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# An Argument against Satellite Resiliency

## Simplicity in the Face of Modern Satellite Design

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### Introduction

"I watch what our adversaries do. I see them moving quickly into the space domain; they are moving very fast, and I see our country not moving fast, and that causes me concern," US Strategic Command Commander Gen John E. Hyten told the Halifax International Security Forum in November 2017.[1]

The US Air Force and the wider US government rely heavily on space-based capabilities in various orbital regimes to project national security and sovereignty. However, these capabilities are enabled by the design, launch, and operation of satellites produced with a design methodology that favors large, monolithic, and technologically exquisite space systems. Despite the ability for these satellites to provide enduring and resilient capabilities, they suffer from a woefully long acquisition process that debilitates any prospect of rapid satellite reconstitution in the event of a space war.

Classically, the satellite design process has focused on hardening and protecting spacecraft from the hostile natural space environment. Now the emphasis has shifted to address man-made and counterspace threats in a broader context of securing spacecraft survivability in space as a war-fighting domain within which to operate. The most prevalent, nonhostile man-made threat comes from the generation of space debris resulting from on-orbit satellite breakups and collisions. Most notably, debris resulting from breakup events such as the Chinese antisatellite (ASAT) test in 2007, the collision of Cosmos 2251 and Iridium 33 in 2009, and the more-recent Indian ASAT test in 2019 have prompted an increasing awareness of the contested and congested nature of space operations.[2] The cause of debris-generating events in 2007 and 2019, kinetic ASATs, and the broader spectrum of counterspace weapons constitute a progressively pressing belligerent threat to the US Space Enterprise.

A new satellite design methodology is advocated to counter the increasingly hostile space environment and ensure the continued benefits of US space-based capabilities. Its design focuses on a disaggregated architecture comprised of smaller, less capable spacecraft that collectively work together to perform the same task or mission. In 2013, Air Force Space Command (AFSPC) responded to the events described above and proposed the implementation of disaggregated space architecture. This article serves as a complement to the earlier AFSPC study and will discuss the benefits of a US space systems engineering posture that focuses on simplicity rather than resiliency. Such a paradigm shift in satellite design is proffered as a means of national security space enterprise force reconstitution in the event of counterspace hostilities. This shift would ensure continued US access to space capabilities necessary for the execution of national strategy. In terms of structure, this article will examine the thesis by first outlining the role of resiliency in modern space systems engineering as specifically related to satellite design, reliability, and architectures. Next, the argument for satellite simplicity will be presented with an analysis of the advantages and disadvantages of such a design implementation.

## Resiliency and Modern Space Systems Engineering

Since the dawn of the Space Age, emerging space-faring nations have recognized that space is a harsh environment for the operation of both manned and unmanned systems. Also, the inability to perform on-orbit repairs makes space an increasingly challenging environment for which to design satellites. Ionizing radiation from celestial bodies wreaks havoc on sensitive electronics with such radiation causing frequent microscopic damage that can lead to unexpected system restarts, and in some cases, completely circuit burnout. Also, as previously introduced, the rise in spacecraft ASAT tests and other collisions increases the amount of debris that will remain on-orbit for the foreseeable future. The debris generated from these types of collisions can create fragments of millimeters in diameter, which, despite their size, can still pose an incredible danger to spacecraft. For example, an extremely small piece of space debris, "likely no bigger than a few thousandths of a millimeter across," caused a 7 millimeter diameter chip in one of the International Space Station's glass windows,[3] an exterior surface specifically designed for such a collision. In addition to space debris, satellites must also resist adversarial counterspace threats exploiting a diverse array of disruptive, degrading, and destructive capabilities that seek to interfere with and obstruct satellite mission execution. Each of these factors—environmental, man-made, and counterspace threats—should be balanced within spacecraft design. Collectively, they can be thought of as a Venn diagram where the optimal design strikes a balance at addressing each design factor while also meeting cost, schedule, and performance goals, as shown in the accompanying figure.

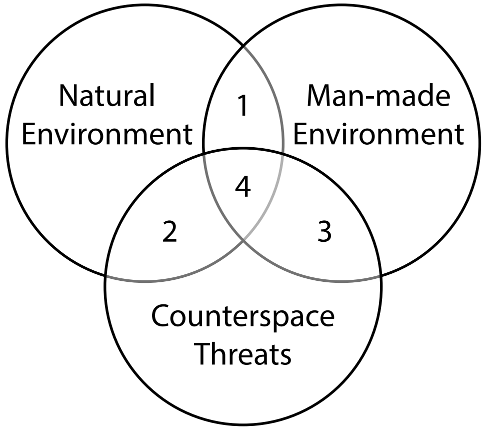


**Figure. Venn Diagram illustrating the key focus areas in spacecraft resiliency**

By their fundamental nature, spacecraft are products of processes and methodologies. The underpinning philosophy of current spacecraft design is the concept of resiliency, which can be broken down into three main categories: design, reliability, and architecture. Current spacecraft designs accomplish resiliency in single-satellite systems by maximizing the on-orbit lifespan through the use of highly optimized components that result in an aggregated highly reliable design. In other words, the expenditure of both significant program funding and schedule will more than likely produce satellites that feature a high design-based level of reliability. Given the historically high costs associated with both satellite component/system design and space launch, it is understandable how cost-saving techniques would dictate that the architecture be monolithic because a requirement for a single launch minimizes total launch costs. Thus, a given single-satellite architecture, paired with a high demand for system capability, often necessitates a highly complex design solution. This design, born out of a peaceful use of space ideology, has been proven to work quite well in providing capability that resists the natural and man-made environment. However, as the political landscape changes and counterspace threats are increasingly considered, our idea of spacecraft design must also evolve.

As a counterpoint to spacecraft resiliency, the term *spacecraft system simplicity* is proposed, which is best described as the movement in the Venn diagram in the preceding figure from Region 1 to Region 4. Historically, when spacecraft were designed with only the natural and man-made environment in mind, the resulting optimal design naturally became a compromise between the two design factors based on the requirements of a given mission. The core idea of spacecraft simplicity can be thought of as a series of changes to "recenter" the spacecraft design methodology. These changes would adequately address the inclusion of the third design factor (counterspace threats) that had not previously been seriously considered because of the reigning peaceful use of space ideology. It is proposed that one of these recentering changes address counterspace threats be in the form of evolving the contemporary architectural paradigm of single-satellite systems to multiple satellite systems. Such a shift would enable the design for each satellite to be less complex, less expensive, and more capable of resisting counterspace threats by relying on a strength-in-numbers approach rather than providing a tailored system defensive response.

Dividing a given space capability across multiple smaller satellite constellations can be accomplished in a variety of different ways. As part of a Defense Advanced Research Projects Agency study from the late 2000s, O. Brown shows a possible future where smaller satellites are organized in a fractionated architecture where individual spacecraft subsystems are broken down into separately flown modules connected via wireless encryption.[4] Fractionated architectures theoretically allow easier system modification and provide the capability of replacing damaged subsystems without having to replace the entire system. To illustrate this idea, Brown provides an example where an on-orbit communication satellite can gain additional uplink/downlink capability by simply launching more communication modules into the midst of the total collection. However, to effectively carry out a fractionated architecture, the US would need to completely rethink how spacecraft are designed and built, which may be too aggressive a move in the short-term for not only for the government but also for the space industry. In light of this obstacle, a disaggregated architecture is proposed.

A disaggregated architecture splits the total capability across smaller, less capable, near-identical platforms. While the individual spacecraft would be inferior in terms of performance compared to contemporary monolithic single-satellite systems, the sum of all capability delivered by the disaggregated architecture can be shown to have significant advantages in terms of overall performance, reliability, and robustness to counterspace threats. In essence, the idea of spacecraft simplicity revolves around the notion of abandoning high levels of individual satellite reliability in favor of a "strength-in-numbers" approach. By abandoning the need to make each satellite highly reliable, the cost and complexity of each satellite can be substantially reduced. As a result, economies of scale can be utilized to quickly and cheaply make higher quantities of these "less resilient" satellites. When cost savings from development and production are paired with the increasingly cheaper access to space, a cost and schedule advantage can be made over the typical single resilient spacecraft paradigm.[5] Furthermore, abandoning redundant components included for extending mission lifetime, reinforced environmental shielding, and other resiliency measures allow the overall size envelope of the satellite to shrink, thus further reducing material costs. These cost and schedule savings have the potential to make responsive space feasible, which would be necessary to rapidly replenish failed or destroyed satellites on-orbit.

In the context of a "congested, contested, and competitive" space environment,[6] another strength that the simplicity model has over the traditional resilient model is the concept of swarming, which can provide both offensive and defensive benefits. Examples of swarm tactics used in nature, namely how wolves hunt, illustrate the benefits of offensive swarming. Overall, a lone wolf is relatively easy to dispatch and poses little threat to a larger prey; however, a pack of wolves makes even the most massive prey extremely cautious. Therefore, as demonstrated by this one example in nature, a large number of weaker attackers can easily overwhelm the defenses of a larger defender, especially when the defender is optimized for countering only one enemy at a time.[7] When this concept is applied to space, a similar effect could be gained from a team of smaller, less capable spacecraft. Faced with space as a war-fighting domain, the concept of spacecraft simplicity results in spacecraft swarms that could provide an edge against the historically strong, single-satellite.

The concept of swarming also carries defensive benefits primarily in the form of improving attribution of hostile action and dissuasion from attack. A swarm is inherently difficult to eliminate, because it requires a persistent show of force to eradicate each member in the swarm. This show of force is much more substantial than a single strike against a single-satellite, and, therefore, is more directly attributable to hostile action. Alternatively, the failure of one satellite can easily be attributed to the natural space environment, or a faulty component or system. Rendleman states that this lack of attribution in today's space environment makes it difficult to enforce existing and future space policies due to plausible deniability.[8] Furthermore, a swarm can operate through an adversarial attack, although at degraded performance, and can be repaired after the attack to full capability with subsequent reconstitution space launches.[9] This idea of repairing damaged system capability is completely infeasible with the current monolithic architecture because repairing any lost capability involves spending millions to even billions of dollars on an entirely new system. This reparability aspect of the simplicity model further illustrates Rendleman's idea of *benefit denial*. This term describes when a potential adversary realizes little gain in attacking the swarm architecture as it is continually reconstituted to the point where no lasting capability was lost or even temporarily placed offline. It is hoped that a logical adversary would conclude such an attack is pointless, thus reinforcing the idea of deterrence from hostile actions that is gained from a swarm architecture over the existing single-satellite alternative.

## Simplicity as a Counter to Satellite Resiliency

The current methodology of achieving architectural resiliency can be vastly improved by the simplicity model. Instead of making an already complex system last longer through the use of adding more redundant components, a better strategy would be to utilize a disaggregated architecture comprised of less complex spacecraft that boast higher reliability both as individual systems and when integrated as an architecture. This strategy is achievable with the spacecraft simplicity model, which allows for less complex designs through the reduction in overall form factor by eliminating or reducing system components such as certain redundant modules and bulky shielding. While the individual spacecraft may seem logically less resilient as a result, the reliability actually increases. In a study conducted by G. F. Dubos, J. F. Castet, and J. H. Saleh, the overall reliability for medium-sized satellites (500–2,500 kilograms) was shown to be actually higher than any other size category, thereby reducing the likelihood of failure when compared to the larger exquisite systems (>2,500 kilograms).[10] This increase can primarily be attributed to the observed trend that medium-sized satellites enjoy the "best of both worlds" in terms of reduced complexity (when compared to larger satellites), and higher quality of components (than those used in smaller satellites).[11] By having a disaggregated architecture, the maintaining organization now can replace worn-out spacecraft individually without replacing the entire architecture. In a way, this can be seen as reserving spares to act as redundancies and deploying them only when needed. This practice is statistically optimal and more resource-efficient as redundancy is used only when needed and can be done without taking the system capability offline. Thus, research shows that reliability statistically favors medium-sized satellites, making a disaggregated architecture all the more appealing when compared to monolithic, single-satellite systems.

The concept of simplicity also opens new doors to the expanded use of commercial-off-the-shelf (COTS) and government-off-the-shelf (GOTS) components in the satellite design process. The need for contemporary satellite systems to be highly capable and resilient requires a highly optimized solution. This solution often excludes the use of COTS/GOTS simply because either a tailored solution is required to meet required system specifications or that the COTS/GOTS solution lacks the on-orbit heritage of legacy space-tested components and systems. With a shift toward simplicity, the use of these readily available components could substantially reduce the system hardware and development costs, while also decreasing production timelines required for larger satellite formations to be viable. The use of more standardized parts enables research and development efforts to be diverted from focusing on developing highly specialized parts for one particular spacecraft toward the development of new components that can be used in a variety of different space systems, independent of the mission. In other words, instead of spending time reworking current technology into a highly optimized part for a particular satellite mission set, development could instead work toward inventing new technology and/or evolving current technologies for incorporation into future component designs. Doing so spurs the development of new technology, which, along with the shorter design life of spacecraft in the simplicity model, allows a greater technology refresh cycle to be realized. Finally, the on-average faster production time observed for less complex satellites within the simplistic model means newer generation spacecraft incorporating better technology can be more quickly fielded to outpace current monolithic satellite systems that are still operating with technology likely developed in the preceding 10–20 years. The result is the capability to respond, adapt, and incorporate the impact of new technology that current monolithic satellite design architectures cannot maintain the pace.

## Counterarguments for Simplicity

The concept of simplicity brings several challenges that would hamper its implementation. First, the introduction of more satellites requires an increased launch tempo, as well as an increased integration complexity of payload stacks on the launch vehicle to ensure maximum usage of launch capability. While cheaper access to space could theoretically allow more launch vehicles to be purchased (thereby increasing launch tempo), the nation's launch infrastructure would also have to be expanded to handle the extra launches. The proposed strategy for increasing launch capability (while current launch infrastructure is built up), is to utilize rideshare to ensure maximum efficiency in the current use of launch capacity. Offices such as the DOD's Space Test Program (STP) can help overcome the logistical and programmatic challenges inherent in rideshare if their lessons learned and expertise were incorporated into mainstream system program office activities. Ultimately, this change in launch tempo is necessary to replace failed or decommissioned spacecraft within the disaggregated architecture since the individual satellite lifetimes would be shorter than those observed with most contemporary space missions. Finally, controlling a dynamic constellation of satellites in space requires the state-of-the-art guidance, navigation, and control (GNC) algorithms to precisely perform rendezvous and proximity operations (RPO) without the risk of inadvertent collisions. These topics are discussed in more detail below to illustrate how these required advancements do not represent insurmountable obstacles to the concept of simplicity.

The need to increase the launch tempo is evident for spacecraft simplicity to be fully realized since more spacecraft would be required to operate on-orbit with shorter total lifetimes compared to those currently in operation today. The current market price per kilogram to space has recently begun to drop from an average of $18,500 from 1970–2000 to $2,700 in 2010 with the debut of the Falcon 9.[12] This considerable reduction results from the expansion of launch vehicle options, as well as the introduction of commercial entities such as SpaceX into the launch vehicle market. From an interview in 2012, SpaceX CEO Elon Musk stated that the secret to the company's success "stems from one core principle: simplicity enables both reliability and cost. Think of cars, is a Ferrari more reliable than a Toyota Corolla or a Honda Civic?"[13] Thus, SpaceX has demonstrated the effective use of simplicity regarding launch vehicles, thereby demonstrating the idea works and also taking the first steps toward increasing the launch tempo that is required for the spacecraft simplicity model to work. By reducing the costs of the exquisite traditional monolithic spacecraft to cheaper simplistic spacecraft, and by leveraging increasingly cheaper access to space, the idea of spacecraft simplicity takes steps toward an executable plan that is cheaper than traditional models if the current cost trends continue.

An increase in integration complexity is evident if launch capabilities are to be fully utilized. Ensuring that each launch vehicle is launched with a full payload complement (to prevent a waste of launch capability) is the specialty of STP, which has been launching primarily smaller research payloads for various government and university customers for the last 50 years.[14] At STP, commonplace is the negotiation of different organization's operational requirements as payloads from all types of communities are manifested onto a single launch vehicle. The logistics of multiorganization, multiobjective missions are sorted out by matching procured launch capability to forecasted and prioritized needs through a variety of rideshare mechanisms such as the Space Experiment Review Board process. For the concept of simplicity to be effective, expertise within the STP process needs to be applied to mainstream operational satellite processes to both prioritize launches to replace degrading architectures and to ensure each launch is full to effectively use each launch vehicle. The USAF is taking a step in the right direction by recently standing up organizations such as the Space & Missile's System Center's Multi-Mission Manifest Office.[15] This new organization's creation shows that the US is starting to take practices utilized by STP to mainstream operational mission sets. The expertise provided by these organizations will be critical to the idea of simplicity since there will be a need to effectively manage how architecture replenishment should be prioritized and how each launch vehicle should be filled to meet the increased demand.

In terms of on-orbit operation, if the idea of spacecraft simplicity was implemented now without the required advancement of GNC for RPO, then the current cadre of spacecraft operators would certainly find themselves overwhelmed in controlling the disaggregated architecture against the unpredictable space environment. For example, Earth's oblateness causes gravitational effects that disperse spacecraft formations under natural uncontrolled motion.[16] Thus, controlling a spacecraft formation requires constant maintenance, which is added on top of normal mission operations. Managing the architecture instead of managing the mission would undoubtedly call for an increased shift burden to an already undermanned career field without the use of autonomous or semiautonomous GNC for RPO. This type of autonomy could help keep formation integrity, prevent accidental spacecraft collisions with other members in the architecture, and reduce the number of commands to be sent from the ground stations (thus reducing the operational workload). Ultimately, these advancements in autonomous station and formation keeping are needed to ensure spacecraft operators can focus on the mission and not on tasks such as orbit maintenance, formation integrity, and other mundane tasks.

## Conclusion

Since the end of the twentieth century, the US has examined the disaggregation of space resources in response to new emerging counterspace threats but has yet to act as evidenced by the continued development of monolithic satellite architectures. The concept of spacecraft simplicity provides a way to realize the shift to disaggregated architectures because it utilizes multiple less capable satellites to fulfill the role historically taken by exquisite high-value, flagship space systems. The idea of a multiple satellite swarm enhances the combat effectiveness and ability to attribute hostile action, both of which is assessed to deter a potential adversary from conducting counterspace operations against existing space-based resources. Finally, satellites that supplant the notion of complicated resiliency schemes in favor of a "strength-by-numbers" approach reduces their technical complexity (i.e., cheaper to produce) and makes them lighter, smaller in mass, and reduced in form factor (i.e., easier to launch on a responsive scale and more reliable). All of these factors point together to form an effective argument against today's idea of spacecraft resiliency toward tomorrow's idea of how spacecraft resiliency methodologies should evolve. ✪

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