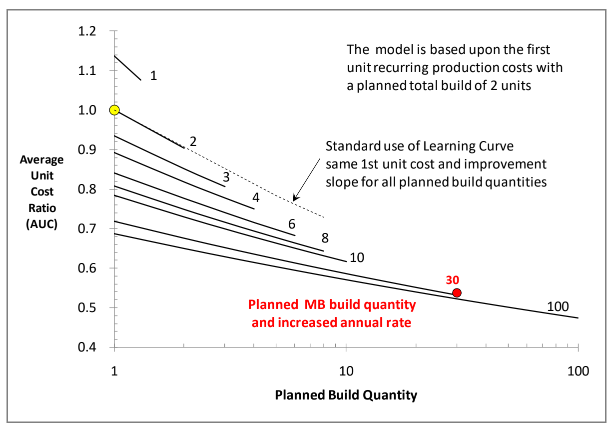


Figure 9: Planned Build Quantity. *A notional learning curve where a manufacturer lowers unit costs to 55 percent of initial average unit costs after building 30 units. For any manufacturer producing multiple units, a reinforcing feedback loop can emerge, providing increasing capability for lower marginal costs.*

Transformation to Agile, Higher-Volume Space Production

Advance from Buying High-Value Assets to Continuous Production Agility

Figure 10 summarizes the various operational paradigms. There is no right or wrong operational paradigm, but there is a right and wrong *time* for each.

For today's threat environment, the DOD space enterprise should break out of the high value asset procurement model. Instead, an agile, higher volume space production concept will deliver modular buses and payloads that can rapidly evolve. CPA's high-tempo, launch-on-schedule strategy will deliver an entire operational constellation over a short period (targeting five years for most constellations) and will replenish the constellation on a schedule-certain basis. The additional quantity of satellites drives manufacturing certainty and incentivizes industry to make capital investments in manufacturing capability for efficiency and speed.

Integration Challenges

A military spacecraft does not exist in isolation—it must operate within a space enterprise with other space infrastructure and other defense capabilities, and with other unified commands. Working within this framework, the DOD must adopt a "systems-of-systems" view of the space enterprise. Dedicated modular bus designs can be combined, as needed, with specific payloads to respond to various threats that USSPACECOM determines to be a priority. Under the CPA framework, the government can avoid purchasing individual customized spacecraft and instead become the orchestra conductor, working to oversee spacecraft integration (buses, payloads, and ground systems) by using modular contracts to optimize mission needs coupled with digital engineering practices to more efficiently and securely execute new design and integration efforts.

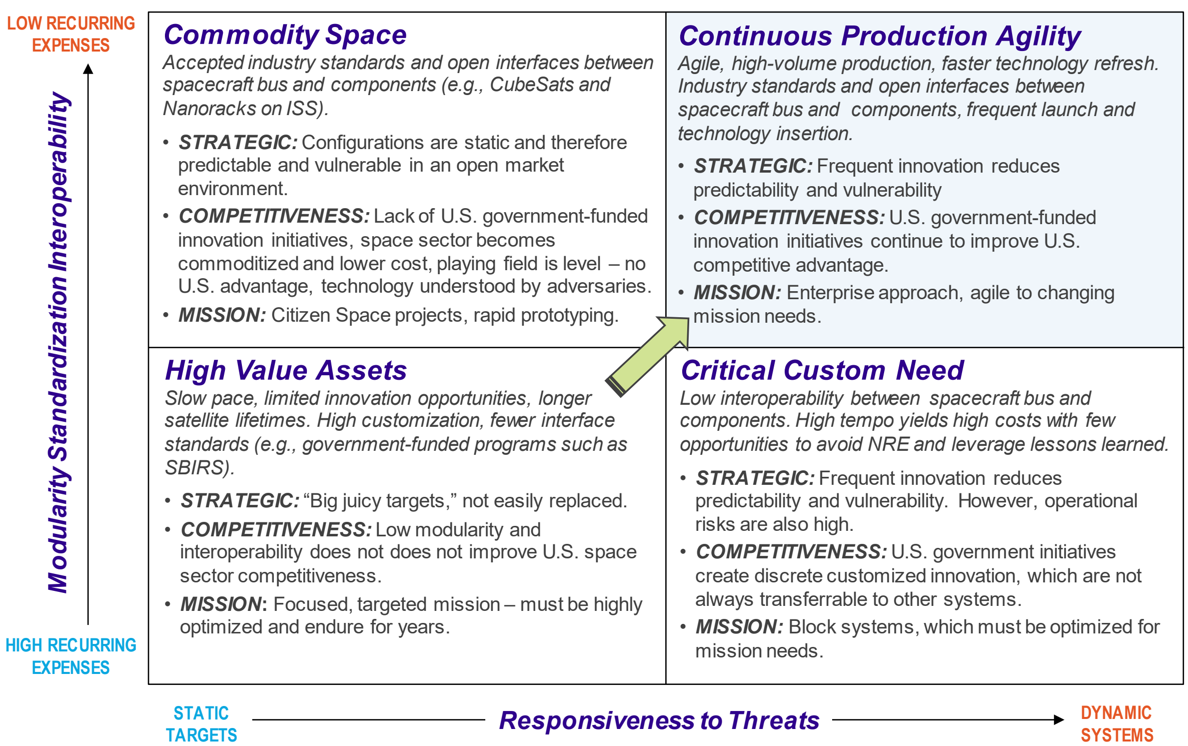


Figure 10: Space Sector Operational Paradigms.

Conclusion

The CPA initiative is designed to enable the U.S. to outpace the threat by making our national security space capabilities more resilient and responsive to adversary actions. CPA will also provide strong pathways to bring innovative technologies to program baselines, leveraging open modular systems architecture and frequent technology insertion.

The transformation to CPA will require an acquisition strategy and cultural shift from point solutions to agile solutions based on a regular production cadence and modular architecture principles. It will also require DOD and congressional support for increased budgets, adjustments to expectations, careful selection, and training of the government workforce. This transformation is necessary to adapt at the speed of relevance to meet the threat. The time is *now*. By leveraging robust space architecture through increased quantities, interoperability, on-orbit reserves, and production flexibility, the U.S. space enterprise (including government and commercial stakeholders) can move quickly at a time when potential adversaries are rapidly catching up.

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