COMMERCIAL DEDICATED RIDESHARE TO CATALYZE THE SPACE INDUSTRY

daniel Lim
TriSept Corporation, dlim@trisept.com

ABSTRACT

Recent debate has arisen about the viability of distributed space architectures as a strong contributor to realizing the vision of more cost-effective, capable, and resilient space systems. Ideally, disaggregating some mission functions off of the current large, highly expensive programs of record should create a hybrid network of satellites with increased technology refresh rates, lower cost and risk spacecraft with architectures that would be more resilient to malfunction, disruption, or destruction. However, a recent government report seems to cast doubt in the ability to distribute architectures with smaller satellite systems to help address the issues that plague the US and international space industries.

This paper begins with a summary of the Government Accountability Office (GAO) report on the feasibility of small satellite distributed architectures, highlighting some of the underlying assumptions that drove their conclusions. The paper evaluates the validity of the conclusions of the report and then presents a case outlining how distributed small satellite architectures are indeed a vital part of the health of the US space industry. The paper will then outline how commercial dedicated rideshare missions comprised of both commercial and US Government small satellites will effectively catalyze the industry as a whole.

Several commercial third party integration service providers have emerged in the US market that have been seeking to harness the benefits of aggregating launch opportunities for multiple spacecraft on a single mission to increase the frequency of launch and decrease the launch costs for large and small satellites alike. Small satellite systems are the seeds for reaping future larger class systems, in addition to providing useful operational and/or scientific missions themselves. This paper outlines the mechanics of setting up successful commercial dedicated rideshare missions and advocates for the US space industry to embrace this low risk, low complexity, and cost-beneficial means to realizing the benefits of small satellite in future architectures.

SETTING THE STAGE: THE STATUS QUO JUST WON'T DO

The Need for Reform

Divine prophetic powers are not necessary to foresee the accelerating increase of threats to the viability of the United States (US) space industry, let alone the security and prosperity of the US as a whole. In the 2014 Quadrennial Defense Review (QDR), the US Government (USG) states that "space also remains vital to U.S. security as well as to the global economy," implying that a threat to the USG space capabilities poses risk to the security of the world and its economy as a whole, not merely to the defense of the United States[1]. The USG is quick to cite the external threats to their space systems, both active threats brought by adversaries' increased counter-space capabilities, as well as passive threats, such as increased congestion in orbits and the harsh space environment as a whole[2]. However, the QDR is does not seem to explicitly call out the internal (i.e., self-induced) threats to the US space program, namely, the tightening USG budgets and the highly unwieldy and Cold War Era-based space acquisition process with its associated difficulty in defining and maintaining requirements baselines and struggles in soliciting and awarding contracts in a responsive and effective fashion[*].

In fact, it is easy to argue that the internal threats to US space dominance are actually more pressing than the external threats. Indeed, the external threats are real and can pose catastrophic damage to US space power.

[*] To further exacerbate the problem, the second or third order effect of our current space acquisition processes is that the US faces a more fragile space industrial base, which then circles back as an additional internal threat, among several others. Included is the risk of fielding on-orbit systems that are obsolete or ineffectual

However, the internal threats are both more imminent and eminent. They are more imminent because the threats are already directly affecting the US space industry, that is, fiscal constraints have already begun to threaten US space capabilities. In his testimony to the Senate Armed Services Committee (SASC) in March of 2014, General William Shelton, the previous US Air Force Space Command (AFSPC) Commander, outlines the damaging impact of the recent Government sequestration on AFSPC programs[3]. He testified that the recent budget cuts resulted in civilian workforce pay freezes, significant reduction of contractor services, deactivation of some operational capabilities, and addition of $100 million of additional risks to space system sustainment funding, "virtually [eliminating] any margin in [system Operations and Maintenance]." The external threats, however real they are, have not yet culminated into actual attacks with permanent degradation or destruction of US space assets. However, US space acquisition challenges and shrinking budgets have already started to negatively impact space and ground system programs.[†]

The internal threats are more eminent than the external ones because of the fundamental nature of the internal threats. As shown in Figure 1, the roots are basically essential to the health and viability of the entire tree because they provide the means to transmit nutrients and water from the soil to the rest of the tree, as well as serve as an anchor and foundation for the entire tree. Analogously, without funding (i.e., water and nutrients), nor the means to which to effectively and easily transmit the funding to procure space systems (i.e., the function of the roots), the entire space industry languishes and eventually perishes. General Shelton stated frankly to Congress, "[AFSPC remains] concerned that continued sequestration-induced budget cuts in [Fiscal Year 2016] and beyond, as well as overall funding instability, could undermine our space capabilities for years to come." The trend data for the future budgetary outlook for the USG further demonstrates that fiscal challenges are both eminent and imminent. In this author's paper for last year's Space Symposium Technical Track entitled "Defining a Roadmap to Bringing the US Space Industry Back to Health", this author cited the grave fiscal forecast that Bryan Benedict from Intelsat presented at the 2014 Space Tech Expo, depicted in Figure 2[4]. The figure makes clear that since the level of federal expenditures significantly exceeds federal revenues, even with projected levels of sequestrations, the budgetary pressures facing the US space program will indefinitely propagate unless a substantial change is made to the US budgetary system.

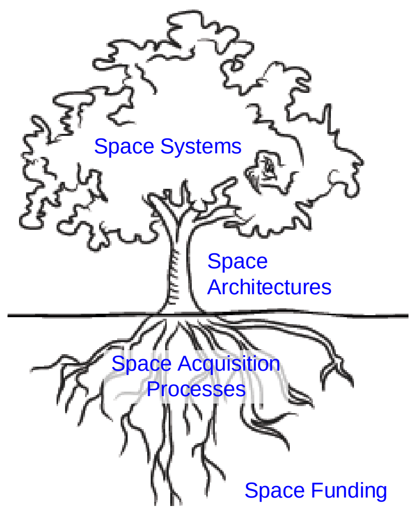

Figure 1. The fundamental role of space acquisition processes and funding.

In order for the US space industry to survive and thrive, the highest echelons of the USG leadership must be made equally aware of the internal threats to US space dominance in additional to the alarming growth and advancement of the external threats. ***More importantly, USG leadership must decisively act to counteract the internal threats to the US space industry.*** Major General (retired) Thomas Taverney, in

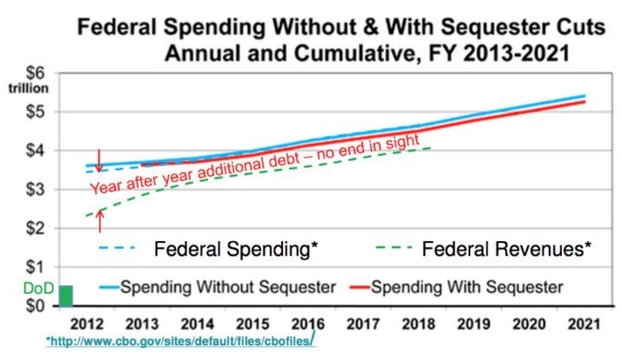

Figure 2. USG spending trends indicate persistent future US space program budget challenges.

[†] Further examples will be provided later in this paper that exemplify this point, such as challenges in GPS ground systems and SBIRS upgrades. Other examples include the cancellation of the Transformational Satellite (TSAT) and National Polar-orbiting Earth Observation Satellite System (NPOESS) programs. For the sake of brevity, further details on how current USG acquisition problems and shrinking budgets are not discussed in detail in this paper.

an essay entitled "Resilient, disaggregated, and mixed constellations" in *The Space Review* opined, "The problem with [the USG's] attempts at reducing cost was that they were really about trying to 'find efficiencies' in the status quo," spending large sums of dollars in "trying to make industrial practices more efficient". The problem, he states, is that the Government has, over the course of many years, virtually distilled almost all of the efficiencies out of the processes. He states poignantly:

> *"…there is just not much meat left on the bone to save after years and years of searching for efficiencies. Unfortunately, the assumption that our space industry could solve all its program problems with efficiency improvements was like throwing a thimble of water in the ocean. Perhaps a program can reap a few percentage points in savings with efficiency efforts, but more likely not in amounts that can move the needle on the problems and challenges we are facing.* ***All of these efforts have been hamstrung by the real problem, an acquisition construct that is unaffordable.***[5‡]*"*

General Shelton also firmly asserted to Congress that, "With the threats to our space systems increasing and defense budget uncertainty, ***the status quo is no longer a viable option***.[6§]" Mere rhetoric about the need to balance capability, resiliency, and affordability is grossly insufficient. ***The USG must decide and act upon reforming the acquisition of space capabilities to ensure that the precious dollars that are infused into the space program are effectively and efficiently utilized.*** Failure to address the problems in the fundamental practices and processes for acquiring space systems will inevitably result in the (potentially irrecoverable) loss of US space dominance. Even if the USG produces the most superior operational strategies in the world, and even if the Government conceives the most effective and reliable space architectures versus their adversaries, it would be largely meaningless if the USG is unable to affectively acquire the systems and enablers necessary to build and employ these strategies and architectures. This is especially true in light of the alarming rate of technological and operational advancement in space technologies and capabilities of the US' adversaries. Furthermore, as the US and international commercial space industries are increasing in capabilities and technological innovations, the USG must be able to quickly access and infuse these advancements into their systems and acquire the latest solutions faster than its rivals in order to remain relevant and effective in the space domain.

THE GAO REPORTED ON DISTRIBUTED ARCHITECTURES

Assessing Disaggregation: What the GAO Found

In October 2014, the Government Accountability Office (GAO) submitted a report to the SASC entitled "Additional Knowledge Would Better Support Decisions about Disaggregating Large Satellites" that evaluated the pros and cons of distributing critical military space systems[7]. Because the concept of distributing the architectures of the large programs of record has been identified by the US space industry as a strong viable means to making space systems more affordable and resilient, the SASC mandated that the GAO conduct an assessment of the "potential benefits and drawbacks of disaggregation and examine if it offers decreased costs and increased survivability for selected [Department of Defense (DOD)] satellite systems." Specifically, the SASC directed that the GAO evaluate disaggregation for the Advanced Extremely High Frequency (AEHF), Space Based Infrared System (SBIRS), and Weather System Follow-on (WSF) systems. The GAO reported back to Congress that they were unable to assess "whether or to what degree disaggregation can help the [DOD] reduce acquisition costs and increase the resilience of its satellite systems," because the DOD had just begun their evaluation of disaggregation concepts and a "variety of unknowns [that] remain." Instead, the GAO focused on outlining the pros and cons of distributing the

---

‡ Emphasis added by this author.
§ Emphasis also added by this author.

capabilities of these systems and provided an assessment on the DOD's ability to "make informed decisions regarding disaggregating AEHF, SBIRS, and WSF.[8]"

However, the GAO made several statements that cast serious doubt into the viability of disaggregation as a whole. They stated, "Benefits and limitations aside, there are longstanding barriers to implementation," citing the potential increased delay of ground stations and user equipment as an example of a potential effect. They also reported that "significant uncertainty- including how to quantify a broad range of potential effects- remains," raising concern that the current USG Analysis of Alternatives (AOAs) studies for SBIRS, AEHF and WSF are "not intended to comprehensively assess the effects of disaggregation." They recommended that the Government gather more knowledge on disaggregation, warning of the potential of the USG making "poorly informed decisions."

Casting a Shadow…

Although the GAO explicitly stated that they "believe [the USG] should demonstrate the operational feasibility of disaggregation," the report itself as a whole seemed to sound a negative undertone on the concept of disaggregation as a possible key contributor to the overall mission assurance of US space systems. Mike Gruss, in his *Space News* article "GAO: U.S. Air Force Needs More Info Before Committing to Disaggregation" that reported on the GAO study also seemed to highlight the report's negative backdrop, summarizing the report as stating that disaggregation "may solve some problems for the Defense Department but would also create new difficulties.[9]" He emphasized the reports criticisms of distributed architectures, highlighting that the GAO reported that "a disaggregated portfolio also could lead to a more complex and more expensive ground system, more frequent launches and therefore higher launch costs, and higher overall costs for nonrecurring engineering".

The GAO's call for the USG to further explore disaggregation as a means to increase resilience seems to be slightly obscured by the negative light cast on the use of distributed architectures as a whole. Based on the study, readers are left to wonder, "Is it still worth the USG to evaluate disaggregation as a possible means to increase mission assurance and affordability?" However, critical evaluation of the assumptions, premises, and the assertions of the report make a compelling case for the reason why the USG should remain optimistic about the role that disaggregation can play in rehabilitating the US space industry as a whole.

RESPONSE TO THE GAO STUDY ON DISAGGREGATION

Positive Aspects of the Report

Tempers Expectations on the Role of Disaggregation

It is plainly evident that parts of the USG are very optimistic about the role that disaggregation of the large programs of record (PORs) has in fostering rehabilitation of the faltering US space industry. And rightfully so. In their paper, "Disruptive Challenges, New Opportunities, and New Strategies," Lieutenant General Ellen Pawlikowski, Doug Loverro, and Colonel (ret.) Tom Cristler clearly detail the forces in the US space industry as a whole that create an accelerating destructive trend for the US[10]. They cite General Taverney's *Space Review* article to outline his "vicious circle of space acquisition" that mires down progress of the US space industry, as shown in Figure 3[11]. Based on their careful examination of the factors and problems associated with the current state of the US space industry at large was that "the best means available to affordably provide resilient space capabilities the war

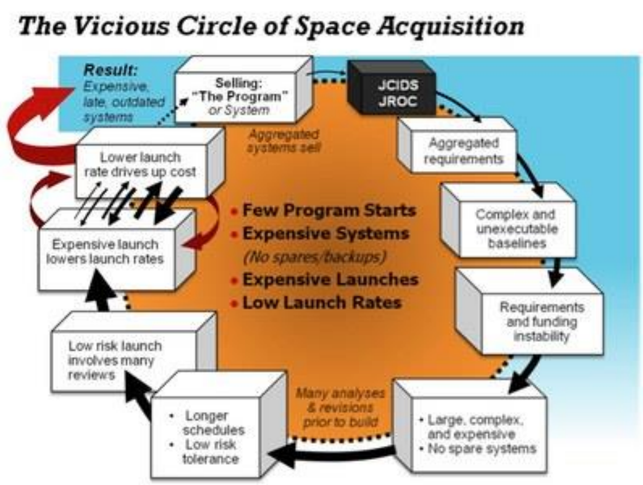

Figure 3. Taverney's Space Acquisition "Vicious Circle" from his *Space Review* article.

fighter can depend upon and adapt as mission needs evolve is to **use a distributed architecture strategy** coupled with a payload-focused acquisition strategy…[12**]" General Taverney also elevated the necessity of disaggregation's role in breaking the vicious circle, recommending that the USG "deploy disaggregated solutions with constellation mixes determined on mission-by-mission basis.[13]" Additionally, AFSPC published a white paper entitled "Resiliency and Disaggregated Space Architectures", in which the Air Force clearly asserts that "disaggregation improves mission survivability," and that it "is of value whether the threat is a hostile adversary, or an environmental threat…[14]" They state that the strategy of employing disaggregation provides "options within architecture to drive down cost, increase resiliency and distribute capability," as well as creates "less complex, easier to maintain" systems and "improve industrial base stability.[15]" This optimism in distributed space architectures has drawn much interest into the possibility of disaggregating the monolithic space programs into more manageable, lower cost, and less vulnerable constituent systems.

However, although AFSPC clearly states that "disaggregation is only part of the equation for space system resiliency," and even though Generals Taverney and Pawlikowski treat disaggregation as only one several components to bringing health back to the US space industry, the concept of distributed architectures has risen as one of the prevailing solutions to counteract the issues ailing US space programs. In Mike Gruss' *Space News* article "Pentagon's Top Space Contractor Recognizes Imperative to Change", he stated that Rick Ambrose, the executive vice president of Lockheed Martin Space Systems called disaggregation "in vogue," and implied that many were viewing distributed architectures as "a panacea" to the US space industry's problems[16]. ***Therefore, one of the positive effects of the GAO report is that it tempers expectations on the extent to which distributing the space system architectures can provide benefits to costs, resiliency, and the technical capabilities brought by adopting this approach.***

USG and commercial leadership must realize that disaggregation is just one strengthening contributor to the overall health of the US space industry, not the sole solution to the problems of affordability and vulnerability. In his testimony to the SASC in March 12, 2014, Mr. Doug Loverro, the Assistance Secretary of Defense for Space Policy emphasized that his main priority was in the assurance that end-users would be able to carry out their missions when they desired, and that resiliency was one of three main components that enable this mission assurance, in addition to "the ability to replenish lost or degraded capabilities, and defensive operations to provide warning of and interruption to an adversary's attack.[17]" This is represented in Figure 4. Mr. Loverro testified that "appropriate distribution" and "well-reasoned disaggregation" were among four other contributors to "strengthened or resilient space architectures." Understanding that disaggregation is just one of several means to the goal of resilience is imperative when formulating robust future architectures. The GAO report infused a more realistic expectation of disaggregation by delineating many potential benefits and limitations of disaggregation.

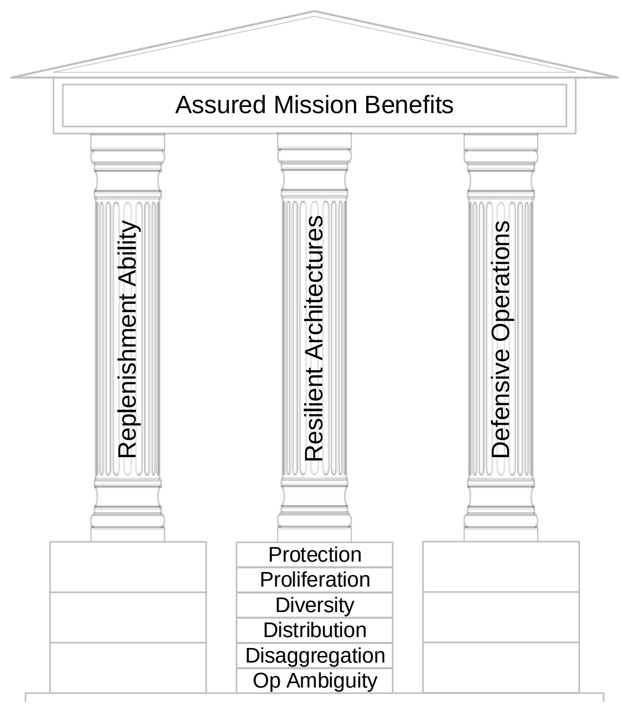

Figure 4. Author's representation of Mr. Loverro's statements on the role of disaggregation and resiliency based on his testimony to the SASC on 12 Mar 2014.

** Emphasis added by this author.

Starting Point for Disaggregation Evaluation Criteria for Architecture Studies

By systematically laying out the potential pros and cons of utilizing a distributed systems approach to future space architectures, the GAO brought to light the immense difficulty in planning, building, and fielding the next generation of systems, in general. The report, despite its apparent negative tone, rightly concludes that further investigation should be made to assess the total impact of disaggregating specific space program architectures. The GAO states that the AF has voiced the positive aspects of disaggregation, yet "less has been said about potential limitations, such as changes that would need to be made to interconnect the systems… and the investment those changes would require.[18]" In Gruss' article about the GAO report, he highlights the GAO's concern that the USG has focused "more on technical than operational feasibility" when evaluating distribution of space systems[19]. The report rightly concludes that "focusing more on operational feasibility would help to empirically quantify the effects of disaggregation and address implementation barriers.[20]" They are correct to voice the concern that lack of careful study on disaggregation's total effects may cause "poor decisions" by USG leaders.

It is to be noted that many of the vocal proponents of employing a disaggregation approach to future architectures have already been advocating for the careful study of the applicability of distributing the mission functions of the existing POR systems. General Taverney recommends, "***Where it makes sense***, architectures of mixed constellations of smaller disaggregated satellites and larger, flagship-class exquisite systems could be developed… ***Look at our architectures by mission area and select good candidates for disaggregation***.[21††]" Further, the AFPSC white paper clearly warns, "As a strategy, disaggregation requires careful analysis and mission-specific assessment," and states plainly that "there are specific challenges that need to be addressed.[22]" The paper cautions that disaggregation may possibly transfer complexity from the space segment onto other parts of the space architecture, to include impacting ground systems, frequency allocation, and satellite Telemetry, Tracking and Control (TT&C) assets. The fact that the paper clearly states that "innovative satellite operations concepts need to be examined along with disaggregation to avoid transferring the satellite savings to ground segment costs," demonstrates that the AF clearly understands the complexity associated with making any change in space architectures, to include disaggregation.

All in all, ***the GAO paper's list of benefits and limitations of the disaggregation approach serves as a strong starting point to develop a more systematic rubric of which POR systems and mission areas would be best suited and poor candidates for disaggregation. Further, the GAO report can be used to distill a more comprehensive list of the potentially impacted systems and segments***, such as ground entry points, end user equipment, and the launch enterprise, as well as ***helping to foresee potential second, third or fourth order effects of distributing functions and systems*** from the large existing POR assets and architectures. Table 1 below provides some examples based on the GAO report's findings. The purpose of Table 1 is not to go into all of the specific minutiae of the GAO report, but to provide an example of how the GAO findings could be used to synthesize a list of evaluation criteria for PORs, architectures and systems that would be strong candidates for adopting a disaggregation approach, as well as compiling a list of possible systems and segments affected by disaggregation. The table is not meant to be an exhaustive list, and it is based on a cursory evaluation of the GAO findings. However, as shown in the table, the GAO findings have much value in helping USG leadership to make better informed decisions during their future architecture trade studies and AOAs in defining the next generation of national space assets and operations.

[††] Emphasis added by this author.

Table 1. Examples of possible evaluation criteria for identifying systems for disaggregation and possible systems affected by disaggregation, based on the findings of the GAO report[23].

GAO Findings	Possible Evaluation Criteria for Strong Disaggregation Candidates	Possible Systems Affected
"Less complex satellites may reduce risk in technology research and development, integration, and launch, thereby reducing overall costs."	Systems with payloads that do not have a currently mature technology readiness level (TRL) at time of acquisition; systems that require more frequent technology refresh, such as advanced electro-optical payloads	Launch vehicles, spacecraft buses, ground entry points, user equipment
"If disaggregation involves splitting strategic and tactical capabilities onto separate payloads, the more demanding and costly requirements associated with strategic capabilities… may be isolated and allow DOD to leverage the commercial market for potentially less demanding and less costly tactical capabilities. As a result, overall costs may be reduced."	Systems that have mixed mission modes, such as strategic and tactical capabilities; systems that can be conceivably augmented or replaced by commercial systems	Tactical vs. strategic data communications links, ground systems, operational data exploitation concepts of operation
"Transitioning from existing satellite system designs to disaggregation may increase costs in the near-term to support interoperability between—and potentially duplicate ground systems to support—legacy and new systems simultaneously. In constrained budget environments, the costs of transition may be prohibitive."	Systems that have more flexible ground architectures; programs that have not definitized the future ground systems architectures	Legacy space and ground systems; ground entry points
"More satellites may require more or more complex ground systems—including user terminals—and more frequent updates to ground systems, adding to life cycle costs."	Systems that have more simple or flexible ground architectures; programs that have not definitized the future ground systems architectures	Ground entry points, ground systems, user equipment
"Increased numbers of satellites or payloads may require more launches and increase overall launch costs."	Not applicable	Launch vehicle systems; launch integration hardware (i.e., adapters, dispensers, etc.); access to space strategies (e.g., rideshare, hosted payloads, dual launch, commercial launch/rideshare, etc.)

Fundamental Criticisms of the Arguments

Despite the positive merits of the GAO report, several inaccuracies and inconsistencies in assumptions and assertions undermine the study, and instead of being influenced with an overall negative view on disaggregation, the USG and commercial space industries should continue to be excited about the merits of the disaggregation approach and invest time and effort to rightly applying disaggregation to appropriate systems and architectures. It is not the intention of this paper to go into detailed, point-by-point critique of the GAO report. This author intends to generate a subsequent paper that provides a more detailed critique of individual points presented in the report. Therefore, for the scope of this paper, only a high level critique of the overall premises and underlying assumptions will be presented.

Change is Going to Happen Anyways, and It's Gonna Hurt No Matter What

The GAO rightly asserts that "there are significant longstanding barriers to implementation" of disaggregation applied to the existing PORs[24]. However, in light of the current USG space acquisition paradigm, the same premise is true for any future acquisition for any type of space program, to include the untenable and self-destructive conclusion of just continuing forward with the current status quo. For instance, take some USG space programs as a prime example. In Kenneth Grosselin III's doctoral dissertation for the Pardee Rand Graduate School entitled "Actualizing Flexible National Security Space Systems," Grosselin presents data on the prolonged acquisition lifetime of the National Polar-orbiting Operational Environmental Satellite System (NPOESS), AEHF, Wideband Global Satellite Communication (WGS), and SBIRS programs, shown in Table 2[25].

Table 2. Statistics on select USG space program acquisitions from Grosselin's paper, demonstrating the long acquisition cycles of these systems and percentage cost growth.

	NPOESS	AEHF	WGS	SBIRS-High
Acquisition cycle time (Months)	200	134	94	TBD
Increase from initial cycle time	16%	20%	88%	TBD
Estimated unit cost (FY08)	$2677M	$2272M	$406M	$3490M
Increase from initial unit cost	153%	88%	8%	300%

Since the dissertation was delivered, recent data shows that it took SBIRS Geosynchronous Orbit (GEO)-1 fifteen years from contract award to the first launch in 2011. Combining this with Grosselin's data shows the long duration of the acquisitions of the large PORs. During the time of first start of acquisition and system design to the present, and even projecting to future launches of the same architecture, many of the sub-tier component suppliers are either out of business, or the technologies are so antiquated, the satellite builders are unable to find the same components to merely create copies of the same systems. This parts obsolescence increases costs due to the need to validate new components to legacy systems, increasing the cost of merely purchasing the same systems for the future.

Likewise, largely because the large number of requirements aggregated for these large PORs, ***future follow-on programs and systems, in general, require extensive changes to all parts of the satellite architecture***, to include ground systems designed with decades-old technologies, protocols, and concepts of operation (CONOPS), user equipment, and changes to frequency and bandwidth requirements brought by information-hungry end-users. For instance, for each new generation of Global Positioning System (GPS) satellites and type of SBIRS satellite, there has been a need for dramatic and costly upgrades and changes to the ground architectures. For instance, the GAO in 2013 estimated that the Next Generation GPS Operation Control System (OCX) ground system that is being developed to operate the next generation GPS III satellites will see a 43 percent (approximately equating to $1B) cost increase to a total of $3.7B, according to a *GPS World* article entitled "GPS OCX Ground Control in GAO Report.[26]" The article cites "stringent accuracy, anti-jam, and information assurance requirements," as well as the requirement to be backward compatible will all current GPS satellites has driven the costs up. Furthermore, the GAO report itself stated, "The program has experienced significant requirements instability and schedule delays while in technology development.[27]"

This is true as well for "mere upgrades" to the current space architecture capabilities. For instance, *Space News* stated that the AF published a report on the possibility of upgrading the SBIRS GEO-5 and 6 satellites with focal plane array technology based on a request from the SASC[28]. The article stated that the AF report, entitled "SBIRS 5/6 Focal Plane Technology Insertion," was written to respond to the Senate's concern that SBIRS GEO-5 and 6 would be launched with "30-year old technology," while modern digital focal plane with superior capabilities were available today. The AF, according to the article, reported that the costs for just this payload sub-component upgrade, ***not the entire satellite itself***, would exceed $800M and "cause delays leading to gaps in coverage," holding back spacecraft delivery at least by two years. This is in light of the expected cost of the two satellites ***combined*** of $1.9B.

What this all means is that ***the effort to modernize our aging space systems is going to be extremely difficult and very costly, regardless if the future architecture employs disaggregation or not***. Therefore, every instance in the GAO report on disaggregation that speaks of the high potential risks associated with the acquisition and fielding of disaggregated systems and architectures is equally valid for any future acquisition, to include maintaining the status quo. For the most part, the GAO infers that majority of these risks as specific only to the disaggregation approach.

For instance, the GAO states that disaggregation may "exacerbate" the problem of "aligning the delivery of satellites with associated user equipment and ground systems, which means that satellites may be in orbit for a long time with limited use.[29]" As a potential capability limitation, they report, "Adding more satellites and new technology may complicate efforts to synchronize satellite, terminal, and ground system schedules, limiting delivery of capabilities to end users[30]." The GAO report itself concludes that this phenomenon occurs because of unresolved "leadership, management, and oversight issues that have led to these delays.[31]" ***The acquisition process needs reformation, which is a fact regardless of whether the USG employs disaggregation or not.*** A prime example is in the other GAO report on OCX, where they reported "Aligning the schedules of GPS OCX and the GPS III satellite is a considerable risk for the program[32]." The GAO stated that the Air Force estimated the first GPS III satellite launch to be in mid-2015, but the OCX ground system to become operational in late 2017. To merely state that disaggregation may complicate the issue of synchronizing space and ground segments is unsubstantiated and highly dependent on the underlying assumptions associated with the claim. It seems to imply that an increased number of satellites will increase complexity in space to ground system synchronization, which may be true if the argument was based on the assumption that both the space and the ground segments are as complex, or near the complexity of the current systems in today's paradigm. More will be discussed on this in the subsequent sections. But the numerous "may" statements also has an associated "may not" possibility associated with it.

Regardless of the method to bring more capable, resilient and affordable systems on orbit, the current acquisition paradigm must change. And it's going to be painful. But that does not preclude the necessity to transform and adapt so that the US space industry not only survives, but continues to lead in the future. General Taverney put it very poignantly and succinctly:

> *"**We need to change the assumptions** for our space enterprise and forge different business models with different logic and inherent costs and resulting in different mission architectures. This change will bring different risks. …**Our understanding of what constitutes unacceptable risk must evolve**, and be balanced with cost, adaptability, technology insertion, and resilience. Indeed, such risk is clearly in the "eye of the beholder". Given the financial challenges our country is facing, **the level of what can be considered acceptable risk must change**. Accordingly, **the risk presented by disaggregated/mixed constellation acquisition models is acceptable, and should be wholly considered**[33‡‡]."*

The US space leadership must boldly face the challenges brought about both the external and internal threats to ensure the viability of the US space industry as a whole, both the USG and its commercial conjugate. ***Merely stating that change is going to be difficult is essentially of no value***, and one of the primary bottlenecks to overcome is current set of acquisition practices and methods that hinder progress towards a healthier space industry. For example, when the GAO makes statements such as, "Disaggregation could require DOD to make significant cultural

‡‡ Emphasis added by this author.

and process changes in how it acquires space systems," they, in essence, seem to imply that the DOD doesn't need to or is entirely unable to "make significant cultural" changes, as if the status quo is somehow acceptable[34]. The statement also seems to imply that disaggregation may somehow serve as the proverbial straw that breaks the camel's back. As evidenced above, ***change is going to be hard no matter which architectural changes the USG chooses; through strong leadership, the USG can deliberately and wisely craft future space architectures that blends in the right mix of resiliency enablers*** depicted in Figure 4, ***to include disaggregation***. If a certain space system can effectively plan for and utilize disaggregation among other means to achieve a robust and affordable future architecture, the majority of the risks identified in the GAO report can be assuaged.

Over-Projecting the Current Paradigm onto the Next

As stated earlier, many of the premises in the report were based on projecting the current practices, systems, and the resultant effects of those practices onto the possible future architectures that may be comprised of more numerous and diverse mix of satellites. And this is perfectly understandable because past experiences are key to informing the future. However, careful examination must be made in applying the underlying assumption that "things are going to be the way they already have been" to the analysis of future architectures. Certain assumptions of the current paradigm should be projected forward, such as the fact that "the launch equation is the launch equation," that is, based on current access to space technologies, it is, and will remain to be extremely difficult to launch satellites into orbit because of the immense delta velocity required to loft objects to their desired orbital locations. Therefore, some projection of current paradigms are most likely valid in discussing the probable future.

However, wise thought must be applied to make sure that the appropriate measure of projection be applied to the fundamental assumptions of the evaluation of these future architectures. As an example, take the previously mentioned conclusion about ground systems: "Adding more satellites and new technology may complicate efforts to synchronize satellite, terminal, and ground system schedules, limiting delivery of capabilities to end users." The likelihood of this increased complication is high if the assumption is to extend the current paradigm of ground system architectures and acquisition forward. But the probability of disaggregation exacerbating the complexity of ground system development and synchronizing space and ground development schedules goes down if the assumption is that it doesn't have to be the way is has been. That is, the current state of ground system development is very slow, complex, and expensive. Therefore, it is natural to assume that increasing the number of satellites after disaggregating larger single systems may oversaturate and further destabilize ground system development and synchronization efforts.

But the validity of this assumption must be ascertained, especially in light of technological and system advancements and innovations, as exemplified in the commercial space industry. In an interview with Thomas Rivers, Vice President, National Programs in the Federal Solutions Group of Kratos Technology and Training Solutions, who is an expert in both USG and commercial ground systems, he agreed that the current way of building and buying satellites doesn't have to be extrapolated forward based on advancements in ground system technologies and practices[35]. He contended that the majority of the benefits (and limitations) that the GAO listed in their report are valid for the disaggregation of ground systems from highly expensive and complex ground architectures that are bogged down by a vast number of requirements and interfaces. Furthermore, he stated that disaggregating requirements and functions from space segment systems into simpler smaller solutions would actually serve to greatly simplify the requirements for ground systems to operate and communicate with the disaggregated systems. "Simpler space platforms equate to simpler ground systems," he stated. Breaking up the space architectures would allow a conjugate disaggregation for ground systems with simpler requirements baselines. "For instance," he stated, "narrowing down to one or two [ground segment] interfaces makes cybersecurity much simpler."

The previously mentioned GAO report on OCX corroborates the premise that simpler cybersecurity/information assurance requirements equates to easier acquisitions and architectures when they reported that "the [OCX] contractor initially underestimated the scope and complexity of the necessary information assurance requirements which required additional personnel with the necessary expertise and increased government management," which contributed to the increased costs and delays of that ground system[36]. When asked about the potential cost savings in utilizing smaller distributed ground systems versus the existing ground architectures, Rivers stated that the current ground systems, such as GPS's current Architecture Evolution Plan (AEP), had development costs in the "billion dollar range," whereas, each ground station for smaller systems are in the "millions to tens of millions of dollar" price range. He stated that acquisition of these distributed ground systems could bring up to two orders of magnitude cost savings versus the current ground architectures. And although a larger number of smaller ground systems would be required to operate and control these simpler small satellite constellations, Rivers pointed out that "it would be a matter of addition of costs, not multiplication," inferring that ***the aggregate cost of distributed ground stations necessary to support a disaggregated space segment would still be substantially lower than the current ground system architectures.***

Furthermore, Rivers outlined how ***innovations in the small satellite arena are bringing greater simplicity, cost savings, and rapid development and deployment benefits***. He explained how the commercial small satellite (smallsat) industry is taking advantage of state of the art innovations such as cloud networking, emerging standardized ground interfaces, and automation, which reduces operations and maintenance (O&M) costs by requiring less personnel to operate many of the ground stations and functions and enables smallsat operators to create "lights out" centers with very small personnel and resource burdens. And since they are all smaller, simpler, and lower cost, Rivers pointed out, they are simpler to reconstitute in case of failure and upgrade with the latest technologies. Rivers argued that this allows the users to then focus more on the re-aggregation and synthesis of the data coming in from distributed space sensors versus being bogged down in the development and management of monolithic, slow to develop/deploy and costly existing ground stations.

Therefore, the way that the GAO treats the ground segment is one prime example of how the report improperly projects the current paradigm instead of recognizing the current technological and operational advancements that are superseding the past way of building ground systems to operate space segments. Other examples of how the GAO unfittingly projects the current paradigm is in their discussion on access to space, which will be discussed later in this paper, as well as radiofrequency allocation and interference and orbital congestion. ***Again, USG leadership should be mindful of the applicability of the projected assumptions from the current state of systems, operational concepts, and methodologies.***

Overuse of the Hypothetical

When discussing the potential benefits and limitations of disaggregation, the report provides a comprehensive list of hypothetical outcomes, both good and bad. However, the validity or probability of realizing the potential effects are never qualified or quantified; it is merely a list of all of the possible outcomes associated with disaggregation. ***The problem with this is that some of these statements are more hypothetical than others in terms of probability of occurrence, therefore it is difficult to ascertain which of these points are valid or not.*** Table 3 provides an example of how this can skew and cloud the decision making process. In this illustrative imaginary scenario, one is evaluating the benefits and limitations of choosing to walk to work versus driving. Obviously, some of the potential benefits and limitations are more probable than others, such as the benefit of increasing general health or the limitation of taking time away from family or friends because of the increased commute time to work. But even these potential pros and cons are based on a certain set of assumptions, such as the relative distance to the workplace, the regular work hours, or the general climate the person resides in. And each of these assumptions factors into the relative probability of experiencing the potential benefit or limitation. Furthermore, although each of the listed outcomes is a valid possibility for the pedestrian, some are much more hypothetical than others. For instance, the premise "Longer travel time may result in missed meetings and decreased productivity" is a valid possible outcome, it is a weaker argument because the person may have the ability to effect the outcome, i.e., control his/her work schedule, and may have the ability to avoid this limitation, e.g., start his/her commute earlier.

Additionally, some of the outcomes, even though they are logical and valid potential results, may be highly improbable or very difficult to measure the likelihood of occurrence, such as the risk of a lightning strike or being struck by an automobile while walking, or even the potential benefit of cheering a person up by walking.

Table 3. Simple example scenario that hyperbolically demonstrates how unsubstantiated hypothetical outcomes may skew decisions.

Example Scenario: Evaluating the pros and cons of deciding to walk to work versus driving	
Potential Benefits	**Potential Limitations**
• Will burn more calories, which will most likely increase general health • May increase sun exposure, increasing Vitamin D production, which may promote health • May provide mental diversion, which may relieve stress and promote happiness • May decrease the probability of getting into a fatal automobile accident	• Will most likely increase the time to arrive at work, which may decrease available time spent with family and friends • Longer travel time may result in missed meetings and decreased productivity • May increase exposure to the sun, which may result in contracting skin cancer • Prolonged travel time may necessitate having to work until sun down, which may require traveling at night time, which may result in increased probability of being struck by an automobile on the commute • May increase the probability of being struck by lightning

Although the illustration is somewhat hyperbolic to emphasize the point, it is clear that the manner in which hypothetical outcomes are presented can alter the perspective of the potential decision maker. Let's face it; who wants to get struck by lightning or by a car, right?

Unfortunately, in the difficult task given to the GAO to report the potential benefits and limitations of disaggregation, the report is filled with many listed pros and cons that are difficult to substantiate, are over-biased by the current paradigm, or may be able to be affected in a manner that easily assuages the concerns. Table 4 on the following page provides some examples of specific instances of these statements. ***Although the effort to be thorough in listing the possible benefits and limitations of disaggregation was a noble aim, more careful consideration of the arguments would have better served the report by providing a more realistic list of probable pros and cons of employing disaggregation to space systems.***

Additional Extraneous Premises

In addition to the three aforementioned points about the general premises of the GAO report, a couple of other points should be made concerning the document's assertions. First of all, of no fault of the GAO, ***they were tasked by the SASC to evaluate two of the most difficult programs with respect to disaggregation: SBIRS and AEHF.*** It is understandable why the SASC chose these two programs: (1) they are some of the highest dollar space programs in the DOD budget to date, as shown in Table 2 earlier. Therefore, if disaggregating the systems will save the Government money, these would be the programs that would be of most interest in saving costs; and (2) these two programs have highly aggregated requirements that would seem as ideal candidates for disaggregation. For instance, AEHF has both strategic and tactical protected communications missions, and SBIRS has five mission areas associated with their architecture[37].

However, they are programs with some of the highest institutional inertia such that changes to these architectures are most likely to increase costs, impact critical functions, and create significant delays in operational fielding, since both of these programs are highly aggregated and high dollar, as exemplified earlier in the AF study on the potential focal plane array upgrade for SBIRS GEO-5 and 6. Furthermore, these two systems require larger satellite systems to accomplish their missions, such as aperture size, cryogenic coolers, and power requirements to transmit and receive communications data, based on the currently available technologies. Therefore, it should come as no surprise that the Air Force Science Advisory Board (SAB) recommended that these two programs were not viable candidates for disaggregation into small systems in their study entitled "Report on Microsatellite Mission Applications (MMA)"[38]. Although it is not impossible to disaggregate the mission areas for these two programs, they are perhaps the most difficult programs to distribute across several smaller space systems. Therefore, the SASC would likely have more favorable recommendations on disaggregating other mission areas, such as satellite imagery, precision navigation and timing (PNT), and unprotected military satellite communications, in addition on the defense weather capability.

Table 4. Several samples of GAO statements of limitations with uncertain or low probabilities of realization or inconsistencies in basic assumptions[39].

GAO Statement	Concerns with the Statement
"Transitioning from existing satellite system designs to disaggregation may increase costs in the near-term to support interoperability between—and potentially duplicate ground systems to support—legacy and new systems simultaneously. In constrained budget environments, the costs of transition may be prohibitive."	It is difficult to quantify the amount of near term cost increase without knowing the specific systems; conceivably, smaller, simpler ground systems would provide a low enough price point to attract procurement of the system
"More satellites may require more or more complex ground systems—including user terminals—and more frequent updates to ground systems, adding to life cycle costs."	Disaggregated space segment systems will most likely simplify each corresponding ground system if the operator chooses to procure a ground asset commensurate in simplicity as the space component; disaggregated space assets may result in simplified and lower cost user equipment, possibly even commercial off the shelf
"Increased numbers of satellites or payloads may require more launches and increase overall launch costs."	This assumes that the algorithm for calculating launch costs for smaller satellites is a matter of multiplying costs associated with existing large spacecraft missions; launch costs may not increase substantially increase, and may even decrease overall, depending on the ability for the customer to launch a larger number of smaller satellites on the same launch vehicle
"Adversaries may be more likely to attack small tactical satellites because they may be viewed as lower risk with regard to escalating hostilities."	Pure conjecture on the likelihood that an aggressor will or will not attack a tactical satellite; it is unknown the cost benefit for the aggressor and/or the defender, e.g., if the small tactical satellite is low cost, then (a) is it worth the monetary and diplomatic expense to attack the satellite, and (b), if it is a low cost satellite and the target nation is able to rapidly reconstitute or continue operations through other workarounds, does the target nation even care as much?
"Some systems may not be simplified to fit on smaller satellites without losing capabilities. For example, some capabilities require higher power and inherently complex components… that smaller satellites would not be able to accommodate."	(1) This statement assumes that disaggregation equals small satellites. It is possible to disaggregate some of the mission areas from complex PORs and yet, still result in some larger satellite systems. For instance, breaking off some of SBIRS's mission areas to other systems may result in smaller systems compared to the current large system, but not necessarily small satellite systems. The result of disaggregation may likely still require a larger system for SBIRS's main mission area because it's an infrared payload; (2) This limitation also assumes that the system architect would somehow choose to shrink the size of the spacecraft to the detriment of the mission capability for the sake of disaggregation. A system that cannot be broken into smaller constituent parts is a poor candidate for disaggregation, and the architect would merely have to choose not to disaggregate this system to avoid this "limitation" altogether

Another point should be made concerning a possible bias that may have been introduced into the source material for the GAO study, again, not by the implicit fault of the GAO. The report states that their source material included documents and interviews with officials from USG agencies, "contractors, and third parties" to aggregate their list of pros and cons of disaggregation. However, it is unclear which contractors were consulted during their study on disaggregation, but the ***concern lies in the potential conflict of motives of some of the major commercial stakeholders that build and operate the USG's high dollar space and ground segments for the current PORs***. For instance, in the *Space News* article on Lockheed Martin's recognition of the need for change in space architectures, Gruss reported that Lockheed had conducted a study on resiliency, drawing the conclusion that "it takes larger numbers of satellites than commonly assumed to truly reduce constellation vulnerability to likely threats. The upshot: Disaggregation will not necessarily save money.[40]" Yet Gruss astutely recognizes the possible impaired objectivity of the Lockheed study since they "must walk a fine line between protecting its franchise while seeking to demonstrate that it can adapt to a future architecture where key capabilities are dispersed on smaller satellites…" It is not clear to what extent a potential bias may or may not have been inadvertently infused into the GAO study; however it is a possible factor that should be noted when internally processing the whole of the GAO report.

MOVING FORWARD: HOW TO HARNESS THE POWER DISTRIBUTED ARCHITECTURES

All in all, the merits of the approach of evaluating the right systems to disaggregate mission areas and functions of proper candidate programs stand and should, by no means, should be discouraged by the GAO report. The USG would benefit in embracing the report's overall recommendations to "Comprehensively examine—either through the AOA studies or through other assessments—the full range of disaggregation issues, including those that go beyond the satellite systems themselves" and to "expand demonstration efforts to examine the operational feasibility of disaggregation by empirically quantifying its benefits and limitations as well as addressing longstanding barriers that could hinder its implementation.[41]" Further, they should be encouraged by the concluding statement that "Disaggregation of satellites may offer a viable option for addressing affordability and resilience challenges that DOD is facing." ***Despite all of the potential challenges associated with infusing smaller satellite and ground segment technologies into future architectures, USG leadership should recognize that these simpler, lower cost systems are a vital component to the overall health of the US space industry as a whole.***

The Crucial Role of Smallsats in Rehabilitating the Space Industry

In order to better understand the integral role that smallsats must play in bringing the US space industry back to a vector that better ensures its ability to maintain its space dominance and effectively promotes the well-being and security of the US and international community as a whole, it is imperative to better clarify the correlation between smallsats and disaggregation. In the same way that Mr. Loverro clearly emphasized in his testimony to the SASC that disaggregation is only one of several contributors to resilient space systems, it must be made plain that disaggregation is just one way that smallsats can contribute to the overall health and stability of the US space industry. Figure 5 illustrates the vital role of smallsats to space system mission assurance, increased affordability of space programs, and the assurance that the fielded space systems will be up to date with the latest technological advances. This figure synthesizes the "primary considerations" of capability, affordability, and resilience for space architectures mentioned in the GAO report with Mr. Loverro's testimony to the SASC and other considerations[42]. Furthermore, the figure identifies the areas in which small satellites can provide positive contribution towards each means to the ideal state of space architectures. As shown in the illustration, ***smallsat technologies not only enable disaggregation as a means of resilience and mission assurance, but the utility of these smaller systems extends across many other means towards strong space architectures and the ideal state of the US space industry as a whole***.

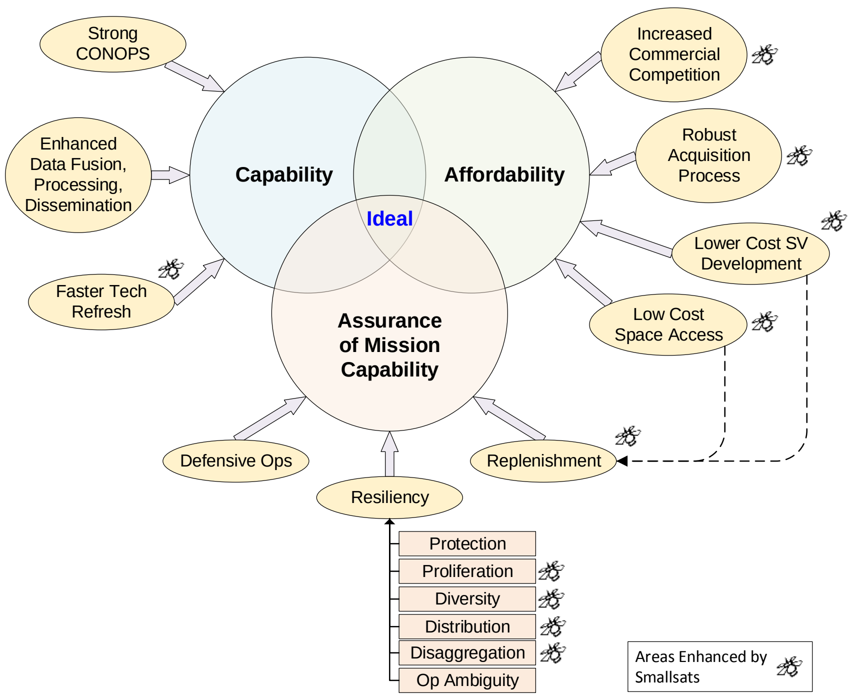

Figure 5. Depiction of the composition of factors that create the ideal state of space systems, as well as identified areas where smallsats can positively contribute.

For instance, to enable the means of resiliency of space systems, smallsats can play an integral role not only in disaggregation, but also in the distribution of capabilities and functions, diversity of services, and proliferation of lower cost elements and functions. Also, since smallsat systems are significantly lower cost than the current large PORs, they are a strong enabler for the ability to replenish and reconstitute on-orbit assets and capabilities much more than larger, more expensive systems. In terms of enabling more affordability, the shorter development timelines for most smallsat systems enable demonstrations that will be able to prove out more flexible and responsive acquisition practices, such as simpler requirements baselines and quicker contracting actions. Furthermore, the affordability of smallsat systems enable more industry standards and assembly-line approaches to spacecraft development, lowering costs of satellite development, and subsequently, lowering the cost of launch due to more increased launch demands and decreasing requirements for mission assurance of each individual component. This aligns with the conclusions drawn in the author's previous paper for the 30th Space Symposium Technical Track mentioned earlier, which described in more detail the role of smallsats in the recovery of

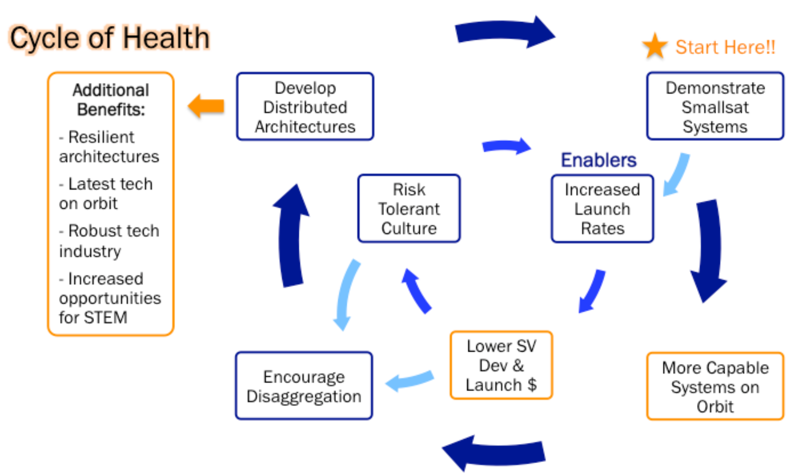

Figure 6. The "Cycle of Health" that depicts how smallsat systems can help catalyze the US space industry towards breaking the "Space Acquisition Vicious Circle."

the US space industry. Figure 6 depicts the "Cycle of Health" proposed in that paper, showing the important part that smallsats play in restoring the industry as a whole and counteracting the "Space Acquisition Vicious Circle" that General Taverney described. To enhance the author's previous arguments for the importance of investment and embrace of smallsat technologies, Figure 7 depicts in more detail how smallsats can feed into the overall ecosystem of a healthy space architecture.

As shown in the figure, technology demonstration smallsats contribute to capable, affordable and robust future architectures in five ways:

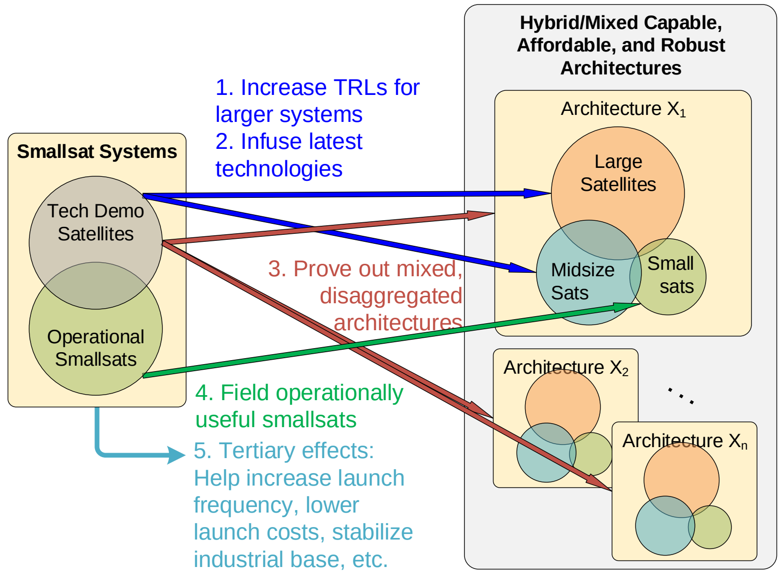

Figure 7. Depiction of five ways smallsats feed into future mixed/hybrid architectures.

1. They enable the increase of the technology readiness levels (TRLs) for emerging technologies that will feed into larger systems. This is key to reducing technical, schedule and cost risks to upgrades of current large satellite systems and the development of future larger-class space vehicles. Lt Col Robert Atkins, in his Master's thesis for at the Naval Postgraduate School pointed out that one of the prevailing contributors that drives "program failure or extreme overruns" that have plagued many highly complex space system development efforts is rooted in the attempt to incorporate new technologies with low TRLs, which translates to a program that is "frequently delayed and [that] will experience cost overruns.[43]" Utilizing smallsat platforms to increase the TRL of these fledgling technologies will help shake out the challenges in development and integration of these technologies into the more expensive larger systems, driving down risk in cost, schedule, and technical performance.

2. By testing and proving out technologies and operations and tactics on orbit, tech demo satellites can further enable the infusion of more up to date technological innovations into larger-class spacecraft. This would assist in precluding situations such as the aforementioned description of the SASC's concern about fielding 30 year old technologies in the future build and deployment of the SBIRS GEO-5 and 6 spacecraft. Not only will it drive down the technical and programmatic risks during the spacecraft development, but proving technologies in smallsat tech demos will increase the technology refresh rates of the larger satellites significantly more than the current system architectures.

3. Aligning with the GAO report's call for further demonstrations of the operational feasibility of disaggregated architectures, smallsat tech demo missions will allow for USG program architects to better assess the true benefits, limitations, and proper bounds for employing disaggregation as a means towards resiliency. More than that, small sat tech demo missions will effectively prove out the other means towards resiliency, such as technologies, tactics, and operational strategies for proliferation or distribution. These missions can also test innovative acquisition and contracting approaches to greater utilize innovative commercial systems, enablers, and services.

4. Furthermore, as Moore's Law and technological innovation enables more operationally useful smallsats, these systems will be infused into future architectures comprised of a mixture of multiple sizes and functions of spacecraft. Smallsats are not to be considered to be a one-to-one replacement of current POR systems; however, they will become integral components to these highly capable, affordable, and resilient hybrid space architectures. As an aside, the term operational does not only have to connote a defense application, but can also describe a useful Civil or scientific function.

5. Additionally, an increased number of both tech demo and operational satellites translates to an increase frequency of launches to keep up with the demand for access to space, which then in turn, should lower launch costs because of the increased number of launches themselves, a stabilizing flow of launch vehicle production, as well as decreasing mission assurance burdens on the booster because the architectures are lower cost and each component is less sensitive to failure. Finally, all of this in aggregate should help stabilize the US space industry as a whole, both USG and commercial, by increasing space capabilities and decreasing the barriers to entry into the space market.

All in all, another simpler way to illustrate the relationship between smallsats and larger class spacecraft is to borrow an analogy from biological ecosystems, as depicted in Figure 8.

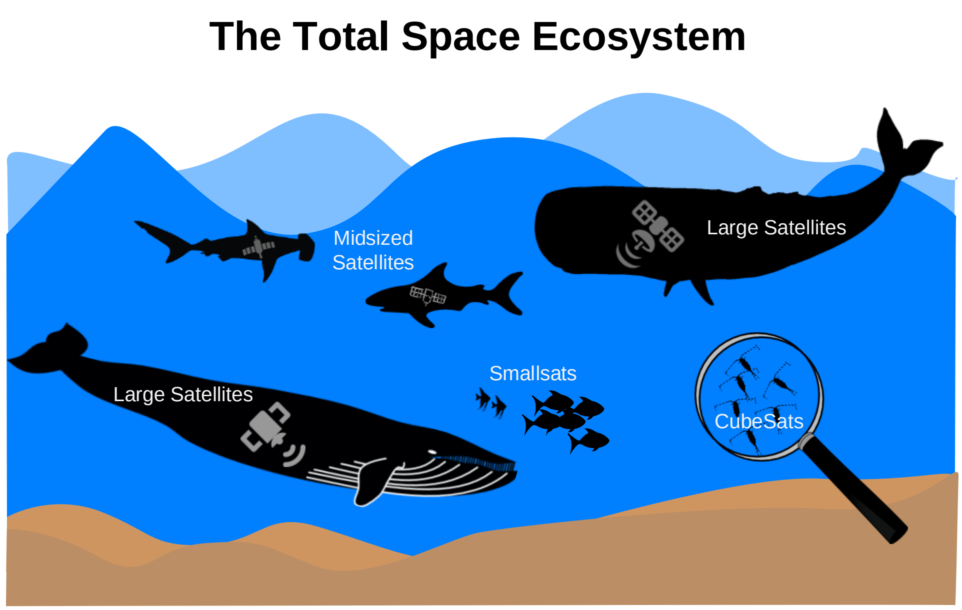

Figure 8. Analogy of ocean ecosystem to demonstrate the relationship between all classes of satellite to the overall health of the space industry.

Just as in the ecosystem of Earth's oceans, each organism in the biosphere is crucial to the overall health of the total ecosystem. Larger fish and animals consume smaller ones, even down to the microscopic level, like the plankton depicted in the figure. The reduction or loss of one set or class of organisms, whether large or microscopic can have a substantial impact on the ecosystem as a whole. In the same manner, the US space industry has experienced the effects of this phenomenon. Take, for instance, the general observation of the low numbers of Evolved Expendable Launch Vehicle (EELV) Standard Payload Adapter (ESPA) - class satellites, weighing around 180 kg. Based on the author's experience in seeking launch opportunities for smallsats, there are far fewer ESPA-class spacecraft being developed versus small sized smallsats.

This phenomenon is largely the result of a stunting of the growth over the decades of sub-ESPA class spacecraft, retarding the development of ESPA class spacecraft and larger microsatellite class smallsats. As explained in this author's Space Symposium paper from last year, for commercial investors and USG programs, there is a progression of technology development that has evolved where satellite program leadership is reluctant to invest tens of millions of dollars on ESPA and microsatellite-class spacecraft until the technology, capabilities and operations has been proven by smaller-class spacecraft, such as smallsats in the 50 to 100 kg range and below[44]. The paper explained how the increased CubeSat satellite market has begun to evolve to increase interest in the 50 to 100 kg-class of spacecraft, which will eventually result in an increased number of ESPA and larger-class smallsats into the US commercial and government markets. These more capable ESPA and larger-class satellites will then feed into the process described in Figure 7, serving as both tech demos and operational systems themselves for future hybrid mixed constellation architectures. ***Neglect of the smallsat industry may very well result in the eventual extinction of all larger class satellites, especially in light of the internal threats described previously***, just as the impact that the loss of plankton would devastate the oceanic biosphere.

Dedicated Rideshare as an Enabler for a Healthier Space Industry

Thus, if smallsat systems and technologies are integral contributors to helping to break the "vicious circle" of the current space acquisition paradigm, ***emphasis should be made by decision makers to seek ways to further exploit smaller system technology demonstrations and operational smallsats***. As part of the process, leadership should be made aware of the factors that bog down both smallsat tech demos and operational systems. Figure 9 illustrates three of the major impediments to increased frequency of smallsat missions. First of all, ***reticence of the leadership for USG and some commercial organizations towards shifts in programs creates an immense "institutional inertia" that bogs down any potential change in practices and methods***[§§]. Oftentimes, this tendency to maintain the status quo (i.e., objects at rest tend to stay at rest) or continue down the course of the "vicious circle" of the current paradigm (i.e., objects in motion tend to stay in motion) serve as a bottleneck to explore incorporating smallsats into future concepts and dissuade investment into tech demos or operational demonstrators.

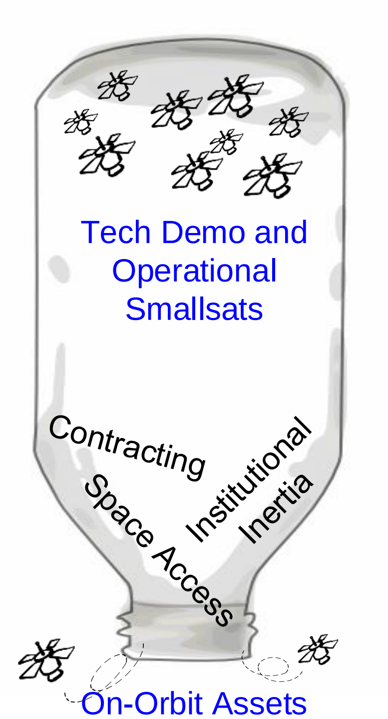

Figure 9. Illustration on impediments to increased smallsat missions.

A second factor that holds back the ability to provide smallsat solutions to end-users thirsty for the potential capabilities that these systems can provide is a lack of straightforward and readily accessible means of contracting to purchase the systems and key associated components, like ground systems and launch opportunities. This is especially true of the difficulty the USG has in procuring commercially available smallsat systems, ground assets, and launch opportunities. Lack of straightforward contracting mechanisms will most likely result in the USG losing opportunities to exploit commercial launch opportunities for their smallsats that cost a fraction of the amount they would pay for a similar USG launch. It would strong behoove the USG to create a construct similar to the indefinite duration, indefinite quantity (IDIQ) contract that the AF has created for commercially hosted payloads or to exploit a mechanism that allows the USG to purchase launch services in a similar fashion as they procure commercial off the shelf (COTS) products and services. This is a topic that deserves its own careful examination, and this author intends to compose a subsequent paper on this topic in the future. But it is clear that difficulties in accessing capabilities through contracts hinders escape from the proverbial bottle.

Finally, ***high launch costs and infrequent launch opportunities greatly impede the ability to demonstrate the operational capabilities and prove out emerging smallsat technologies, concepts of operation, and processes***. As evidenced in the 2014 National Defense Authorization Act (NDAA), US leadership views access to space as a priority for USG space programs, so important that they mandated that the Executive Agent for Space conduct a study and report on "responsive, low-cost launch efforts," to include "greater exploitation of innovative methods.[45]" The current space access construct is prohibitive for both USG and commercial satellite launches that places far fewer smallsats on orbit than the possible opportunities that could be exploited by ridesharing spacecraft on existing missions.

§§ A more detailed description of the concept of institutional inertia is contained in this author's previous Space Symposium paper, cited in the references at the end of this document.

To break through the barriers to frequent, low-cost launch for all sizes of satellites, this author presented six possible enablers that contribute to the overall solution, as shown in Figure 10.

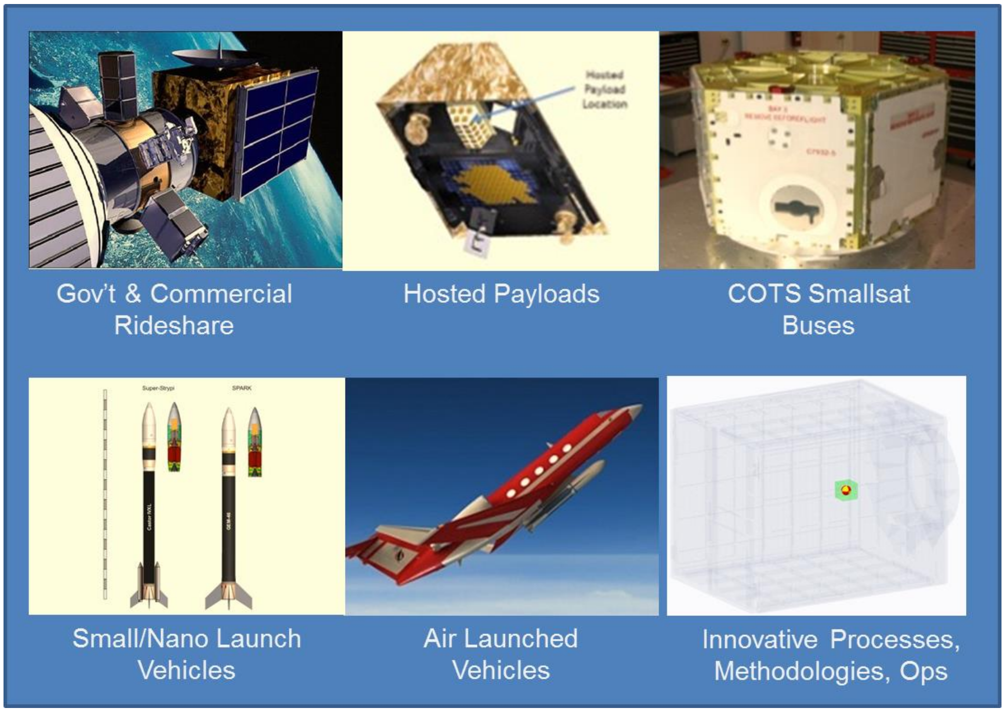

Figure 10. Smallsat access to space enablers, as presented in this author's previous Space Symposium paper (Photo citations from top right to left and bottom right to left: [46, 47, 48, 49, 50, 51])

Although much discussion can be made about the pros and cons for each enabler, the remainder of this paper will focus on commercial dedicated rideshare as one strong enabler to help break the bottleneck of high cost, infrequent launch opportunities[***].

What is Commercial Dedicated Rideshare?

The concept of ridesharing spacecraft has been promulgated extensively in the US space industry for close to a decade. Traditional (or standard) rideshare launch opportunities consist of a primary spacecraft launch mission that has excess payload fairing (PLF) volume and available mass margin to allow additional spacecraft to, in essence, "hitch a ride" to orbit, much like the automobile commuting construct from which rideshare derived its name. These ridesharing spacecraft are commonly referred to interchangeably as secondary payloads, auxiliary payloads, rideshare spacecraft, secondary spacecraft, and in Europe, "piggy-back" spacecraft.

In traditional rideshare missions, the secondary spacecraft do not have any control over the mission requirements for the launch, such as launch date, integration timeline, final orbit, etc. In essence, they are only along for the ride, and they are typically required to remain powered off during launch and ascent until the primary spacecraft has separated from the launch vehicle (LV) interface. Usually, rideshare spacecraft are given the authority to deploy on orbit after the LV completes the primary mission of delivering the primary spacecraft to its intended orbit.

There are many ways that standard rideshare missions could be built. They can be created either prior to or after the primary spacecraft has contracted with the LV provider. Also, rideshare spacecraft could either contract

[***] Further details on each enablers can be found in this author's previous Space Symposium Technical Track paper.

directly with the LV provider or the primary spacecraft provider, depending on the launch opportunity and the terms of the launch services agreement (LSA) between the primary spacecraft and the LV provider. Historically, there have been both USG and purely commercial rideshare missions.

The overall advantages of standard rideshare missions are two-fold, as shown in Table 5. They are the potential increased cost savings for all parties, as well as increased number of possible launch opportunities for smallsat providers. However, standard rideshare has two main associated disadvantages, the first being possible increased risk and mission complexity for the primary mission, which serves to discourage many LV and primary spacecraft providers from desiring rideshares on their missions. Furthermore, traditional rideshare is burdensome for the rideshare spacecraft because of its inherent loss of operational and mission requirements control. Although there may be more pros and cons to this approach, these are the prevalent factors that either encourage or discourage users of the standard rideshare approach.

Table 5. Concise list of the general advantages and disadvantages of traditional rideshare missions.

Traditional Rideshare	
Advantages	**Disadvantages**
Cost savings: - For the primary spacecraft provider: Overall reduction in launch cost for the primary mission, bringing savings prior to launch and on-orbit checkout, if contracted directly with rideshares - For the LV provider: Maximizes the potential revenue generated from unused mass, PLF margin, if contracted directly with rideshares - For the rideshares: Significant price reduction than purchasing an entire booster by themselves; with more rideshares on the manifest, allows for greater division of launch costs across all rideshares	For primary spacecraft and LV providers: Possible increased risks and mission complexity - Mission integration timeline for primary spacecraft is 24 months or more - Timeline for smallsat development/integration is typically 12-18 months or shorter - Rideshare spacecraft entering or leaving the manifest late in the mission flow may invalidate previous analyses (e.g., coupled loads, separation, etc.), possibly impacting schedule and risk
Increased launch opportunities for smallsat providers, since launch manifest for larger class spacecraft are more numerous than for smaller spacecraft missions	For rideshare spacecraft: No mission requirements or operational control over the mission - Launch schedule at whim of primary spacecraft and LV providers - May result in sub-optimal orbits for smallsat mission - Additional requirements burdens added by primary spacecraft and/or LV providers

Commercial dedicated rideshare (DRS), however, is an altogether different approach to ridesharing. A commercial DRS mission consists of a third party integrator (3PI) that purchases the launch services of an entire rocket directly from the LV provider, then divides up the launch among a group of ridesharing spacecraft. ***Because this type of mission removes the single primary spacecraft from the equation, the DRS approach affords specific benefits associated with this particular means to space access that address many of the challenges associated with traditional rideshare missions.*** For clarification sake, this paper addresses this approach with respect to a commercial 3PI purchasing a DRS mission as a completely commercial endeavor, outside of specific USG acquisition process. Commercial DRS missions may still have USG payloads flying on them; however, those USG customers would sign a commercial LSA with the 3PI to exploit this type of mission opportunity.

In order to make the DRS approach more effective, TriSept Corporation, one of the 3PIs in the market that is manifesting both standard and dedicated rideshare missions, has found that a two-tiered stakeholdership construct is most optimal for dedicated rideshare missions comprised of numerous smallsat providers that comprise an overall integrated manifest. A smallsat provider that chooses the top tier for a mission is designated a principal stakeholder spacecraft (PSS) provider for that launch. PSS customers enjoy the ability to gain stakeholdership into the overall operational and mission requirements for the launch, to include launch date, and final orbital requirements. In exchange for a voice in the determination of the overall mission requirements, the launch costs for PSS providers are higher than those for other non-PSS customers on that mission.

The second tier of customers on a DRS mission are standard rideshare spacecraft (SRS) providers. An SRS customer essentially assumes the same status as a spacecraft provider on a traditional rideshare mission. That is, in exchange for a lower price point for launch, SRS providers have no input into the overall mission and operational requirements; they are essentially along for the ride and will launch when, where, and how the mission requirements dictate, based on the PSS providers' requirements. ***In this effective construct, the PSS providers serve as the anchor customers for the mission, and the SRS providers provide additional cost savings to the overall manifest.*** Further discussion on the benefits of this approach will be discussed later in this paper.

Why Commercial DRS Is So Compelling

The US and international commercial market has taken the lead in operationalizing smallsat systems, creating a commercial paradigm that changed the view of smallsats as more than mere high school and university science projects. In many respects, the commercial industry is already underway in pathfinding future hybrid architectures of satellite systems as shown in Figure 7 earlier. In her presentation "2015 Small Satellite Market Observations," Elizabeth Buchen from SpaceWorks Enterprises, Inc. (SEI) reports a significant boon in the commercial smallsat industry in 2014, stating that "107 commercial nano/microsatellites (1-50 kg) launched," and that "thousands of commercial smallsats are planning for launch over the next fifteen years.[52]" Her emphasis on "commercial" further demonstrates that it is a significant matter that over a hundred smallsats flew last year solely from the commercial sector. Buchen cites "recent multi-million and multi-billion dollar investments" from commercial investors "confirm the commercial sector's continued interest in the nano/microsatellite and small satellite industries." ***More interestingly, the data in the report makes clear that these investments into smallsat technologies are for operational smallsat assets***, such as the 93 PlanetLabs' earth observation (EO) CubeSats launched last year, the 46 Iridium-NEXT satellite communications microsatellite-class spacecraft, and the recent announcements of more than a billion dollars of investments by Google and Fidelity Investments into SpaceX and Virgin Galactic and Qualcomm into OneWeb for two competing satellite broadband "internet in space" smallsat constellations[53,54]. ***These trends demonstrate that the commercial operational smallsat market has well exceeded $1B in value in early 2015***.

With the incredible burst forward of operational smallsats into the US and international space industry, ***the limitations inherent to traditional rideshare launch approaches are becoming more intolerable to this surging flow of spacecraft providers desiring launch opportunities***. Now with commercial investment backing and in a growing competitive commercial market, smallsat providers are pressured to ensure that their satellite systems can be placed in their desired orbit at their desired time to market, just as the larger-class commercial satellite operators. The disadvantages with traditional rideshare in the bottom right box of Table 5 are unacceptable to these smallsat providers. For instance, these operational smallsats must be placed in their desired orbit to achieve their mission objectives, and the standard rideshare construct that forces them to lose the ability to choose their orbit is highly undesirable. ***Placement into sub-optimal orbits will most likely force spacecraft design changes, impacting overall cost, delaying delivery, and possibly degrading the capabilities promised to the investors and potential customers***. In another example, since rideshares are subject to the launch schedule of the primary mission, it is the author's personal experience that this has caused substantial delays to orbital delivery, even to the extent of years. ***With investor pressure and the need to bring capabilities to market to compete with rival smallsat providers, loss of control over the launch schedule could be devastating to an operational commercial smallsat provider's business***.

These premises are validated by the topics discussed in the recent forums and conferences with respect to launch and responsive access to space. For example, during the launch vehicle panel at this year's Satellite 2015 Conference in Washington DC, the concept of "schedule assurance," that is, the ability to launch satellites at the time that the satellite providers desire was a recurring topic of discussion[55]. Furthermore, during his presentation at the Reinventing Space Conference in London last November, Jonny Dyer, the Chief Engineer of Skybox Imaging emphasized the vital importance of having a high level of confidence in a predetermined launch date for his satellites, boldly stating that Skybox eagerly seeks after dedicated launch opportunities that would provide "schedule assurance at [traditional] rideshare pricing," even on an experimental launch vehicle[56]. ***This statement demonstrates an interesting shift in perspective from traditional legacy space programs, that is, that operational commercial smallsat providers seem to place a higher premium on launch schedule and affordability over technical risks of the launch itself***.

Since the traditional rideshare approach intrinsically introduces unacceptable limitations on launch for operational smallsat providers, they are faced with several options to obtain the operational and mission requirements control necessary to field their space segments, as depicted in Figure 5. As shown in the figure, commercial operational smallsat providers must balance between three main competing requirements: Operational control over mission requirements, schedule assurance, and affordable launch opportunities. It is to be noted that schedule assurance is also a function of the LV reliability and capability to sustain the contracted mission launch tempo. For the purposes of this paper, it is to be assumed that the LVs chosen will have reasonable schedule reliability themselves.

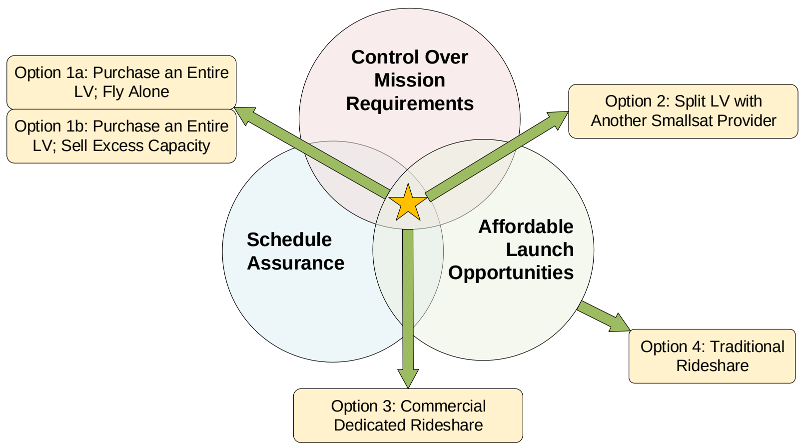

Figure 11. Possible launch options for operational smallsat providers when balancing competing requirements.

The figure also presents four possible launch options for these smallsat providers: Option 1a: The smallsat provider can directly purchase launch services with the LV provider and be the only customer on the manifest; Option 1b: The smallsat provider can directly purchase launch from the LV provider, and by themselves or with the help of a 3PI, sell the excess capacity to other standard rideshare spacecraft providers; Option 2: The smallsat provider can find another suitable smallsat provider to split the cost of the launch as a dual launch manifest; Option 3: The smallsat provider can purchase launch services from a 3PI on a DRS mission as a PSS customer; Option 4: Traditional rideshare for situations where mission requirements and schedule control is not as important than affordability; ideal for replenishment, constellation augmentation, or customers that can accommodate slow constellation deployment.

Each of these approaches have associated pros and cons based on the three competing criteria. These benefits and limitations are summarized in Table 6. As evidenced in the data in the table, smallsat providers that choose to be a PSS customer on commercial DRS missions gain the advantage of obtaining considerably more control over the overall mission requirements and launch schedule than for traditional rideshare missions, while achieving a greater amount of launch cost savings because the manifest is divided up between more rideshare providers than the other options. TriSept estimates that the launch price for PSS providers on DRS missions fall several millions of dollars less than the fractional cost of splitting the launch costs for an entire launch†††. The 3PI is able to achieve these cost reductions by bringing additional savings to bear by manifesting a compliment of SRS customers on the mission. For instance, TriSept estimates that ***a DRS mission approach is able to produce launch prices for PSS and SRS customers on US launch vehicles that are within the competitive price range of the Russian launch market.***

Table 6. Lists of benefits and limitations of operational smallsat launch options with respect to competing criteria.

Launch Option	Competing Criteria			Comments
	Control Over Requirements	Schedule Assurance	Affordability	
1a. Purchase Entire LV, Fly Alone	+++	+++	+	High control over requirements and schedule assurance, but most cost prohibitive
1b. Purchase Entire LV, Sell Excess Capacity	+++	+++	++	High control over reqmts & sched. assurance, but costs still high; provider assumes risk for manifesting entire msn
2. Split LV With Another Smallsat Provider	++	++	++	Split control over mission requirements with another spacecraft provider; both providers split risk for manifesting msn
3. Commercial Dedicated Rideshare	++	++	+++	As PSS, split control over msn reqmts; increased savings with more rideshares; 3PI assumes risk of manifesting msn
4. Traditional Rideshare	+	+	+++	No control over mission requirements or schedule; however, this is traded for maximum cost savings
+++ Much advantage ++ Some advantage + Little or no advantage				

Moreover, since the 3PI contracts directly with the LV provider, ***the 3PI assumes the entire mission cost and programmatic risk associated with manifesting enough spacecraft to afford the overall launch cost***, versus the smallsat provider having to assume this risk when exercising Options 1 through 2 above. This dramatically decreases risk to the individual spacecraft providers, especially since TriSept's experience has shown that most launch vehicle providers desire to minimize the number of interfaces with spacecraft providers. Consequently, this preference drives some LV providers to demand a single integrating contractor to develop and manage a dual launch or rideshare mission, transferring the risk of filling and integrating the manifest to the spacecraft providers, which decreases the practical ability to exercise Options 1a, 1b, and 2 described above. As a result, several LV providers have chosen not to take the responsibility of dealing with individual smallsat providers, preferring instead to use 3PIs to handle the "cat herding." Coupling all of these advantages together makes DRS a highly attractive means to launch, especially in light of the premium placed on schedule reliability and launch affordability.

These Advantages Apply Beyond the Commercial Sector and Smallsat Industry

Looking at the competing requirements and preferences of the commercial smallsat industry, it is easy to correlate the applicability of the advantages of DRS to USG programs as well. Many Government space programs share the same desires of control over mission requirements, the ability to dictate the launch schedule of a mission, and increase the affordability of space access for their missions, in addition higher levels of mission assurance requirements. Furthermore, the commercial DRS principles are agnostic of particular launch vehicles and size of

††† The actual prices for each mission is dependent on the specific mix of rideshare spacecraft for a particular manifest on a DRS mission. Certain orbits, for example, are in more demand by the smallsat community, like the most popular sun-synchronous orbit (SSO) between 450 and 600 km. The price values listed above are based on the current demand for the most desirable SSO orbit for launch in the 2017 and 2018 timeframe.

spacecraft. For example, a competent 3PI would be able to build a DRS mission comprised of two larger-class PSS customers and six or more ESPA-class SRS providers on an EELV-class launch vehicle going to geosynchronous transfer orbit (GTO). This is of importance since Moore's Law and technical innovation is allowing for decreases in size and weight of larger class spacecraft buses due to technologies such as all-electric propulsion and decreased avionics hardware footprints, according to the keynote speech presented by David Madden, the Executive Director of the Air Force Space and Missile Systems Center (SMC) at the 2014 Interplanetary Small Satellite Conference in Pasadena[57]. He emphasized that these decreases in satellite buses could translate to the ability to open access to more rideshare opportunities, to include dual launch of two larger spacecraft on the same mission.

The Mutual Benefits of Government and Commercial Collaboration in Smallsat Space Access

It is plainly evident that the USG has the potential to exploit the many strong capabilities brought by increased innovative technologies, methodologies, and enablers created by the commercial space industry. Based on language of the 2014 QDR, 2014 NDAA, and Mr. Loverro's SASC testimony previously cited in this paper, the USG has already recognized the need for increased collaboration between the Government and commercial space sectors. However, each of these documents seems to indicate that the USG is focused primarily on commercial/government cooperation in areas of commercial satellite communications bandwidth acquisition, hosted payloads, and the introduction of new launch vehicle entrants to the USG launch fleet.

In light of the tremendous exponential growth of the commercial operational smallsat market, its associated growth in demand for control over affordable launch options, as well as the highlighted benefits of commercial dedicated rideshare, the USG should consider ways to exploit these phenomena to increase the number of tech demo and operational smallsat systems that will prove out, mature, and become integral parts of future architectures of mixed hybrid constellations of satellites of all sizes and various functions. This also aligns with the GAO, AFSPC and AF SAB's recommendations to further examine the operational feasibility of smallsats and disaggregation concepts to inform robust and affordable future space architectures.

Furthermore, the USG should create and employ easily and quickly accessible contract mechanisms to allow for USG smallsats to take advantage of the low cost commercial launch opportunities. This provides a mutual benefit for both the government and commercial space industries. It helps the USG by increasing the number of launch opportunities for smallsat tech demos and operational missions, as well as allow Government to exploit the lower price point for commercial rideshare opportunities. Moreover, increased USG smallsats in commercial launch manifests help the commercial space industry by increasing the number of paying customers, either as PSSs or SRSs, helping to more quickly and decisively fill out commercial rideshare launch manifests. As a result, there will be an increased frequency of commercial rideshare opportunities, opening even more launches for commercial and government smallsats and further driving down launch costs for spacecraft of all sizes, to include medium and large satellites. All in all, this will serve to initiate and perpetuate the "cycle of health" described earlier, helping to move the US space industry as a whole on a vector that helps ensure that the US space industry continues to lead the world's space programs.

CONCLUSION: DON'T DISREGARD THE ROLE OF THE SMALL

In summary, the US space industry should grow in their optimism in the increasing operationally utility of smaller-class satellite systems. Smallsats are integral in helping to demonstrate and mature technologies and operational concepts that will feed into the future space systems and architectures. Furthermore, they will be integral pieces of hybrid mixed constellations that make up the space segments of future programs. Since small satellites play an important role in the overall ecosystem of the US space industry, USG leadership should invest time, effort and dollars into seeking out ways to take advantage of the innovative systems, methods and enablers that propel the growing operational commercial smallsat industry.

Moreover, USG leadership should recognize the bottlenecks that hold back the space industry as a whole, to include smallsats, and actively work to remove these impediments. First, the USG needs to be cognizant of the internal threats to the US space industry, i.e., a failing space acquisition paradigm and shrinking Government budgets, and decisively seek to rectify and reform the US space acquisition process that threatens the livelihood and forward progress of US space programs with as much zeal as they have in confronting the external threats to US space systems. Additionally, since space access is one of the major bottlenecks to fielding satellite systems of all sizes, the US space industry should be encouraged to take advantage of innovative approaches to space launch, such as commercial dedicated rideshare. And finally, it is critical for the USG to open up more easy-to-use contract avenues to exploit commercial systems, services, and enablers, to include commercial rideshare launch opportunities.

Overall, USG leadership should not be discouraged about the potential difficulties that lie ahead on the path to reforming the US space industry, to include the possible challenges of employing new means to increasing mission assurance and resiliency, such as disaggregation, distribution, and proliferation. Instead, the US space industry needs decisive and courageous leadership to make wise and informed decisions on how to reform a space acquisition paradigm that is based on a bygone era. The recent surge of operational commercial smallsat innovations and capabilities should breathe hope that effective changes are possible to help the US to maintain space dominance and leadership for the decades to come, and the USG and commercial partnership is critical to achieving that end.

---

[1] “2014 Quadrennial Defense Report”. Government Printing Office, Washington DC. 2014, p.7.

[2] Ibid., p.7.

[3] Shelton, William L. “Fiscal Year 2015 National Defense Authorization Budget Request for National Security Space Activities”. Air Force Space Command. Colorado Springs, CO. 12 Mar 2014, pp.5-6.

[4] Lim, daniel. “Defining a Roadmap to Bringing the US Space Industry Back to Health.” 30th Space Symposium Technical Track. Colorado Springs, CO. 2014.

[5] Taverney, Thomas, D. “Resilient, Disaggregated, and Mixed Constellations.” *The Space Review*. 29 Aug 2011, p.1.

[6] Shelton, p.2.

[7] Chaplain, Cristina T. “GAO-15-7: Additional Knowledge Would Better Support Decisions about Disaggregating Large Satellites.” Government Accountability Office (GAO). Report. Washington, DC. Oct 2014.

[8] Ibid., p.2.

[9] Gruss, Mike. “GAO: U.S. Air Force Needs More Info Before Committing to Disaggregation.” *SpaceNews.com*. http://spacenews.com/42464gao-us-air-force-needs-more-info-before-committing-to-disaggregation/. 5 Nov 15. Accessed 27 Mar 15.

[10] Pawlikowski, Ellen, Doug Loverro, and Tom Cristler. “Disruptive Challenges, New Opportunities, and New Strategies.” *Strategic Studies Quarterly*. Spring, 2012.

[11] Taverney, p.1.

[12] Pawlikowski, et al., p.50.

[13] Taverney, p.2.

[14] Air Force Space Command (AFSPC). “AFD-130821-034: Resiliency and Disaggregated Space Architectures.” White Paper. Colorado Springs, CO. 21 Aug 2013, pp.2-3.

[15] AFD-130821-034, p.5.

[16] Gruss, Mike. “Pentagon’s Top Space Contractor Recognizes Imperative to Change.” *SpaceNews.com*. http://spacenews.com/39130pentagons-top-space-contractor-recognizes-imperative-to-change/. 16 Jan 2014. Accessed 29 Mar 15.

[17] Loverro, Douglas L. “Statement of Mr. Douglas L. Loverro, Deputy Assistant Secretary of Defense for Space Policy Before the Senate Committee on Armed Services Subcommitee on Strategic Forces.” Testimony. Washington, DC. 12 Mar 2014, pp.6-7.

[18] GAO-15-7, p.7.

[19] Gruss, “GAO: U.S. Air Force Needs More Info Before Committing to Disaggregation.”

[20] GAO-15-7, Summary Page.

[21] Taverney, p.2.

[22] AFD-130821-034, p.9.

[23] GAO-15-7, p.10.

[24] Ibid., p.8.

[25] Grosselin III, Kenneth. "Actualizing Flexible National Security Space Systems." Doctoral dissertation. Pardee Rand Graduate School. Santa Monica, CA. Sep 2011, p.5.

[26] Cameron, Alan. "GPS OCX Ground Control in GAO Report." *GPSWorld.com*. Web article. http://gpsworld.com/next-gen-gps-ground-control-system-in-question/. 30 May 2013. Accessed 30 Mar 15.

[27] Dodaro, Gene L. "GAO-13-294SP: Assessments of Selected Weapon Programs." Government Accountability Office (GAO). Report. Washington, DC. 28 Mar 2013, p.74.

[28] Gruss, Mike. "Report: SBIRS Tech Update Would Be Costly." *SpaceNews.com*. Web article. http://spacenews.com/41483report-sbirs-tech-update-would-be-costly/. 4 Aug 2014. Accessed 30 Mar 15.

[29] GAO-15-7, p.8.

[30] Ibid., p.12.

[31] Ibid., p.8.

[32] GAO-13-294SP, p.74.

[33] Taverney, p.2.

[34] GAO-15-7, p.15.

[35] Rivers, Thomas. Personal interview. 26 Mar 2015.

[36] GAO-13-294SP, p.74.

[37] Atkins, Robert. "EELV Secondary Payload Adapter (ESPA) Ring: Overcoming Challenges to Enable Responsive Space." Master's thesis. Naval Post Graduate School, Monterey, CA. Sep 2011.

[38] United States Air Force Scientific Advisory Board. "SAB-TR-13-1: Report on Microsatellite Mission Applications". Report. 1 Aug 2013.

[39] GAO-15-7, pp.10-12.

[40] Gruss, "Pentagon's Top Space Contractor Recognizes Imperative to Change."

[41] GAO-15-7, pp.24.

[42] Ibid., pp.6-7.

[43] Atkins.

[44] Lim, pp.11-12.

[45] United States Congress. House of Represenatives. Committee on Armed Services. *National Defense Authorization Act for Fiscal Year 2014- Legislative Text and Joint Explanatory Statement*. Washington: GPO, 2014. Print.

[46] Lockheed Martin. "Typical mounting scenario of secondary payloads on the ESPA ring." Illustration. 2002. STP-1. *Earth Observing (EO) Portal*. Web. 2 May 2014.

[47] Iridium. "Allocation of the hosted payloads on the Iridium NEXT spacecraft." Illustration. 2002. Iridium NEXT. *Earth Observing (EO) Portal*. Web. 2 May 2014.

[48] "ATK 200 Series Bus." Photograph. 2002. *ATK 200 250 Data Sheet*. ATK. Print.

[49] Garvey Spacecraft Corporation. "Planned Vehicle Evolution." Illustration. 2013. Garvey Receives SBIR Phase II Award. *Parabolic Arc*. Web. 2 May 2014.

[50] Generation Orbit. "Generation Orbit's planned launch system." Illustration. 2013. Generation Orbit to Pitch to Space Angels Network Members. *Parabolic Arc*. Web. 2 May 2014.

[51] Lim, daniel. "Transparent representation of FANTM-RiDE's mass/dynamic response tuning capability." Illustration. TriSept Corporation. 2015.

[52] Buchen, Elizabeth. "2015 Small Satellite Market Observations." SpaceWorks Enterprises, Inc. Atlanta, GA. Presentation. 2015.

[53] Henry, Caleb. "SpaceX Satellite Project Boosted by $1 Billion Google, Fidelity Investment." ViaSatellite. Website. http://www.satellitetoday.com/launch/2015/01/21/spacex-satellite-projects-boosted-by-1-billion-google-fidelity-investment/. 21 Jan 2015. Accessed 31 Mar 2015.

[54] Knapp, Alex. "Virgin and Qualcomm Are Investing In Satellite Internet Company OneWeb." Forbes.com. Website. http://www.forbes.com/sites/alexknapp/2015/01/15/virgin-and-qualcomm-are-investing-in-satellite-internet-company-oneweb/. 15 Jan 2015. Accessed 31 Mar 2015.

[55] "Commercial Launch Leaders: Next-Gen Rockets and Vehicles Revealed!" Satellite 2015 Conference. Panel Discussion. Washington, DC. 18 Mar 2015.

[56] Dyer, Jonny. 12th Reinventing Space Conference. Keynote presentation. London, UK. 19 Nov 2015.

[57] Madden, David W. 2014 Interplanetary Small Satellite Conference. Keynote speech. Pasadena, CA. 28 Apr 2014.