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DEFINING A ROADMAP TO BRINGING THE US SPACE INDUSTRY BACK TO HEALTH

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ABSTRACT

The global economic downturn continues to drive the United States (US) space industry's interest in distributed architectures and disaggregation of large and expensive satellite systems to lower costs and increase resiliency of on-orbit systems. Much focus has been placed on exploring future spacecraft architectures to distribute mission requirements across a combination of large and small satellite platforms. However, the answers to how to actually encourage implementation of disaggregation and bring about real improvement of US launch costs continue to remain unclear to the US space industry. Several solutions, such as hosted payloads, rideshare, and dedicated nano-launch vehicles, are receiving growing interest that have the potential to reducing some of the launch costs. Nonetheless, each solution has yet to proffer long-term cost savings, and the US space industry has not yet formulated an overall roadmap to achieving the goal of providing low-cost, low-risk launch opportunities for all future missions, regardless of the size of the spacecraft.

This paper casts the vision of frequent, resilient and low-cost launch options to putting large and small satellites on orbit, and it provides a notional and simple, yet achievable and effective roadmap to solving the problem of high US satellite and launch costs. The way to achieve these ends is the proper investment and application of six major space access enablers: Smallsat rideshare, hosted payloads, commercial small satellite buses, dedicated small and nano-launch vehicles, air-launched vehicles, and innovative methodologies, processes and operations. Currently, each of these means is being explored and utilized independently; yet to be effective, an overarching roadmap is necessary to outline the ways each enabler should be invested into and utilized to successfully drive down costs and risk. Careful future planning must be accomplished to best utilize the current resources to realize the vision, especially in this fiscally constrained and risk-adverse environment.

INTRODUCTION

The current outlook for the US space industry predicts significant troubles based on the existing US Government (USG) and commercial market. The high cost of development of large, vulnerable program of record (POR) satellite systems that drive high launch costs on US boosters serve to appreciably stunt development and on-orbit capabilities. If these trends continue to propagate, US space systems face the risk of losing the technological edge of on-orbit systems with respect to competing international space programs, as well as sit vulnerable to physical, electronic or cyber attack.

Realizing these risks, USG leadership has analyzed the vulnerability of the US space program, and they have characterized the root of the issue as being large, aggregated satellite architectures. Further, they have set out a rudimentary path forward to bring the US space industry, specifically the Defense space program, back to a healthier state in terms of robust, resilient, and technologically advanced systems on orbit. However, the USG's movements down the directed path have unearthed some challenges in exploring distributed architectures in terms of launch opportunities for technology demonstrations. This paper identifies some of the two key roots that threaten to bring progress to a grinding halt, and in understanding these issues, projecting solutions to drive the process forward to fostering the US space industry back to a path towards a healthier state. Further, this paper outlines a specific roadmap ("Cycle of Health") to resolving the issues that plague the US space industry and provides recommendations on how USG leadership can foster strong distributed architectures. A keen understanding of the issues, careful and deliberate planning and preparation, and decisive action must be taken to ensure that the US remains a forerunning leader in space and technology in the international community, as well as provide the US cutting edge, highly effective and resilient systems on orbit.

THE NEED TO CHANGE

The US space industry faces serious challenges in the near future. Fiscal challenges will only increase in the foreseen future, well beyond the impacts of the recent global fiscal downturn starting in 2008. Bryan Benedict from Intelsat shared some stark statistics at the 2014 Space Technology Conference demonstrating how US Government (USG) program dollars will shrink in an accelerated pace.[1] He presented how Government sequestration budget reductions make very little impact to the Government budget because of high Government spending, as shown in Figure 1. The figure demonstrates how the Federal revenue curve (dashed green) never intersects the Federal expenditure curve, even with sequestration budget cuts.

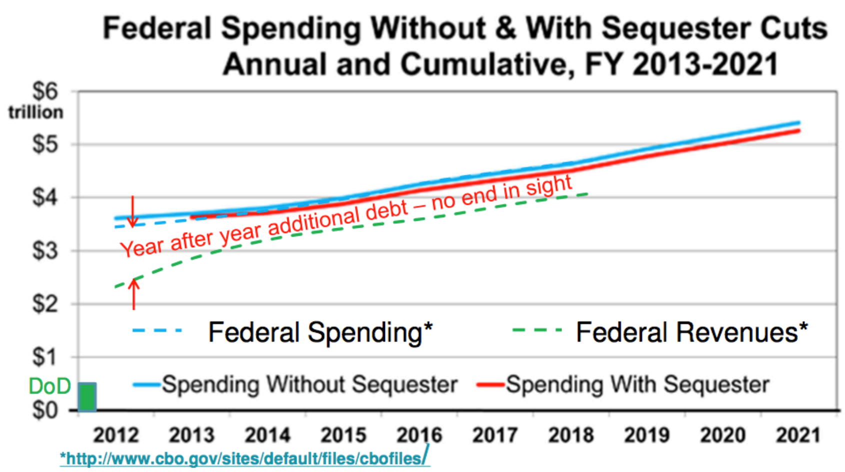

Figure 1: Projected Federal spending with respect to Federal revenues from Benedict's Space Tech Expo briefing, demonstrating the negligible impact of recent Government sequestrations.

Benedict argued that as the USG seeks to balance their discretionary and non-discretionary funding between programs like the Department of Defense (DoD), NASA, health care programs, and Social Security, budget reductions for DoD and Civil Space programs are projected to not just occur in a linear fashion, but "budgets will decline in an accelerating fashion in coming years". In fact, Representative Adam Smith, the highest-ranking Minority member of the House Armed Services Committee (HASC) made it clear in an interview with *Defense News* that sequestration was here to stay, according to a *Defense Community* article.[2]

> "…If you had to bet, you'd bet that sequestration is going to stick around."
> - Rep. Adam Smith, D-WA, 2014

Based on these facts, Benedict posited that no current or future space program was beyond the reach of cancellation, especially in light of some recent cancellations of programs such as the Transformational Satellite (TSAT) Communications Satellite System and the National Polar-Orbiting Operational Environmental Satellite System (NPOESS) program. He asserts that the DoD programs may not be able to "ride out [the US'] budget problems."

One may argue that these budget woes affect only USG programs and that the US commercial industry is insulated from these problems. However, tightening USG Defense and Civil (and subsequently, DoD space and NASA) budgets affects the entire US space industry because USG practices and regulations permeate across the entire US space industry. Firstly, the predominance of US missions launch USG (i.e., DoD and NASA) customers. Figure 2 presents how the majority of launches on US boosters are for the USG versus the US commercial industry. The top pie indicates that between April 2004 and April 2014, 80 percent of the 153 missions on US LVs were for USG primary satellites. This data is based on launch data processed from the Launch Log from *Spaceflight Now* and the *List of USA Launches* on Wikipedia, and it excludes International Space Station (ISS) manned missions.[3,4] The lower pie, derived from an unofficial manifest maintained by the Aerospace Corporation, demonstrates how this trend continues for missions projected from May 2014 to calendar year (CY) 2019, with 82 percent of US launches are for USG primary customers.[5] Additionally, Figure 3 provides a more detailed breakdown of the ratio of USG to commercial missions from May 2014 to CY 2019. Although it is expected that additional missions will be manifested in the outlying years, the strong trend of the prevalence of USG launches in future US missions is expected to continue forward.

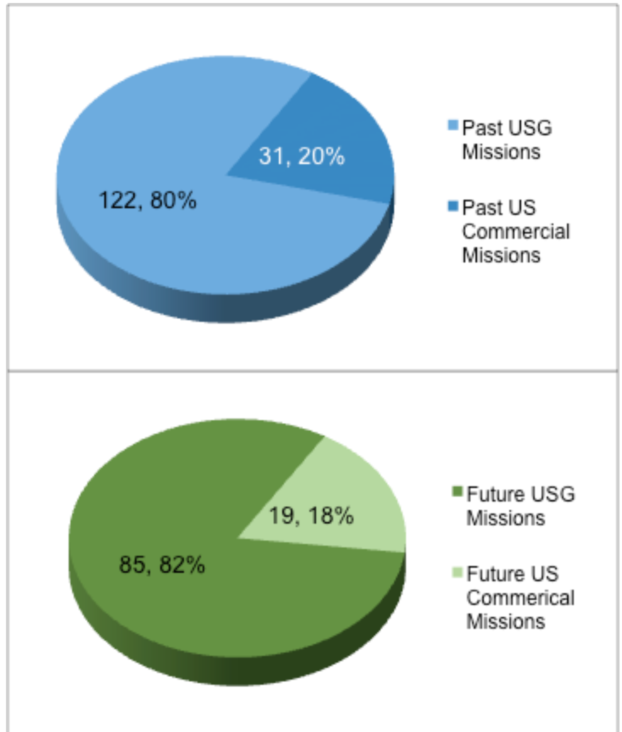

Figure 2: Ratio of past and future (May 2014 to CY 2019) manifested USG versus US commercial launches.

Since the majority of US launches are for USG customers, the majority of Government programs consist of huge, expensive satellite systems that drive very costly launch vehicles (LVs) and associated integration and launch operations and ground systems. In terms of boosters, the majority of LV providers use the same rocket systems for both USG and commercial customers. Therefore, the high launch costs derived by flying USG payloads transfer to a majority of the US commercial customers desiring to fly on these US boosters. Similarly, many of the requirements levied by the entities that provide flight certifications for space vehicles (SVs) launched from the US are the same between USG and commercial providers.

Moreover, high launch costs are a primary driver for causing the US commercial industry to seek international launch options. The Hosted Payloads Alliance published a policy paper in MilSat Magazine that provides some provacative statistics that demonstrate this phenomenon[6]:

> "Over the past decade, commercial companies have primarily relied on affordable and reliable access to space from non-U.S. launch providers. For the dozen years from 2000 through 2011, more than 80 percent of all commercial [Low Earth Orbit] LEO satellites have been launched overseas. Over the same period, more than 90 percent of all commercial [Geosynchronous Orbit] GEO satellites were launched by foreign rockets, notwithstanding that U.S. spacecraft manufacturers built two-thirds of these GEO satellites."
>
> \- Hosted Payloads Alliance, 2012

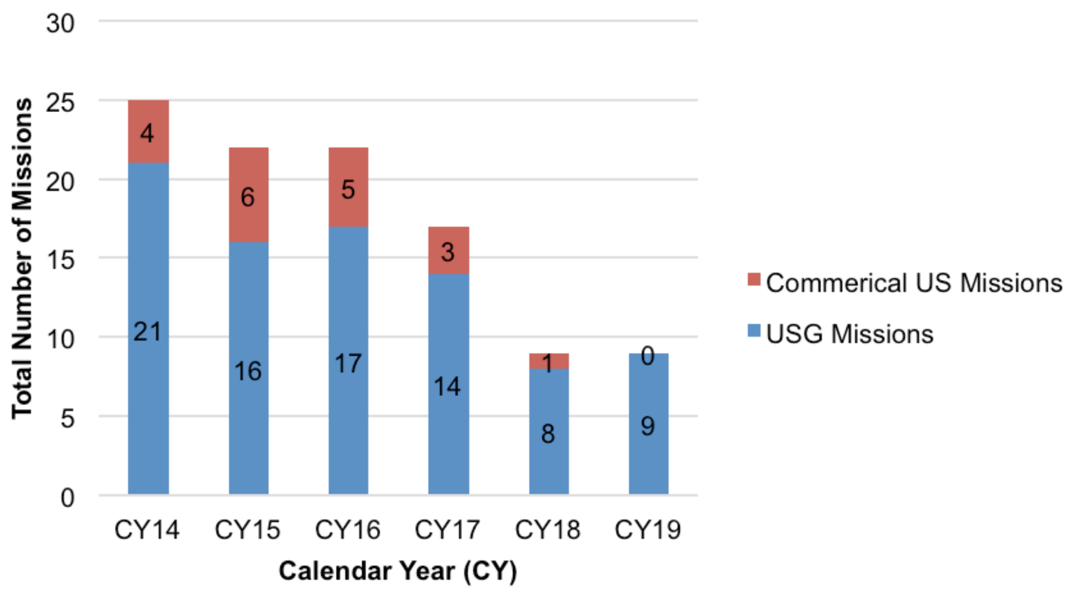

Figure 3: Breakdown of projected USG versus US commercial launches between May 2014 to CY 2019.

However, the high price point for launch on US boosters is only one problem among several others that stunts the growth of the US space industry. Lieutenant General (LtGen) Ellen Pawlikowski, the Commander of the Air Force Space and Missile Systems Center (SMC), and her staff analyzed the key problems that plague the US space industry, to include Defense space programs and released a key paper with their findings entitled "Disruptive Challenges, New Opportunities, and New Strategies". In this paper, LtGen Pawlikowski's team spell out the woes of the US space industry with respect to a "vicious circle" composed of issues that include high launch costs, high spacecraft development costs, high mission assurance requirements, and significant instability of program requirements, schedules and funding that result in "expensive, late, and outdated systems." [7] While many in the industry focus on the high cost of launch, the bulk of the issue lies below the surface, as depicted in Figure 4. According to LtGen Pawlikowski's staff, the root of the issue is that the system architectures of the current PORs are large, expensive, and highly aggregated.[8] Simplistically, these "flagship" aggregated architectures force highly vulnerable and expensive systems to accomplish several mission areas and functions on large platforms, driving up spacecraft development costs. Further, as shown in Figure 4, this creates a highly risk-adverse culture that demands an elevated mission assurance posture that further increases spacecraft development costs: SV providers cannot chance loss of functionality or degradation due to malfunction because these systems cost so much.

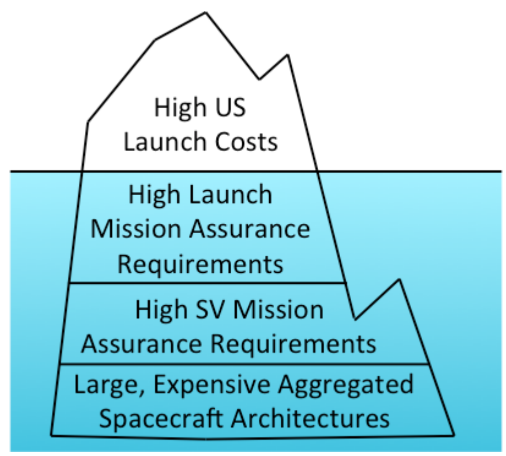

Figure 4: Simplistic representation of the root of high launch costs on US missions.

Also, since these large systems cost so much to procure and develop, the USG cannot afford to lose a single spacecraft due to launch failure, the USG has increased mission assurance requirements onto LV providers to ensure that their SVs are successfully placed into their intended orbits. As mentioned in this author's paper for the 2014 4S Symposium, the US launch industry has experienced a 96 percent success rate from April 2004 to April

2014.[9] However, this high success rate is a proverbial double-edged sword because high LV mission assurance requirements translate directly to high launch costs on US boosters. Figure 4, therefore, depicts a basic progression of factors that increase overall launch costs on US launches.

The "vicious circle" causes a downward spiral for the US space industry because these aggregated, expensive systems and high launch costs create a tendency for USG leadership to fixate on the status quo for the current PORs and maintain highly aggregated requirements baselines. However, in light of the bleak forecast for USG spending on space programs, the US space industry faces an impending crisis that includes cancellation of necessary systems, degradation in mission capability, decrease in science and technology demonstrations on orbit, highly vulnerable architectures, and out of date technologies put into operation. All in all, the US space industry is at risk of being surpassed by the space programs of other advancing nations, losing the technological and space dominance that the US has enjoyed through history so far. For instance, Doug Messier from the *Parabolic Arc* states that former US astronaut Leroy Chiao predicts that China may surpass the US's space program in as little as seven years.[10] Although there are varying assessments on the forecasts of competing nations' space programs, the trajectory that the US industry is headed down paints a bleak picture of the strong possibility of significant decrease, even obsolescence of US space power. The question remains: How does the US space industry break the "vicious circle" that is dragging down the entire space ecosystem?

HOW TO CHANGE? (PART 1) CURRENT APPROACH TO REHABILITATION

Based on their careful analysis of the US space program, LtGen Pawlikowski's staff presented a solution path to bring the industry back to a state of health:[11]

> "… We conclude the best means available to affordably provide resilient space capabilities the war fighter can depend upon and adapt as mission needs evolve is to use a **distributed architecture strategy** coupled with a **payload-focused acquisition strategy**."
>
> - Pawlikowski, et al., 2012

This "distributed architecture strategy" refers to carefully spreading out mission areas and capabilities among several spacecraft platforms versus a single large SV. The "payload-focused acquisition strategy" is one that calls for end-users to concentrate on the payload requirements and then integrated these payloads onto standardized SV buses. This approach saves development costs, as well as allows payload developers to center their attention on payload development and releases them from worry about the SV bus development.

In order to achieve the end goal of lower cost, more resilient, technologically cutting edge, distributed architecture space systems, LtGen Pawlikowski's team laid out a general plan, summarized in Figure 5. Their process begins with conducting studies on distributed architectures with respect to the various mission areas, such as overhead persistent infrared (OPIR), communications, and precision navigation and timing (PNT). Once these disaggregated architectures are defined and projected, the concepts are proven through prototyping and demonstration, usually utilizing small satellite (smallsat) systems. This begins a deliberate transition to smaller architectures and starts the weaning process of the larger legacy systems of the PORs.

Initial steps have been taken to date to begin architecture studies among USG programs. However, the current approach has several problems that points to a negative outlook on the feasibility of distributed architectures. What is holding this proposed process back from propelling the US industry back to health?

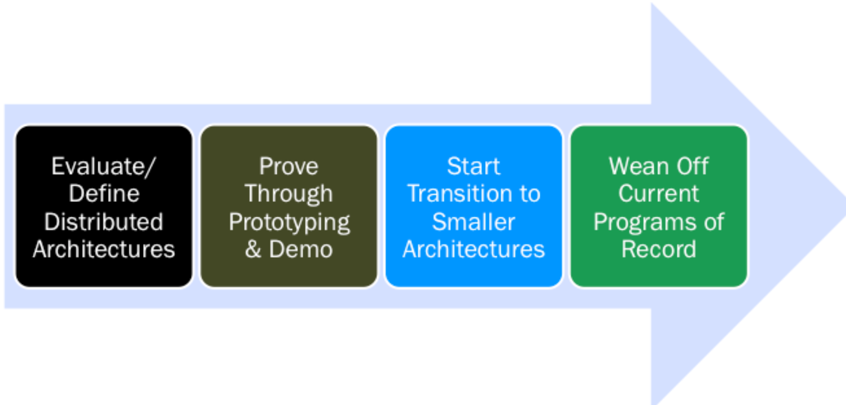

Figure 5: LtGen Pawlikowski's staff's proposed approach to rehabilitate the US space industry.

WHY ISN'T IT WORKING? BARRIERS FOR THE CURRENT APPROACH

As shown in Figure 6, the proposed process is most often halted at the end of the first stage of evaluating distributed architectures. Two main phenomena hinder forward progress towards disaggregation: The "Launch Cost Dichotomy" and institutional inertia.

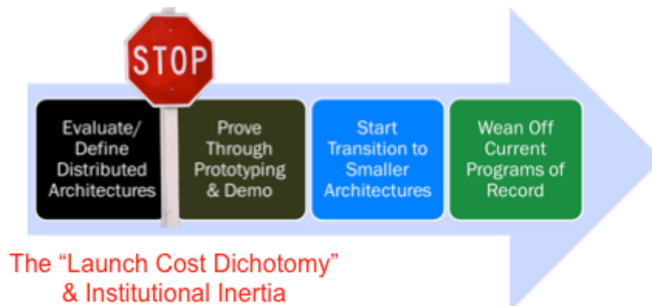

Figure 6: Summary of why the proposed approach is not working to rehabilitate the US space industry.

The Launch Cost Dichotomy

Forward progression is stymied because of high price point for US launches for all sizes/classes of spacecraft. This is illustrated in Figure 7 with the analogy of the debate of the age-old question: "Which came first: The chicken or the egg?" In this philosophical dispute, the subject is debated on the origin of the chicken and the egg; that is, was there first a chicken who laid the egg, producing subsequent chickens that lay eggs, or did things begin with an egg that yielded a chicken to start the cycle?

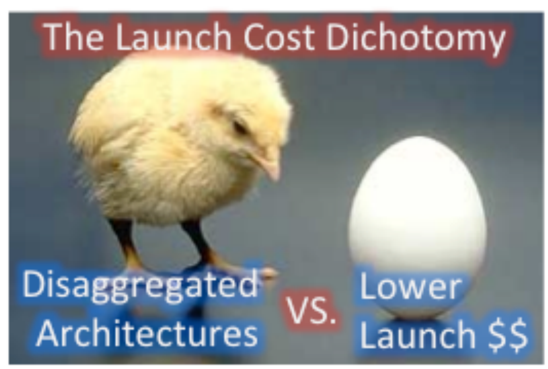

Figure 7: Depiction of the standoff between distributed architectures and launch costs.

A similar dichotomy exists in the current US space industry. Leadership desires smaller, distributed space system architectures to lower SV development and launch costs. However, when conducting future architecture studies, many programs will find that the smaller systems are not feasible based on the current high price point for launches on US boosters. Therefore, this author briefed the following conclusions in a presentation given at the 2014 Space Technology Conference:[12]

> "High launch costs [substantially] narrow distributed architectures trade studies… Disaggregation [is] almost impossible with today's [known] launch options."
> - Lim, 2014 Space Technology Conference

Basically, future architecture studies on disaggregation are very likely to conclude that distributed architectures are not feasible because it costs too much to launch the larger number of smallsats to compensate for larger system architectures, based on a cursory assessment of launch costs based on today's market in the US. Yet, in theory, distributed architectures will lead to lower launch costs. But unless launch for smallsats becomes more affordable, disaggregated systems will not have the chance to be proven out. Subsequently, many program offices will have very little incentive to disaggregate their architectures. This Launch Cost Dichotomy will bring most efforts toward distributed architectures to a grinding halt.

Institutional Inertia

Although not universal with all USG space programs, it is to be expected that the leadership of the current PORs have little incentive to transform their architectures to be distributed across several platforms. Just as with inertial properties of objects in the realm of physics, objects [programs and practices] in motion tend to stay in motion, and objects [programs and practices] at rest tend to stay at rest. Four sub-phenomena intrinsic to USG (and even some large commercial) programs serve to incentivize program leadership to maintain the status quo and dissuade them from embracing initial movement towards transformation: "Show Me First", "We're Pot Invested", "Not on My Watch", and "Not Invented Here". These four concepts form a general mindset in USG leadership that stunts progress, not at the fault of the leaders themselves, per se; this perspective has formed based on the declining condition of the US space industry as a whole.

"Show Me First"

As just mentioned above and evidenced in LtGen Pawlikowski's team's approach in Figure 5, small satellite technologies need to be proven out in terms of mission utility, reliability, and affordability before widespread embrace by PORs. The Air Force Scientific Advisory Board (SAB) conducted a study in 2013 on the mission utility of microsatellites, and according to the Office of the Secretary of Defense (OSD) Defense Science Board (DSB) December 2013 newsletter, "the study found that microsatellites have significant near-term (2-5 years) mission capability."[13] However, POR leaders are not likely to embrace disaggregation until these capabilities are actually demonstrated on orbit. Yet, high launch costs prevent many research and development (R&D) and science and technology (S&T) smallsat programs to get on orbit. Thus, forward progress is caught in the Launch Cost Dichotomy.

"We're Pot Invested"

To borrow an analogy from card games, one becomes "pot invested" when they've already invested so much into the hand (the pot) that they believe that it is too costly for them to back out from the hand, driving them to continue (oftentimes to their demise) to play the game, despite knowing that they may lose much more than they've gained. The USG has invested hundreds of millions, even billions of dollars into each individual large, aggregated spacecraft program. The substantial investment in these programs grows with associated factors, such as immense acquisition processes, sizeable program offices, large infrastructures, and aggregated manufacturing bases, which in turn, increase the inertia of the programs. Therefore, many programs tend to fall into this "sunk cost fallacy" or "irrational escalation cognitive bias" because of the great investment put into these systems.

Further, without delving too deeply into political matters, large programs provide huge amounts of revenue for voting districts, which impacts decisions associated with current and future programs and architectures from the highest echelons of the USG. Agnostic of the moral implications of this factor, large dollar programs create an inertia that tends to negate actions that might threaten current programs and discourages paradigm changes.

"Not On My Watch"

To compound matters, since these large programs require huge amounts of investment and funding, program office leaders are naturally going to be more prone to fixate on the current PORs to ensure that program or mission failure does not occur during their tenure on the program. This phenomenon is not based on any malevolence of the leaders themselves, but it is just third or fourth order effect of the quagmire that the US space industry is stuck in. Especially true for DoD programs, yet certainly applicable to NASA programs, as well, a single programmatic or mission problem or failure could be potentially devastating to the career of the leaders of these programs, affecting promotion and follow-on positions. Therefore, it is natural for leadership to predominately focus on the current PORs and less on future architectures, let alone, currently unproven technologies that promise utility in their mission areas. Additionally, for DoD programs, relatively short assignment cycles (approximately two to four years) give leaders only a short window to learn the nuances of their programs and do everything in their power to ensure the viability of their current operations and missions.

"Not Invented Here"

Joel Greenberg and Henry Hertzfeld state plainly in their book *Space Economics* the following:[14]

> "The NIH (not invented here) syndrome has often been attributed to industrial managers who are unwiling to look at a new idea if they originate outside their own research laboratories. However, the same syndrome can, and does, appear within the government." - Greenberg and Hertzfeld, 1992

This syndrome becomes much more prevalent in the face of a bleak outlook on Government funding. The financial squeeze brought about by shrinking USG budgets forces program offices to (sometimes ferociously) protect limited funding allocated to them. This creates a third order effect of driving the tendency for some leaders to shun technologies and/or enablers that do not originate from their program offices because they see it as a possible threat to their own funding lines. Currently, programs outside of the current PORs are developing the majority of the smallsat R&D and S&T technology demonstration spacecraft, and their associated enablers. Therefore, large programs are compelled to be more resistant to embracing these enablers and technologies into their future architecture studies at the risk of losing precious funding paths. Since the demonstration of smallsat technologies is vital to the success of achieving distributed architectures to employ more robust, affordable and resilient systems on orbit, the NIH syndrome stifles forward progress to healthier and more affordable distributed architectures. ■

However, the US space industry is still not beyond remedy. Both the Launch Cost Dichotomy and the institution inertia can be overcome, but mindsets much be changed and decisive action must be taken to overcome these obstacles.

HOW TO CHANGE? (PART 2) A ROADMAP TO HEALTH

The Launch Cost Dichotomy must be broken and the issue of institutional inertia must be overcome to allow the US space industry to continue to traverse down the path of health. To begin discussion on resolution, the desired end state should be defined in order to ensure that the ways and means to achieving these ends are most appropriate. Then the current approach should be reevaluated to determine if it's the best way to achieving these goals by mitigating the Launch Cost Dichotomy and institutional inertia.

Vision of Where We Want to Be

To provide a basis of common understanding, the desired end state, "a state of health" for the US space industry should be clearly defined. Figure 8 presents a summary list of facets of a desired environment, partially derived from LtGen Pawlikowski's team's paper. Various stakeholders in the US space industry may have different desires for the desired end state, so, although not exhaustive, the list in Figure 8 seeks to gather a majority of the things that are wanted. For instance, many smallsat providers merely desire lower launch costs, while military users long for operational value and resiliency in addition to lower costs.

Figure 8: List of aspects of the desired end state of health for the US space industry.

Obviously, every US space program desires lower launch and spacecraft development costs. Directly correlated to cost, end users desire that the systems put on orbit are of highest operational value, be it military utility, science, or other capabilities, such as weather forecasting or communications. No one desires degradation in performance or obsolete technologies placed on orbit. This ties into a desire for the latest state of the art technologies to be incorporated into space systems to meet the end users' needs. Further, especially for the DoD, programs desire for their system architectures to be resilient to natural degrading or catastrophic events or man-made attacks, with the ability to rapidly reconstitute capabilities and maintain critical operations if one or several systems go down.

Additionally, long-sighted proponents for the US space industry desire for the base of these other aspects to be developed: A robust technology industrial base and a motivated next generation of contributors to the space industry. A healthy end state requires a hybrid of strong, agile and innovative small businesses alongside larger, well-funded and stable large technological corporations. Furthermore, as the brain trust of expertise moves into and past retirement age, the US needs a new generation of young people with interest in science, technology, engineering and mathematics (STEM). A boom in US space programs will rekindle a national interest in space technologies and exploration and encourage youth to pursue careers and investment into the US space industry.

Reshaping the Current Approach: The "Cycle of Health"

The linear nature of the approach provided by LtGen Pawlikowski's team can be reshaped to be cyclical in pattern. In physical nature, rotational energy can be harnessed to propel objects forward at great velocities and power, like stones hurled from a swirling sling. Likewise, bending the proposed approach into a circular pattern will help gain momentum to bring the US back to a state of health. This Cycle of Health is presented in Figure 9. This cycle has an outer ring that spirals into an inner ring that subsequently spins back out to the outer ring.

The cyclical pattern is more advantageous because it demonstrates how continual technology demonstrations will encourage program offices to embrace these technologies and enablers into future architectures, which should then include smaller satellite technologies. As more smallsat systems prove out their mission capability and utility (e.g., military, science, etc.) and more capable systems are actually put on orbit versus merely theorized, programs would be more incentivized (or at least, disarmed of any excuses not) to embrace these enablers into their future architecture studies. The orange-bordered boxes in Figure 9 represent the desired end state facets previously discussed.

As a second order effect of demonstrating smallsat systems on orbit is increasing the rate of launches on US boosters. According to basic economics, this serves to decrease launch costs and lower SV development costs because more units are being acquired and launched. Furthermore, increasing launch rates and lowering costs begins to form a more risk tolerant culture of programs that are less adverse to losing a single launch or spacecraft because replacements can be more rapidly reconstituted at a much more affordable level. In turn, decreasing the mission assurance burden through a more risk tolerant culture will only further increase the frequency of launches and spacecraft on orbit, churning the interior cycle even further.

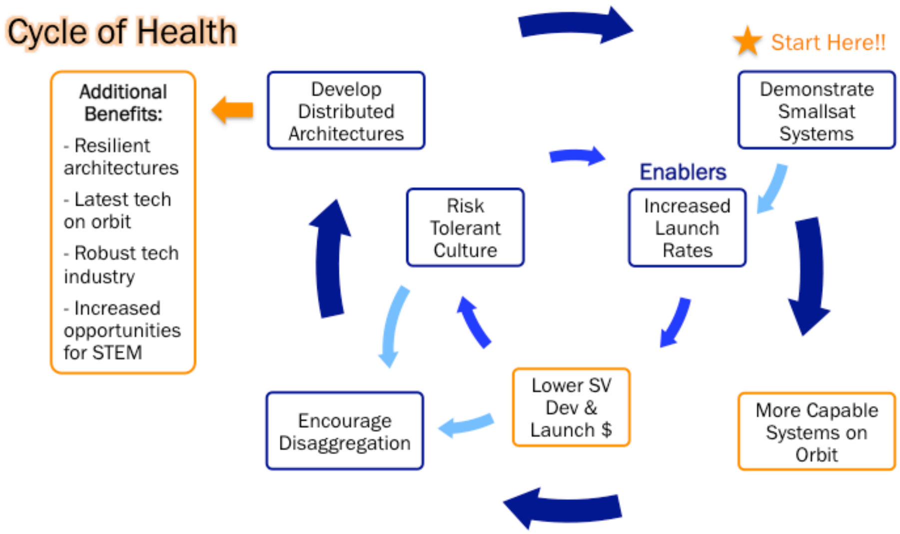

Figure 9: "Cycle of Health": Alternate cyclical approach to bringing the US space industry back to health.

The inner cycle spirals back outward because lower spacecraft development and launch costs, coupled with a more risk tolerant culture will further encourage USG (and commercial) programs to embrace disaggregation and begin incorporating these concepts into their future architectures. All in all, the Cycle of Health begins to serve as an engine to propel the US space industry back to a state of health, as positive end results centrifugally spin out of the cycle.

Breaking the Launch Cost Dichotomy

The smallsat industry is vital to breaking the Launch Cost Dichotomy. LtGen Pawlikowski's group's approach begins with future architecture studies on disaggregation to initiate the process. However, as shown, the Launch Cost Dichotomy is one factor that taints the trade space in these studies. Therefore, instead of waiting for the future architecture studies from the PORs to begin by incorporating smallsat systems and enablers into their future baselines, the smallsat industry must be the initial catalyst, the spark that initiates the Cycle of Health.

Focus on Operationally Useful Technologies

To begin, more smallsat providers should take the initiative to interact with USG program leadership to understand the end users' needs, whether they are military, science or other Civil uses. Based on these discussions, these smallsat developers should focus their systems on technologies that can begin bringing direct mission utility to these customers. Currently, it appears that the majority of smallsat developers myopically seek to prove out "gee whiz" technologies and enablers that have very little impact on larger PORs. The smallsat industry should continue to excel in R&D and S&T and develop disruptive technologies that bring about paradigm changes; this is not a call for smallsat developers to completely abandon these technology demonstrations and science projects. However, it is a call for more smallsat providers to begin seeking to demonstrate technologies that have a direct impact to current programs for the sake of encouraging disaggregation, which will open up many more launch opportunities and spacecraft programs of all sizes of SVs.

Sow Tiny Satellites to Reap Larger, More Capable Systems

An ancient Greek text brings forward a strong principle that applies to investment into smallsat technologies:[15]

> "… A mustard seed planted in the ground. It is the smallest of all seeds, but it becomes the largest of all garden plants; it grows long branches, and birds can make nests in its shade" - Mark 4.31-32 (NLT)

The smallsat industry has grown substantially in the recent years, especially SVs of the CubeSat class. In Dominic DePasquale and John Bradford's *Nano/Microsatellite Market Assessment* published in February 2013, they have projected "strong growth in nano/microsatellite [market]" in the upcoming years. [16] They also concluded that "the nano/microsatellite market has grown considerably with the adoption of the CubeSat standard," among other factors. However, since many of these smallsats are of experimental, R&D, and S&T in nature, some large spacecraft providers will not allow these small spacecraft to rideshare on their high-dollar missions. High launch costs and limited launch opportunities serve to stunt the growth of this emerging market. Yet, investment into this market is key to developing a technology basis for larger class and more operationally useful smallsats.

This is best demonstrated by observing an example investment progression taken by some commercial smallsat development programs, as shown in Figure 10.

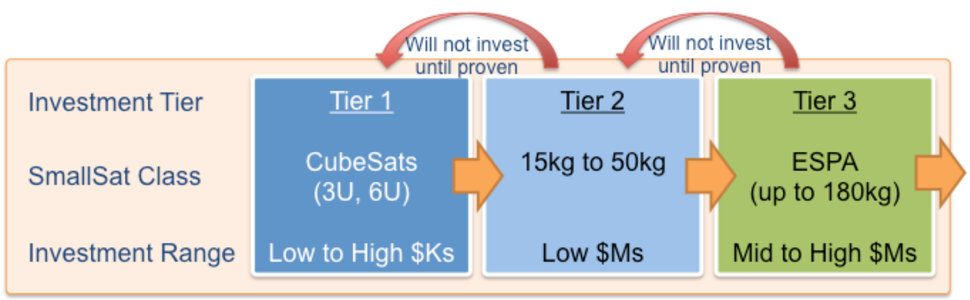

Figure 10: A typical commercial small satellite investment progression.

Many smallsat programs that desire to develop ESPA class (and then larger systems) face three tiers of investors. ESPA class spacecraft development requires "Tier 3" investors to fund the mid to high million dollar range of satellite development costs. However, this tier of investors are usually not willing to provide funding until the technologies on the spacecraft have been proven in a smaller class spacecraft, usually in the 15kg to 50kg range, more or less. This class of smallsats require smaller amounts of funding than the ESPA class, yet still requires development costs in the low millions of dollars range from "Tier 2" investors. Yet, unless the technologies have been already proven, this tier of financial backers will not fund the development of this class of spacecraft until it has been proven in a CubeSat class spacecraft, typically in the 3U or 6U form factor. Therefore, many companies must find Tier 1 investors to develop their CubeSats, or they may choose to develop their CubeSats under their own internal investment funding. This model of smallsat system architecture development also mirrors some USG small spacecraft programs, to include those exploring disaggregated architectures.

Understanding this paradigm, the US space industry needs to invest in the smaller class spacecraft programs as the seed corn for future harvests of operationally useful, reliable, and robust smallsat systems that will compose distributed architectures. CubeSats and other smallsats should not be viewed as mere space debris because they do not provide a direct operational capability; they may provide the proper technology demonstrations that feed into the natural progression of tech development. Another analogy is that of phytoplankton, or "zoo plankton."

Although these microorganisms are barely perceptible to the naked eye, yet they are essential to marine ecosystems. According to the University of Rhode Island Office of Marine Programs, "Since the phytoplankton are the primary link, they must be produced in great quantities to support the estuarine food web. If the plankton disappear, the chain is broken and the [other] animals [in the ecosystem] will suffer."[17] In light of the progression of smallsat systems shown in Figure 10, the US space industry should open up more frequent and lower cost launch opportunities for smaller class of smallsats to grow the number of ESPA class and larger smallsat systems.

This is especially true for the US space industry in light of the small number of ESPA class spacecraft flown on US missions in the recent past. Figure 11 presents data derived from Spaceflight Now's *Launch Log* that indicates that only twenty ESPA class spacecraft have been flown on US boosters in the past ten years.[18] In fact, *SpaceNews* editorial entitled "The ESPA Saga Continues" highlights that "only one ESPA ring has flown since [STP-1], and that one was on a NASA mission [LADEE]."[19] This is striking in light of the ESPA Standard Service policy mandated by Air Force Space Command that will be discussed further later in the paper. In the current market, the US industry has much difficulty in finding enough USG or commercial ESPA class spacecraft to fill all six ports of a standard ESPA ring if one was made available in the near term. This trend will continue with stops and fits of small numbers of ESPA class spacecraft development efforts evidenced in Figure 11 unless proper investment into the smaller class smallsats is made by fostering strong programs and opening up more and less costly launch opportunities for these satellites. Alternatively, all classes of smallsats, and even larger satellite programs will flourish and begin infusing lower cost innovative solutions into their current and future platforms.

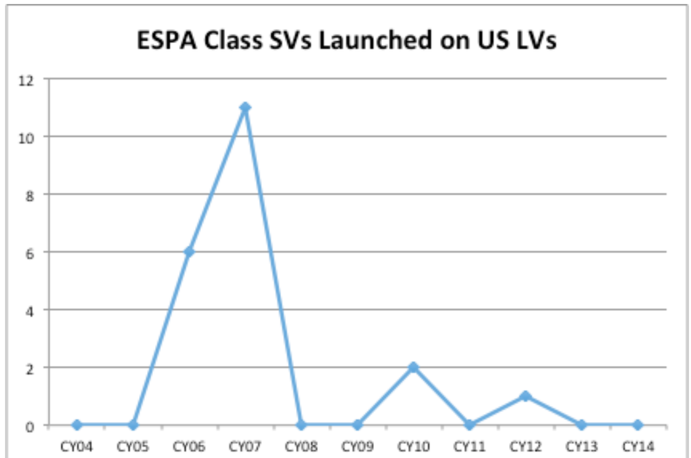

Figure 11: The number of ESPA class spacecraft flown on US missions between April 2004 to April 2014.

Further, in the ecosystem of a healthy space industry, there will always be a need for every size of satellite. The flow in Figure 10 is not a singular evolution, but is a progression followed by many smallsat development efforts. One must not assume that the industry would ever evolve in a manner such that CubeSats would become obsolete; this class of satellites should always exist to prove out new innovative technologies, processes and architectures, creating new development streams that will eventually infuse these results into future capabilities brought by larger small spacecraft and large satellites. In fact, in light of Moore's Law, smaller spacecraft sizes should become more and more powerful and capable in the future, yielding more mission utility in smaller form factors. Therefore, investment in the smaller class smallsat technologies and launch enablers is a wise and worth-while long-term investment for the US space industry.

Invest in Smallsat Launch Enablers

If the high cost of launch for smallsats is one of the primary sticking points of the dichotomy, the US space industry should focus on investing in launch enablers for smallsats to bring down the price point for this class of spacecraft. Figure 12 depicts the general categories of enablers that will facilitate smallsat access to space.

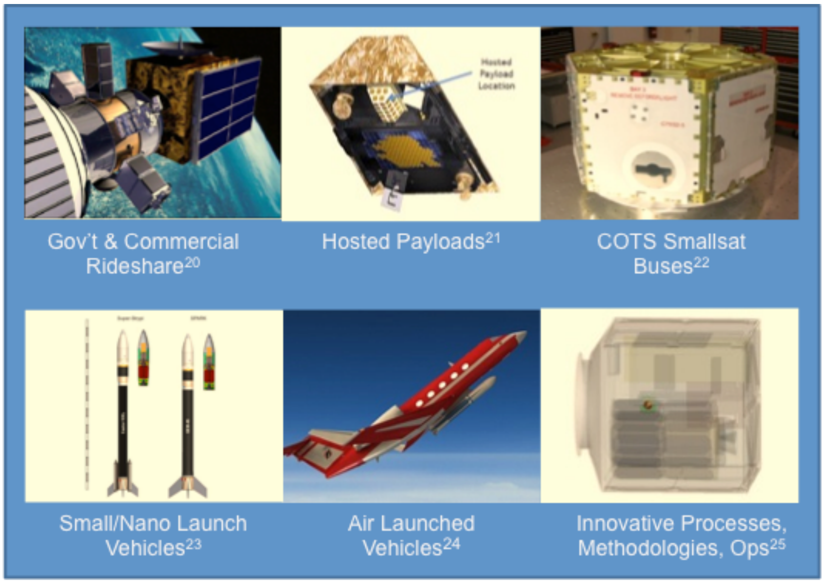

Figure 12: Smallsat access to space enablers (Photo citations in Reference section).

The first category is free-flying smallsat payloads ridesharing on launches. Depicted in Lockheed Martin's representation of several free-flying spacecraft on an Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) ring flown on the STP-1 mission in March of 2007, rideshare missions can consist of Government payloads on USG or commercial launches, or commercial spacecraft on commercial missions.[20] This enabler allows one or many smallsat providers to exploit the residual mass and payload fairing volume margin available on most US launches. This also provides a lower price point for smallsat providers because they do not have to purchase the entire mission (which is almost impossible for most smallsat programs), and also because the cost of launch is spread across several smallsat rideshare customers. The USG mainly harnesses rideshare opportunities through SMC's Satellite Test Program (STP) and NASA's Launch Service Program (LSP), and several US rideshare brokers have emerged to aggregate smallsat rideshares on US launches as well. If one root of the Launch Cost Dichotomy is high launch costs for smallsat providers, the US space industry should heavily invest in rideshare enabling technologies, to include adapters, dispensers, deployment mechanisms and other hardware and software systems that would effectively and affordably facilitate rideshare opportunities on US launches.

The second group of enablers are hosted payload opportunities: Individual small payloads can find access to space opportunities on SV buses that have capacity to host additional payloads in a hosted payload configuration, represented by an artist's rendition of the Iridium NEXT spacecraft in the figure.[21] This dovetails with LtGen Pawlikowski's team's conclusion that the USG programs should become "payload centric" to focus on payload development and the interface with the host instead of also expending time and resources to developing the bus. Significant strides have been taken in the US space industry in exploring this enabler, evidenced in the formation of the Hosted Payload Alliance by numerous large satellite companies and SMC's implementation of the Hosted Payloads Office. The US space industry should continue to develop and define clear interfaces between host spacecraft and hosted payloads to simplify the integration process in order to open additional launch opportunities for secondary payloads.

The third set of enablers are commercial off the shelf (COTS) small satellite buses that would be readily available on the market, represented by ATK's A200 satellite bus[22]. The most effective, reliable and most affordable COTS buses would then become industry standards for payload providers to design towards and save time and costs in SV development. This concept can be extended for all sizes of spacecraft and, theoretically, for all mission types. The current US market has several commercial smallsat bus designers for various sizes of smallsats. It would greatly behoove the USG to instantiate an office analogous to SMC's Hosted Payloads Office that would begin cataloging the commercially available smallsat buses in terms of size, available weight, power, and commodities (e.g., telemetry and control, power regeneration, data downlink, etc.), as well as cost, reliability and performance. This program office can then release this list to potential payload providers to have a menu option to choose COTS buses to reduce development complexity and overall system costs, as well as create contract mechanisms for USG customers like an indefinite duration, indefinite quantity (IDIQ) blanket purchase agreement (BPA) for the highest value COTS buses or the Government Services Agency (GSA) schedule mechanism to greatly facilitate the acquisition of these buses and simplify spacecraft designs.

The next enablers are small and nano launch vehicles, depicted by the Super Strypi and SPARK small launch vehicles developed by Sandia National Laboratories (SNL).[23] Several USG and commercial organizations are developing these small LVs that are designed specifically to responsively place smallsats on orbit. These development programs include the US Army's Soldier-Warfighter Operationally Responsive Deployer for Space (SWORDS) system, as well as the joint effort between the Operationally Responsive Space (ORS) Office and SNL on the Super Strypi rocket. Tied with this enabler are air-launched vehicles, represented in the figure by the Generation Orbit GO Launcher 1.[24] Again, the USG and commercial industry are seeking to pursue this method to flexibly launch smaller payloads to orbit. For instance, Defense Advance Research and Development Agency (DARPA) has recently been pursing two air-launched rocket programs, the Airborne Launch Assist Space Access (ALASA) and the Experimental Spaceplane (XS)-1 broad agency announcement (BAA). Additionally, several US companies have emerged to pursue this enabler in the recent years as well. These two sets of enablers should be pursued for those end users that require flexible and operationally responsive launch opportunities.

Finally, the last set of enablers consists of innovative process, methodologies and/or operations to greatly facilitate smallsat access to space, represented by TriSept Corporation's FANTM-RiDE system.[25] In fact, the USG has recognized this need for innovative enablers as important enough to mention in Section 915. Responsive Launch in the 2014 National Defense Authorization Act (NDAA), with emphasis added by this author[26]:

> "(b) STUDY. -The Department of Defense Executive Agent for Space ***shall*** conduct a study on responsive, low- cost launch efforts. Such study shall include…
> (3) an assessment of the viability of ***greater utilization of innovative methods***, including the use of secondary payload adapters on existing launch vehicles.
> (c) REPORT. -Not later than one year after the date of the enactment of this Act, the Department of Defense Executive Agent for Space shall submit to the congressional defense committees a report containing-
> (1) the results of the study conducted under subsection (b); and
> (2) ***a consolidated plan*** for development within the Department of Defense of an operationally responsive, low-cost launch capability."
>
> -2014 National Defense Authorization Act

These innovative methodologies, processes, and/or operations should be brought forward to the US space industry to inform the different programs of ways to improve or enable more efficient SV launch of spacecraft of all classes. For instance, long-lead integration to a pre-defined set of mechanical and electrical interfaces would greatly reduce complexity of integration of whole smallsats to LV rideshare adapters or hosted payloads to buses.

Enablers like the FANTM-RiDE system bring innovative processes that will reduce the number of complex analyses (e.g., coupled loads, electromagnetic interference and compatibility, etc.) that currently dissuade Primary SVs and LV providers for allowing rideshare of free-flyer smallsats and hosted payloads. These enabling concepts can really facilitate opening up launch opportunities that will enable more smallsat demonstration missions. ■

The USG should continue to heavily invest in smallsat enablers to break down the Launch Cost Dichotomy. Reducing the cost for launch and opening more launch opportunities for smallsats will help the industry move forward towards health. However, this investment needs to be conducted wisely in order to maximize the effectiveness of each enabler.

Careful Approach to Employing Enablers

As mentioned in the previous section, the USG and US commercial industry has begun investment into each of the enablers for smallsat access to space. However, to date, the industry seems to be pursuing these enablers in a seemingly disorganized and uncoordinated fashion. In some cases, several USG agencies and Services are exploring and developing the same kind of enabler, such as the SWORDS and Super Strypi systems mentioned earlier. Additionally, different USG organizations are pursuing these enablers with very small budget allocations. In light of the forecast of decreasing future funding, the USG and commercial industry needs to plan out and time investments into these enablers in order to maximize their effectiveness to drive down launch costs for smallsats and jumpstart the Cycle of Health. Figure 13 presents the popular board game Risk™ to illustrate this need.

Figure 13: Using the board game Risk™ to encourage carefully timed investments into smallsat enablers.

Risk simulates basic warfare, where competing players are waging campaigns to conquer more countries to grow military production to try to dominate the entire map. Many of the principles of war are experienced in the simple gameplay, such as Objective, Offensive, Mass, Maneuver, Security and Economy of Force. Among the other principles of war, experienced players learn to harness Mass and Economy of Force to gain more lands, yet secure them for subsequent engagements. Air Force Doctrine Document (AFDD) 1 states that the purpose of the principle of Mass is to "concentrate the effects of combat power at the most advantageous place and time to achieve decision results."[27] In terms of Mass, successful players have learned to invest into one (sometimes, maybe two) army, concentrating their forces on only one key theater of operation so that they can overwhelm enemy armies in the regions they seek to conquer. Novice players that seek to spread out the investment in their armies across multiple regions end up diluting their effectiveness and becoming easy targets for destruction. Expert players, however, will amass their armies to secure key regions, which enables them to invest in armies in other regions at a later time, eventually culminating in victory.

Also, expert Risk players learn the principle of Economy of Force to ensure they do not spread themselves to thin after each battle. AFDD-1 defines Economy of Force as "the judicious employment and distribution of forces."[28] Novice players will become overzealous after several successful battles to continue a non-stop blitz through a region at the cost of leaving poorly defended armies to defend conquered lands, spreading themselves very thin. Therefore, although these players may achieve significant gains on a single turn, their armies are decimated by the time the next round comes because they did not apply restraint and careful application of forces. They have spread themselves too thin.

The US space industry is currently approaching investment into smallsat access to space enablers in a manner much like novice Risk players. With limited funding and resources, it is imperative that the USG (and subsequently, the US commercial industry) should carefully plan out how and when to invest into each of the enablers to maximize their effectiveness. In terms of the Mass and Economy of Force principles learned in Risk, the USG should focus initial investment on the smallsat launch enablers that will provide the maximum results with the lowest cost and effort, i.e., the "low-hanging fruit." Then, as these enablers allow for an increased frequency of smallsat technology demonstrations to show their mission utility, the USG should pour more investment into other enablers, eventually creating a robust smallsat access to space capability to begin driving the Cycle of Health. This author summarized this thought at the 2014 Space Technology Conference:

> "Don't spread investments into each enabler too thin; Focus on key enablers, then grow others as [the] market matures" -Lim, 2014 Space Technology Conference

Figure 14 provides a simplistic representation of a possible roadmap of investment of these enablers. It begins with the enablers that provide the lowest risk, cost and effort to implement, then, over time, shows investment into the solutions that have higher risk, cost and effort.

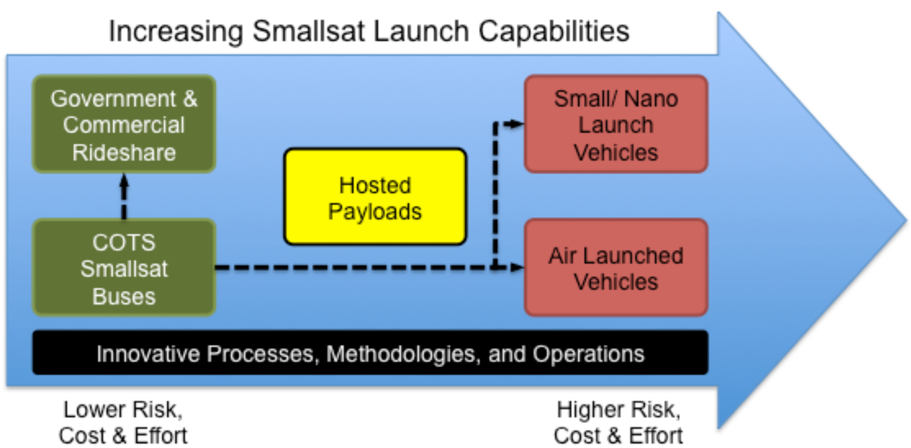

Figure 14: Simplistic roadmap of smallsat launch enabler investments.

In this proposed roadmap, smallsat rideshare and COTS smallsat bus investments should be pursued first. Rideshare was chosen as a "low-hanging fruit" because a large number of US launches have available mass and volume margin to accommodate one or more smallsat rideshares. Further, the US Air Force has already professed support for ridesharing. According to a paper presented at the 24th Annual AIAA/Utah State University Conference on Small Satellites entitled "Small Satellite Access to ESPA Standard Service" the authors state that the Secretary of the Air Force (SECAF) "issued a policy to leverage excess capacity on [EELV] missions" in February of 2008, which culminated into a capability called "ESPA Standard Service".[29] The paper presents that the SECAF's guidance was "to make ESPA-hosted satellite launches a routine operation" in order to "provide routine and affordable access to space for scientific, research, development, and Operationally Responsive Space (ORS) missions." Although ESPA Standard Service has not yet been fully implemented per the guidance, this policy's existence demonstrates the potential availability of this service. As will be discussed in the following section, institutional barriers are a major factor in hindering progress of ESPA Standard Service. However, both the technical and institutional barriers can be easily surmounted with innovative methodologies, as is discussed in a paper co-authored by this author and Joe Maly from Moog CSA Engineering for the 2013 AIAA Reinventing Space conference entitled "FANTM-RiDE-Dramatically Increasing Rideshare Opportunities thru Transparent Solutions."[30] Increased numbers of smallsat rideshare missions, enabled with innovative methodologies, processes and operations, can provide numerous launch opportunities for smallsats at the lowest risk, effort and cost in the near term to help catalyze the whole US space industry.

Additionally, gathering data and cataloging COTS smallsat buses can be accomplished fairly quickly with low cost. Further, creating an IDIQ to pre-vet a list of COTS smallsat bus providers for USG use can be accomplished fairly quickly and simply. Investing in this group of enablers creates a capability to produce more smallsats at lower prices and high reliability. As indicated by the dashed arrows in Figure 14, investing in COTS smallsat buses will synergistically enable more spacecraft to become available for rideshare, small/nano launch, and air-launched missions. Moreover, investment in these commercial smallsat buses will demonstrate the capability to extend this capability to larger classes of spacecraft, eventually creating a paradigm where all future programs will focus on payload development separately from satellite buses with pre-defined interfaces, greatly reducing spacecraft development costs, in line with the Cycle of Health.

Programs should focus on these two enablers first because of their immediate and significant impact at the least amount of cost, risk, and effort. Once these enablers allow for more useful smallsat technologies to be demonstrated on orbit, the USG should then increase focus on hosted payloads, small/nano LVs, and air-launched vehicles. The latter two have the highest risk of development, require the greatest amount of effort to acquire, and demand the most amount of financial investment. Hosted payloads do not require as much risk, effort or costs, but their impact is not as rideshare and COTS buses because several inflexibilities in the hosted payloads construct. This topic is discussed further in another paper presented by this author at the 2013 AIAA Reinventing Space Conference entitled "Hosted Payloads or Dedicated Rideshare? What's the Best Way to Orbit?"[31]

Also, note that Figure 14 shows that the Innovative Methodologies, Processes and Operations enabler is stretched throughout the entire timeline. This enabler feeds into each of the other ones, creating simpler and lower cost/risk acquisition, development, integration, test, launch and operational efforts. Therefore, steady and continual solicitation for inputs on improvements to how spacecraft are bought, developed, launched and operated are very important to fostering a healthy US space industry.

Every one of these types of enablers is important and plays different roles like tools in a tool chest. Nonetheless, careful orchestration of the investment of each enabler is key. For instance, if the space industry invests heavily in developing small/nano and/or air-launched vehicles at the neglect of providing low-cost and frequent launch opportunities for smallsat providers in the near term, then the smallsat market will remain stunted at the time that these new LVs are ready for operation, and there will not be very many smallsats available to take advantage of these new launch opportunities. If that occurs, then the frequency of smallsat launches would be lower because the market cannot produce enough smallsats to reduce costs, thus maintaining a high price point for smallsat launches, as seen today. This will inevitably cause many of these small, nano and air-launched vehicle companies' business cases to fail because the market would not be able to sustain them. The low number of smallsat providers is most likely the strongest contributing factor of why SpaceX halted their Falcon 1 and 1e line of small LVs.

Investments should be timed so that when these additional LVs come to operation, the market will have a plethora of both Government and commercial smallsats that desire access to space, thus driving down launch costs for small payloads. Therefore, it makes much sense to invest in readily available rideshare capabilities and COTS smallsat buses to facilitate small payload development to not only demonstrate highly mission useful spacecraft, but also to increase the smallsat industrial base to be ready to sustain new smaller LVs that cost much and are more difficult to develop. Currently, the USG (and the commercial industry) is focusing on many different enablers simultaneously, diluting each enabler's effectiveness. Understanding that small, nano and air-launched boosters require long lead development timelines, some initial investment in design and development of these solutions should be made at this point. However, the US space industry should focus more heavily on rideshare and COTS smallsat buses from this point forward to ensure that investments into the additional booster programs will be best spent when they come to market.

Redirecting the Institutional Inertia

Decisions to move forward to a state of health must be embraced at all levels of leadership in the US space industry. From the top down, USG leadership should be aware of the four factors presented that dissuade the PORs from moving past the status quo.

Addressing the "Show Me First" Perspective

To counter this mindset, leadership should seek awareness of the great strides in technological advances in smallsat technologies that have been demonstrated so far, sending delegates to symposiums like the Small Satellite Conference in Logan, Utah, or the CubeSat Developer's Conference in San Luis Obispo, California, among others that discuss the game changing advances made by academia, the commercial industry, as well as other Government agencies. Awareness of these capabilities will allow leadership to better forecast future architectures for follow on programs.

Leadership should also be aware of the innovative enablers that are arising from the smallsat industry that currently can reduce launch costs and simplify the complexity of smallsat access to space at low risk to their current programs of record. The author's earlier quote from the 2014 Space Technology Conference: "Disaggregation [is] almost impossible with today's [known] launch options," deliberately used the terms "almost" and "known" because there are several near-term solutions that significantly change the calculus of smallsat access to space, such as the FANTM-RiDE system, an upcoming offering by SpaceX called the Surfboard system, and United Launch Alliance's Aft Bulkhead Carrier (ABC). Knowing about these enablers will allow POR leadership to re-open up the aperture of the trade space on future architectures because the complexity, risk and cost of smallsat rideshare could be significantly driven down.

Diffusing the "We're Pot Invested" Mentality

To tackle this syndrome, both the Government and commercial prime contractors should be aware of the grim outlook on future Government funding to encourage them to invest more into lower-cost distributed architectures. The growth of the small satellite market should be viewed as positive for growth of small, medium and large businesses across the US. Again, continuation down the current path seems to indicate a lose-lose situation where, eventually, any program can be at risk of cancellation, de-scope, or degradation. Investment into newer systems and architectures is vital to ensuring US dominance in the space and technology arenas.

Dissolving the "Not On My Watch" Thought Process

This mindset will naturally dissipate if systems and architectures become smaller, more agile, lower cost, and increasingly resilient. In the mean time, leadership at the highest echelons should encourage and enable each program office to carefully study future lower cost, distributed architectures in parallel with their mission of successful acquisition, development, and deployment of space systems. Closer coordination is necessary between those studying current and future architectures and those that may provide future enablers for those architectures, specifically in the small satellite community. While it seems unlikely that the personnel system will change, USG leadership should strongly consider longer tenure of USG Military and Civil Service personnel on acquisition programs to help maintain continuity of leadership principles and vision, as well as to allow longer time for leadership to take more responsibility for the long-term implications of their decisions concerning future architectures.

Stopping the "Not Invented Here" Syndrome

The only way this perspective is to change is for leadership at every level to strongly discourage this behavior in their programs offices. Government funding woes are here to stay, so the temptation for each program office to fall into the NIH mindset will possibly grow. Since the declining Government funding trend will remain, leadership in each POR must fight against this temptation and embrace strong potential enablers that can decrease program cost, increase efficiency, effectiveness and resiliency of space systems, even when these solutions come from outside their programs.

CONCLUSION

The US space industry is not beyond rehabilitation. Strong decisive actions should be made to carefully invest in and employ enablers that will allow the Cycle of Health to churn, bringing down costs of spacecraft development and launch, and placing more capable and resilient systems and architectures on orbit. The smallsat industry is the catalyst that can begin the process towards a healthier state and breaking the Launch Cost Dichotomy and overcoming institutional inertia. Further, smallsat enablers, such as rideshare and COTS smallsat buses, are the ignition sparks to begin turning the engine that drives the US space industry to back on a path towards remedy. Inaction or poorly planned and coordinated action spells degradation of US space systems, especially in light of the progress of competing nations' space programs. Mindsets must change and real action must be taken now to better secure the United States' continued space superiority and technological dominance.

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