Air Force Space Command

Resiliency and Disaggregated Space Architectures

White Paper

"Our satellites provide a strategic advantage for the U.S., and as such, we must consider the vulnerabilities and resilience of our constellations. My staff at Headquarters Air Force Space Command, alongside the team at the Space and Missile Systems Center, is leading efforts at balancing resilience with affordability. They are examining disaggregated concepts and evaluating options associated with separating tactical and strategic capability in the missile warning and protected communications mission areas. We are also evaluating constructs to utilize hosted payload and commercial services, as well as methods to on-ramp essential technology improvements to our existing architectures. Beyond the necessity of finding efficiencies and cost savings, we may very well find that disaggregated or dispersed constellations of satellites will yield greater survivability, robustness and resilience in light of environmental and adversarial threats."

- General William L. Shelton, Statement to the Senate Armed Services Committee, 24 April 2013

INTRODUCTION

National security space assets provide Joint Warfighters and our nation with strategic warning, assured communication, and precision positioning, navigation and timing—an unrivaled advantage in today's security environment. Use of these capabilities has evolved considerably in recent years; however, the space systems themselves have not. Many of these systems have designs that date back to the Cold War. Requirements in that era were driven by the compelling need for nuclear attack warning and the desire to maintain a bilateral balance of power. Threats to space systems were deemed a tolerable risk, since an attack in space would be provocative and escalatory and might be interpreted as a prelude to nuclear war.

However, the security environment of today is much different than in the past. Previous considerations led to satellite designs that maximized the size, weight, and capability of every payload within the constraints of a given launch vehicle.[1] Performance was prioritized over protection as the threat of "mutually assured destruction" reduced any risk of an attack. System designs naturally evolved to become increasingly complex, integrated and expensive. Our current satellites are marvels of modern engineering, but their suitability is critically dependent on the strategic balance of a foregone era.

This paper examines the need to provide resilient and affordable capabilities to preserve our operational advantage in space. The focus is on "disaggregating" space capabilities onto multiple platforms or systems. Disaggregation improves mission survivability by increasing the number and diversity of potential targets, thereby complicating an adversary's decision calculus

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[1] Lt Gen Ellen Pawlikowski, Doug Loverro, and Col Tom Cristler, "Space: Disruptive Challenges, New Opportunities and New Strategies," *Strategic Studies Quarterly* 6, no. 1 (Spring 2012): 27-54.

and increasing the uncertainty of successful attack. Disaggregation is of value whether the threat is a hostile adversary, or an environmental threat, such as orbital debris.

A NEW SECURITY ENVIRONMENT

Warfighting requirements on the surface of the earth have rapidly evolved. The rate of change continues to accelerate, virtually guaranteeing the future security environment will be different than today.[2] In *Joint Force 2020*, the Chairman of the Joint Chiefs of Staff echoes the defense strategic guidance for that environment, including two elements of crucial interest: projecting power despite anti-access/area denial challenges, and deterring and defeating aggression. Considering the lengthy time required to develop and field our current space assets, almost by default, the space systems that met yesterday's challenges must address today's problems, and today's architectures must address the future security environment.

The overwhelming success of *Desert Storm* delivered a global wake-up call to our adversaries. State and non-state actors saw firsthand the advantages of networked command and control, overhead surveillance and precision targeting. Conventional forces gained prominence as the centerpiece of U.S. national power projection and began to slowly change our adversary's perception of nuclear power as the central focus of national deterrence. Meanwhile, space systems were increasingly viewed as critical to U.S. conventional power. Combined with the fact that space capabilities are provided by a few, relatively vulnerable satellite architectures, led to the assessment that U.S. reliance on space was a potential Achilles Heel.

These factors have contributed to rapid growth in threats to our space systems. Adversaries have had over twenty years to react to *Desert Storm* and they have concentrated efforts on countering our space advantages. In 2007, China successfully demonstrated the capability to destroy a satellite in low earth orbit, and open source reporting described their capability to interfere non-kinetically with optical space systems using laser dazzling.[3] While kinetic threats could obviously be devastating, non-kinetic threats, such as radio-frequency jammers and cyber attacks, can be equally destructive and are far more prevalent. Cyberspace threats, in particular, have exceptionally low barriers to entry and are growing rapidly. Space systems that rely on complex software and radio-frequency links could be susceptible to these attacks, despite robust cryptographic protection.

Not only man-made threats from state and non-state actors have increased; dangers inherent in the space environment itself have evolved, including increased amounts of debris,

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[2] "Capstone Concept for Joint Operations: Joint Force 2020", Martin E. Dempsey, General, U.S. Army, Chairman, Joint Chiefs of Staff, 10 September 2012

[3] "Chinese ASAT Capabilities and ABM Capability, GlobalSecurity.org, viewed 7 Mar 2013, http://www.globalsecurity.org/space/world/china/asat.htm.

competition for electromagnetic spectrum and the sheer number of satellites in space. While not the result of a hostile and intelligent adversary, the environmental hazard is no less real. In 2009, the first collision involving an active satellite occurred when COSMOS 2251 and Iridium impacted on orbit, creating thousands of pieces of debris.[4] In short, the threat environment has changed extraordinarily, and we must adapt critical U.S. capabilities if our operational advantage is to endure.

No discussion of the changing security environment is complete without addressing current fiscal challenges and budgetary trends. Continued funding of expensive space systems is no longer assured, and is in fact assumed to be impracticable. Large, complex systems that require many years of sustained investment to design, develop, field and operate may no longer be affordable. Moreover, given the growing threat environment, they may place a significant amount of national treasure at increased risk. While astute mission assurance measures have decreased launch failures to record lows, there is always the risk that a single launch failure, early-orbit anomaly, environmental event or hostile act could result in the loss of hundreds of millions, or even billions, of dollars.

RESILIENCE AND DISAGGREGATION

Given the challenges of a rapidly changing security and fiscal environment, new and innovative approaches to provide capability in an affordable way merit close examination. One response to these changes that secures capability for the Joint warfighter and the nation is to seek resilience in space systems. With respect to satellite constellations and space architectures, AFSPC/CC defined resilience as follows:

> *"Resiliency is the ability of a system architecture to continue providing required capabilities in the face of system failures, environmental challenges, or adversary actions."*

Disaggregating space architectures is one strategy to improve resiliency, offering a means to trade cost, schedule, performance, and risk to increase flexibility and capability survivability. To establish a common lexicon, we are proposing the following definition of *space disaggregation*:

> *"The dispersion of space-based missions, functions or sensors across multiple systems spanning one or more orbital plane, platform, host or domain."*

A disaggregated system design offers a means to avoid threats, ensure survivable capabilities despite hostile action, and develop the capacity to reconstitute, recover or operate through

[4] "Effects of Worst Satellite Breakups in History Still Felt Today," Space Insider, 28 Jan 2013. http://www.space.com/19450-space-junk-worst-events-anniversaries.html.

adverse events should robustness fail. Carefully pursued, disaggregation can lead to less costly and more resilient space architectures in the face of a rapidly evolving security environment.

ATTRIBUTES OF DISAGGREGATION

Disaggregation is a strategy to affect multiple elements of our overall space architecture. Its purpose is to provide options within architecture to drive down cost, increase resiliency and distribute capability. Disaggregation has other benefits. It allows systems to be less complex, easier to maintain and affords the Air Force the ability to lower per-unit production costs and improve industrial base stability. Given program of record acquisition decisions we are facing in pending budget deliberations, the timing is right for reassessment of the historical paradigm of fielding monolithic space systems that result in costly, and vulnerable, space architectures.

Although the primary focus of this paper is on disaggregation of the space segment, it is important to note that disaggregation should be considered at an enterprise level, to include connecting nodes, ground systems, command and control, and launch vehicle architecture. System planners should consider all aspects of an architecture, including additional ground entry points, added complexity for mission planning and command and control, and commercial or foreign elements intertwined with the DoD ground segment.

Disaggregation offers significant leverage in keeping pace with advancing technologies and associated benefits in terms of requirements discipline, sustainment of the space industrial base, achieving affordability, and deterring adversary action against U.S. space systems. Each of these opportunities is described below, with considerations for operational impact and costs.

Increased Technology Refresh Opportunities

Current satellite systems have developmental timelines of up to 14 years.[5] Once on orbit these systems routinely exceed 10 years of life. During development, incorporating advances in technology is often difficult as it slows design development and adds significantly to system costs. Once on orbit, hardware upgrades are not practicable. This combination results in technology being "locked in" for what may be a lengthy period of time. This is a substantial drawback considering the pace of technology change, rapidly evolving user needs, and constantly changing tactics, techniques and procedures of adversaries. To remain responsive to these demands requires mission flexibility and an adaptable acquisition process. Through less complex satellites employing more flexible designs, disaggregation facilitates the incorporation of new technology before the end of a space constellation's lifetime. In this regard, it represents an evolution of system acquisition that enables adaptable platforms, software, and capabilities to more effectively match emerging needs.

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[5] Pawlikowski et al, "Space: Disruptive Challenges, New Opportunities and New Strategies" 34.

Improved Requirements Discipline

As discussed, one consequence of our historical approach to space system design is an extended development timeline. Coupled with rapidly advancing technology, these timelines and associated acquisition paradigms may place pressure on program managers and system developers to adapt and incorporate new requirements during the design phase—to make systems exquisite, in other words—adding significantly to their costs.[6] Disaggregation and the potential to refresh technology, as discussed above, provides an opportunity to enforce stricter requirements discipline with all the associated value in cost and schedule. That is, program managers have increased opportunity to lock in a firm requirements baseline that will not be deviated from, as they know there may be increased opportunity to incorporate system changes later, even after satellites have begun launching. This model of "constant adaptability" is a significant deviation from current acquisition practices, and could improve affordability and resiliency.

Increased Launch and Space Industrial Base Stability

As noted in the most recent National Space Policy, the U.S. space industrial base plays a vital role in providing and sustaining space capabilities and national security. Continuous incorporation of new technology into space systems and higher rates of production will also enable industry to remain on the cutting edge of technology and provide additional business stability and incentives. Higher throughput and more stable production rates should produce a larger market for space-qualified parts, thus providing incentives for more companies to enter the marketplace. Improving stability is an important factor in maintaining critical system expertise and sustaining "one-of-a-kind" manufacturing capabilities.

Disaggregation could also foster healthy competition and assist with distributing workload over multiple contractors. Payloads flown on separate spacecraft groups could be provided by different contractor teams, potentially dividing large contracts, creating industrial competition and allowing technology insertion on independent timelines. While beneficial, this approach would require increased focus on integration efforts, starting with stated requirements, and spanning multiple contract team products.

Depending on the approach to disaggregation employed, it could lead to more frequent and predictable launch profiles. An increased launch rate may smooth episodic launch schedules, providing a more stable workload for the launch industry. Further, increased frequency of launch would allow industry to amortize the significant specialized manpower costs associated

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[6] "Prevent project cost overruns with these four essential processes", TechRepublic, http://www.techrepublic.com/article/prevent-project-cost-overruns-with-these-four-essential-processes/1038752, Viewed 7 Mar 2013

with the operation and maintenance of launch capabilities, while helping to sustain individual suppliers whose only customer arises with each individual launch.

Higher production throughput and increased stability may further enable incorporation of commercial best practices[7] and competition into national security space architectures when commercial best practices align with system requirements. Commercial best practices in satellite system designs have been shown to minimize the amount of redesign required for different missions, reducing cost and production time. For example, the commercial satellite bus market has demonstrated the ability to produce satellites in 24 to 36 months and at much lower price points than DoD has been able to achieve.[8] Less complex systems may also increase the willingness for sponsors to forgo the costly mission assurance associated with current launch vehicles and accept increased risk.

Increased Affordability

The DoD is facing a fiscal environment that requires innovative approaches to deliver required mission capability. Declining budgets will mean fewer resources available for system sustainment, procurement, manpower and operation. These factors, combined with cost escalation in the space domain that far exceeds the Consumer Price Index ,[9] drives a requirement for systems that are less costly to manufacture, operate and maintain. Smaller, less complex and lighter systems may shorten procurement timelines, save upfront RDT&E investment and reduce risk in technology development. Combined, these characteristics of disaggregated space architectures may lead to cost savings. Increased production lots would also allow manufacturing production lines to be utilized for longer periods of time at optimized production rates, thus reducing per unit cost and leveling procurement spikes. A good example of this effect is the Global Positioning Satellite system, where larger production numbers provide a more stable manufacturing environment and long-term facility and equipment utilization.

Previous satellite system acquisition programs have experienced large cost overruns and schedule delays. While root causes vary by program, a common reason for cost increases is the difficulty of integrating multiple payloads onto a single bus. This often proves to be technologically challenging and can significantly delay fielding a system. In the National Polar-

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[7] True higher production throughput is achieved through proliferation of disaggregated payloads that have been further simplified.

[8] Futron Corporation, Satellite Manufacturing: Production Cycles and Time to Market, May 2004, 2, http://www.futron.com/upload/wysiwyg/Resources/Whitepapers/Satellite_Manufacturing _Production_Cycles_0504.pdf.

[9] According to the Future Years Defense Plan (FYDP) for 2006 through 2011, funding for development and procurement of major unclassified space systems grew by more than 40 percent in 2006 (to $6.9 billion from $4.9 billion in 2005). Center for Strategic and International Studies http://www.csis.org/burke.

Orbiting Operational Environmental Satellite System (NPOESS) program, complexity associated with integrating multiple, diverse sensors on a single platform grew to be so expensive and difficult to manage that the program was cancelled, opening the possibility of a future gap in capability.[10] Disaggregation reduces this type of integration risk by focusing on less complex designs that may provide singular functions (or components), but operating together provide a capability comparable to the original monolithic design.

Smaller programs of record across the Future Years Defense Program (FYDP) may also provide advantages in program execution, as large, single investment programs are sometimes needed to act as "bill payers" in times of budget decline. Less costly programs can smooth erratic spikes in program funding profiles, most often associated with a launch event or satellite production. These spikes have a negative impact on other programs in the portfolio, as budgets are typically capped at a pre-determined ceiling and other program schedules may need to be modified to accommodate the short-term increase in spending.

As noted by a recent report from the Government Accountability Office, more action is needed to identify opportunities to leverage the governments' buying power through increased efficiencies in launch acquisitions.[11] In addition to any savings realized in terms of satellites, lighter, smaller systems may benefit from reduced launch costs by combining multiple payloads on a single launch vehicle or by reducing the size and complexity of the required booster. Today, launch services are projected to consume approximately 30% of AFSPC's budget over a 20 year plan; advancing launch capability to create an overall balance between affordability, performance and resilience for space must remain a top priority.

Improved Deterrence

Given U.S. dependence on space systems that are often difficult to defend or protect, it is in our best interest to deter attacks on these systems in the first place. Two characteristics that are often associated with deterrence theory are "imposing costs" and "denying benefit." This follows the "carrot and a stick" idiom for offering rewards and punishment. Repercussions for adverse behavior in space should be apparent while any benefit for attacking space systems should be uncertain. Disaggregation improves this deterrent posture by complicating an

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[10] For an empirical description of the exponential relationship between space system cost and complexity, and the potential gains to be realized from emphasizing less complex space systems, see David A. Bearden, "A complexity-based risk assessment of low-cost planetary missions: when is a mission too fast and too cheap?" *Acta Astronomica* 52 (2003): 371-379. Further discussion of the strategic possibilities inherent in the relationship between complexity and cost are covered in Howard E. McCurdy, *Better, Faster, Cheaper: Low-Cost Innovation in the U.S. Space Program* (Baltimore, MD: Johns Hopkins University Press, 2001) and Liam Sarsfield, *The Cosmos on a Shoestring: Small Spacecraft for Space and Earth Science* (Santa Monica, CA: RAND, 1998).

[11] "DoD is Overcoming Long-Standing Problems, but Faces Challenges to Ensuring Its Investments are Optimized," Government Accountability Office (GAO), 24 April 2013.

adversary's targeting calculus and increasing the uncertainty of successful attack. Smaller payloads that are more easily produced, coupled with rapid/responsive launch capability, also increase the ability to reconstitute quickly, denying benefit to be gained from a successful attack. In short, the goal is to make attack against our systems as difficult as possible, while increasing the possibility of capability survival in the face of hostile action.[12]

If, as many experts assert, an attack in space is inevitable, disaggregation will enable new tactics, techniques and procedures (TTPs) to take advantage of the unique attributes of a dispersed architecture.[13] Mission flexibility may be increased, offering alternatives to how we could "fight through" an attack in space rather than relying on our current valuable, and vulnerable, monolithic satellites. In addition, some missions such as nuclear attack warning would be understood to be clearly "off limits," or the aggressor would risk nuclear escalation.

ADDITIONAL STUDY

As a strategy, disaggregation requires careful analysis and mission-specific assessment. Given the vulnerability inherent in current space architectures, combined with the danger of an escalating threat, our future architectures demand a thorough examination of the potential benefits of disaggregation.

There are specific challenges that need to be addressed. Using disaggregation to off-load complexity from the space segment could transfer this complexity to other parts of the system. Consideration needs to be made for increased ground entry point assets, terrestrial communications, and processing requirements for the ground segment, along with additional demands on frequency allocations and satellite Telemetry, Tracking and Control (TT&C) operations. Thus innovative satellite operations concepts need to be examined along with disaggregation to avoid transferring the satellite savings to ground segment costs.

Higher technology refresh rates put pressure on our ability to mature and transition technology in our space acquisition; it will require greater emphasis on acquisition flexibility and adaptability. If not carefully planned and assessed, each new insertion could lead to changes in the communications and ground segments to adapt to new signal formats, higher data rates, commercial standards, increased data storage needs or multi-level security solutions to meet the latest cyber standards.

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[12] While this approach does not deter attacks to components of the system on the ground, terrestrial systems can be "hardened" and are in general more accessible to initiate repairs or replacement than a system in space.

[13] In 2001, the "Space Commission," led by the Honorable Donald Rumsfeld, warned of a potential "Pearl Harbor in Space." More recently, it has been noted that "the principles of war and the logic of competition remain as they have always been" and this will inevitably lead to competition, contestation, and/or war in space, especially between the U.S. and the People's Republic of China, is inevitable. See Everett Carl Dolman, "New Frontiers, Old Realities," Strategic Studies Quarterly 6, no. 1 (Spring 2012): 78-96.

With regard to using hosted payloads on commercial and allied systems, attention needs to be paid to military requirements for radiation hardening, redundancy, and other protective measures. Being secondary to the primary satellite operator also increases the chances for conflict of interest; for example, the primary operator may want to relocate the satellite when the secondary payload operator, in this case the DoD, does not. These issues are currently being addressed in DoD policy and at the Hosted Payload Office in SMC.

While improvements to industrial base stability offer significant advantages, more detailed study is required in launch costs, range operations and ground system complexity to ensure less costly yet increased numbers of satellites don't offset expected savings. Less complex satellites could cost significantly less than legacy systems, but an increase in the number of platforms on orbit may eventually offset this savings through increased life-cycle costs from additional launches and ground system costs. On the other hand, lighter, less complex satellites may lead to smaller launch vehicle requirements or enable multiple payloads per launch, leading to even greater affordability. These system trade-offs are being carefully assessed within each applicable architecture.

CONCLUSION

Today, our current space architectures are vulnerable to attack. Our adversary's counterspace capabilities and actions continue to grow in sophistication, number and employment with the intent to hold our space systems at risk. If the premise is accepted that national security space assets will someday be attacked, then we have a military and moral obligation to examine protective measures that minimize this risk and protect our nation's warfighters, citizens, and economy. Standing still in an environment populated with intelligent adversaries seeking to contest our leadership in space and the operational advantages it affords is a strategy for falling behind. Disaggregation is an innovative opportunity to stay ahead of our adversaries, to change their targeting calculus, and to mitigate the effects of a widespread attack on our space assets. In addition, resilience serves as a deterrent, which may be the best way to preserve our capability by avoiding an attack.

While disaggregation is only part of the equation for space system resiliency, it offers the possibility to increase technology refresh opportunities, improve requirements discipline, increase launch and space industrial base stability, increase affordability and improve deterrence. The existing Cold War paradigm of protecting space systems through the threat of mutually assured destruction may no longer apply to today's security environment; it must be augmented by a natural evolution of the current status quo, toward innovative and creative solutions such as disaggregated space architectures.

APPENDIX: CONCEPTS FOR DISAGGREGATION OF SPACE ARCHITECTURES

This paper identifies five approaches to achieving disaggregation: *Fractionation, Functional Disaggregation, Hosted Payloads, Multi-Orbit,* and *Multi-Domain*. Each of these approaches has differing advantages and disadvantages and may be more applicable for a certain type of satellite mission. In short, there is not a "one-size-fits-all" approach to disaggregation.

Fractionation refers to the "decomposition of a system into modules which interact wirelessly to deliver the capability of the original monolithic system."[14] In this concept, multiple subcomponents interact on orbit to holistically create the capability of a single monolithic satellite. This approach has several potential advantages, such as being able to upgrade or replace a single subcomponent without having to replace the entire satellite, reduced payload mass expanding launch options, lower integration and checkout cost, and an innate ability to accept more risk.

Functional disaggregation refers to the dispersion of sensors or distinct sub-missions onto separate platforms that were previously hosted on a single system. A good example of functional disaggregation would be decomposing the AEHF satellite into separate strategic nuclear and tactical communication satellite payloads. This concept may reduce platform complexity, increase requirements stability and shorten acquisition timelines, leading to rapid matching of solution to need and more frequent technology refresh opportunities.[15] These reductions in platform complexity through functional disaggregation may lead to cost savings at the system or satellite level. The synergies between launch costs and reduced size and complexity of payloads, described above, may also reduce the overall cost of architectures. While not yet proven, the potential benefits are significant and should drive exploration into these options.

Hosted payloads are similar to functional disaggregation, but take advantage of a primary payload that would typically be fielded even without the secondary, hosted payload. AFSPC experience with the advantages of hosted payloads is extensive. For example, core elements of the Space-Based Infrared System are the infrared Highly Elliptical Orbit payloads hosted on a U.S. government spacecraft. The hosted payload uses available spacecraft power, processing, thermal and attitude control capabilities without the necessity of fielding a separate satellite bus of its own. The host could be a national security space asset or even a completely different mission or agency, such as was the case with the Commercially Hosted Infrared Program

[14] "The Value Proposition for Fractionated Space Architectures," DARPA, Owen Brown and Paul Eremenko, AIAA, 2006.

[15] Note that the amalgamation of multiple missions on a single platform often greatly increases system complexity and creates a daunting integration challenge. A good example of this is the NPOESS satellite program, where nine advanced sensors were intended to operate on a single satellite. Technology maturation and integration issues proved to be too difficult, and the program was discontinued.

(CHIRP). CHIRP is a DoD experimental payload hosted on a commercial satellite.[16] Hosting a government payload on a commercial satellite may lower program costs while complicating an adversary's decision calculus regarding attacking a commercial system.[17] While offering great potential, there are some challenges to address. Secondary payloads aligned with a primary host satisfying a different mission (e.g., ISR sensor on a SATCOM host) face inherent challenges in integration, signal and structural interference and thermal constraints which must be worked early in the systems engineering phases to avoid launch delays. Hosted payloads are beginning to show some promising results, but the added legal and availability concerns need to be carefully weighed.

Multi-orbit disaggregation takes advantage of multiple orbital planes to increase resiliency and complicate an adversary's targeting calculus. We currently employ this type of disaggregation in architectures such as weather and Overhead Persistent Infrared; however, it is done to provide necessary geographic coverage. For example, weather satellites are placed both in a geosynchronous orbit to provide continuous coverage and in a sun-synchronous orbit to provide periodic revisit using sensors that are most effective at lower altitudes. This same concept could be applied to improve architecture resiliency to the extent that the chosen orbit meets both mission needs and resilience objectives. Multi-orbit disaggregation is a well understood option to enhance resiliency, but it often comes at a cost to sensor performance or communication link delays. Multi-orbit options must be examined with an eye towards technology maturation in order to maintain acceptable system performance.

Multi-domain disaggregation would take advantage of systems in more than just the space domain. An example of multi-domain disaggregation is the cooperative contributions of AFSPC Ground-Based Radars and Overhead Persistent Infrared sensors to deliver Launch Detection and Missile Tracking capabilities. This may be the most resilient approach, but would have to be carefully designed to provide a cost effective solution. Multiple systems could be designed to cooperatively provide a complete solution, with space sensors providing wide-area coverage and air- or ground-based sensors providing more tactical solutions. Disaggregated space capability across multiple domains provides inherent contingency planning as compared to parallel development of redundant/replacement systems.

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[16] Pawlikowski, et al.

[17] This is a tactic that may be somewhat analogous to Iraq's attempt to sway public opinion during the first Gulf War by placing signs reading "Baby Milk Factory" at valid military targets that had been attacked. Attacking a commercial communications satellite for example, may instill a much different perception in the public eye than interference with a purely military space asset.