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Survivability Analysis of a Small Satellite Constellation

Ensign Edward Hanlon
Naval Postgraduate School, eahanlon@nps.edu

ABSTRACT

Spacecraft are an integral arm of the United States (US) military, and provide, among other things, a substantial force multiplier. US forces today rely on spacecraft to provide everything from weather predictions to weapons guidance. It is a reliance largely exclusive to the US. While many other countries have military spacecraft, the US Department of Defense is the single largest satellite operator in the world. China, Russia and the US have all pursued the development of anti-satellite weapons. Russia has launched several (non-impacting) tests, while both China and the US have recently demonstrated the ability to destroy a target spacecraft. Spacecraft are fragile; built to the minimum strength necessary to survive launch forces. Once on-orbit, spacecraft are easily identifiable by ground-based observers, making them vulnerable to attack. A single weapons launch against a spacecraft would be sufficient to destroy it. There has been a continual push to increase spacecraft survivability and decrease replacement time. The rise of the "SmallSat" form factor has offered hope to accomplish this goal. With modern miniaturized electronics, a constellation of small satellites can provide the same capability as a $300M high-value large spacecraft. One element of that constellation would cost approximately $1M, with a total constellation cost of $36M. The SmallSats could also be launched with smaller rockets, reducing launch costs to $50M. These constellations would be more challenging and costly to destroy, while providing similar capability as the assets they replace. This paper will assess the survivability of a hypothetical SmallSat constellation intended to conduct intelligence, surveillance, and reconnaissance (ISR) missions. It will explore the current threats to satellite operations and the SmallSat's susceptibility and vulnerability to them. Finally, it will provide recommendations as to how to reduce both factors.

INTRODUCTION

The first "space war" commenced in Iraq in 1991 when the United States (US) demonstrated how advanced space capabilities could be a tremendous force multiplier. Space resources proved to be invaluable assets: from surveillance satellites that provided intelligence on terrain and troop movements; to communication satellites that were "the single most important factor that enabled us to build the command, control and communication network;" to meteorological satellites that provided high-fidelity weather predictions for tactical planning; to navigation satellites that were "the biggest combat multiplier on the battlefield."[1] Since 1991, space-based capability and their military and civilian importance has only grown.

This dependence creates an interesting vulnerability. In July 2000, the Xinhua news agency observed that "For countries that could never win a war by using the method of tanks and planes, attacking the U.S. space system may be an irresistible and most tempting choice..."[2]

Secreted hundreds or thousands of miles overhead, each spacecraft is the multi-year work and investment of hundreds of engineers and hundreds of millions of dollars. Unlike ground vehicles, they cannot be replaced in a tactical timescale. There is no stockpile of spacecraft waiting to be activated, and damaged spacecraft cannot be shipped back home for repair and redeployment. The assets on-orbit or on the way to the pad right now are the assets that are available for the foreseeable future; as yet there is no way to scale production.

Even if the spacecraft were available and ready for launch, there is no tactical way to put them in orbit. It takes months to build a launch vehicle, and even with those on hand, the most reliable rockets are delayed an average of ten days. For comparison, the ground portion of Desert Storm lasted three days.

There has been a continual push to increase spacecraft survivability and decrease replacement time. The rise of the "SmallSat" form factor has offered hope to this goal. Perhaps the multi-million dollar high-value large spacecraft can be replaced by constellations of smaller, cheaper and more swiftly replaceable spacecraft.

This paper will assess the survivability of a hypothetical SmallSat constellation intended to conduct intelligence, surveillance, and reconnaissance (ISR) missions. It will explore the current threats to satellite operations, and the SmallSat's susceptibility and vulnerability to them. Finally, it will provide recommendations as to how to reduce both of these factors.

The paper is organized as follows. The first section describes a hypothetical system and mission which lays the foundation for subsequent analysis. The next section provides an overview of the threats that system will face, followed by a discussion of the system's vulnerability and susceptibility respectively. The vulnerability and susceptibility are then analyzed to find opportunities for improvement. The paper concludes with a recommendation for further action.

HYPOTHETICAL MISSION

A hypothetical representative mission was designed based on current proposed SmallSat missions for the purpose of conducting survivability analysis. Generally speaking, the most common SmallSat constellation mission is to provide persistent access around the world. This capability could be used to provide anything from maritime domain awareness to signals intelligence. The sample constellation is assumed to provide military relevant information to the user, thus making it a target for adversaries.

There were several parametric requirements applied to constrain the research problem. In this study, the following capabilities and design decisions were assumed.

1. *Form Factor*: The spacecraft is assumed to be a 12U CubeSat. The 12U form factor was selected for compatibility with future SmallSat dedicated launch systems currently in development which are intended to provide a rapid "launch on need" capability.
2. *Operations*: The spacecraft is assumed to be able to generate imagery in all lighting and weather conditions. The spacecraft is also assumed to operate as efficiently in eclipse as it does in sunlight.
3. *Construction*: Based on other CubeSat projects, the spacecraft is assumed to cost $5M and take less than one year to construct. Launch costs are assumed to be $1M, in accordance with the predicted cost of dedicated launchers.
4. *Orbit*: It is assumed that the spacecraft will receive a preferential or dedicated launch that will allow it to operate in a designated orbit.

Additional performance requirements for the system are as follows.

1. *Coverage*: Given the expeditionary nature of modern armed forces, worldwide coverage is required.
2. *Revisit*: It is assumed that there is a maximum age requirement for information. For the conceptualization, to be tactically relevant force positioning information must be less than 90 minutes old. Ideally, more frequent information is desired.

The hypothetical system is made up of a constellation of 36 identical spacecraft. Each spacecraft is a 10 cm x 20 cm x 33 cm rectangle, with two large (1 m) deployable antennae. An additional set of deployable solar panels is mounted on the back of the spacecraft. Viewed from the end, the spacecraft looks like an "I" with the base being slightly larger than the top. An image and cross-section of the spacecraft is shown in Exhibit 1.

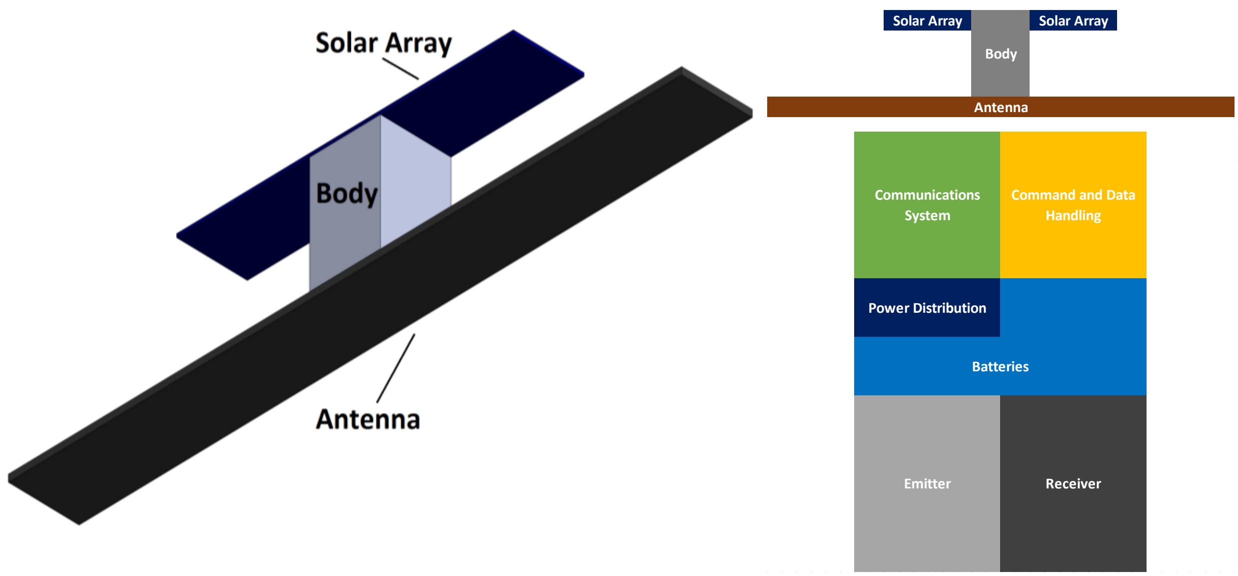

Exhibit 1: Labeled rendering of sample spacecraft.

The Command and Data Handling System (C+DH) contains all of the onboard processing, both for spacecraft bus operations and for payload operations. This system is based on a radiation hardened processor and uses SpaceWire for crosslink. Components are selected to allow for a minimum of five years of operation in the LEO radiation environment.

Each spacecraft has two radios. The first is a direct line of sight S-band radio for large data transfers. This requires the spacecraft to be pointed at a ground station to downlink information. The spacecraft also has a radio intended to communicate with the Global Star satellite network for persistent coverage. As the spacecraft operates below the global star constellation, this radio must be kept “sky” facing.

The spacecraft has an attitude determination and control system (ADCS) which is intended to keep the payload and communication antennae pointed at Earth. It will operate with a combination of reaction wheels (for quick pointing maneuver) and magnetic hysteresis (to “dump” off energy in the reaction wheels).

The spacecraft is solar powered. It has two 15W solar arrays and requires both for full functionality. The power is converted using maximum power point trackers in the Electrical Power System (EPS) and used to charge a set of lithium-ion batteries. Power is distributed around the spacecraft on a 12V, 5V, and 3.3V bus.

The spacecraft has no propulsion system. Should it need to maneuver in its orbit and maintain relative separation, the spacecraft alters the coefficient of aerodynamic drag by changing which face is pointed in the direction of travel.

The hypothetical payload is a synthetic aperture radar (SAR) Emitter and a SAR Receiver. This is paired with the 2 m deployable antenna. The antenna deploys using spring forces and is not retractable. The SAR system achieves 1 m resolution from LEO.

THREAT ANALYSIS

According to the Federation of American Scientists, there are five main categories of threat for spacecraft:[2]

1. *Deception*: Target reports incorrect information.
2. *Disruption*: Target's capability temporarily degraded.
3. *Denial*: Target's capability temporarily disabled.
4. *Degradation*: Target's capability degraded irreparably.
5. *Destruction*: Complete loss of target spacecraft.

Deception, disruption, and denial are all “ground resolvable,” in that there are corrective actions that can be taken on the ground to restore satellite capability, whether that is applying corrective adjustments to the satellite or launching ground strikes against the disabling equipment. The focus of this paper is on the two “non-recoverable” threats: degradation and destruction.

There are three main types of weapons that can accomplish these permanent threats.

1. *Indiscriminate*: Kill vehicle disables spacecraft without intercepting.
2. *Directed*: Kill vehicle intercepts the target spacecraft.
3. *Co-orbitals*: Kill vehicle enters the same orbit as the target spacecraft.

Each of these attack methods is explained in detail in the following subsections.

Indiscriminate

Indiscriminate incidents occur when non-directed weapons attack spacecraft without coming in close proximity to them. They disable spacecraft by creating a hostile area of space that the spacecraft will eventually fly through. These are the most straightforward attacks to accomplish, as they do not require any detailed knowledge of the target spacecraft's orbit or even location. A limitation of non-directed interceptors is that they are indiscriminate and will also affect any satellite passing through that orbital altitude.[3] A mission profile of a typical indiscriminate attack is shown in Exhibit 2.

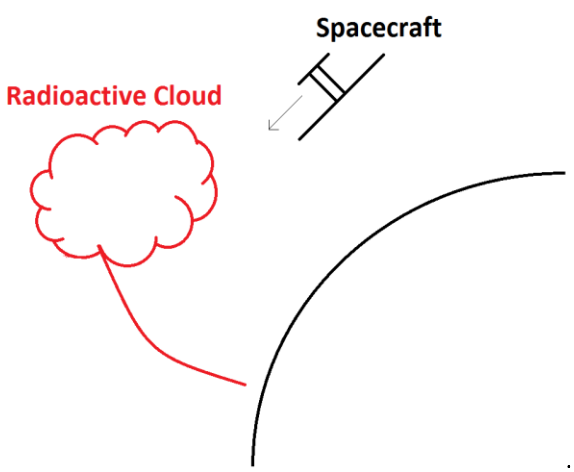

Exhibit 2: Mission profile of indiscriminate attack.

Primarily, research efforts have focused on indiscriminate attacks promulgated through the use of nuclear weapons. As designed, a nuclear warhead would be launched to the approximate altitude of the spacecraft, where it would detonate.

There are two main effects of a high altitude nuclear detonation (NUDET). The most immediate is the electromagnetic pulse effect (EMP). The rapid release of gamma radiation creates a wave of electrons that will severely damage unprotected equipment. An EMP will only affect objects within line of sight of the blast. The best defense against an EMP is faraday-cage like shielding, which most if not all spacecraft already have. The high altitude EMP effects are more pronounced for ground objects and are not a primary failure mode for spacecraft.

The secondary (and most lethal) effect of a high-altitude NUDET is enhanced trapped radiation from delayed nuclear effects.[3] A NUDET in low earth orbit can dramatically change the radiation environment and would affect spacecraft for months. The increased radiation in this area would degrade spacecraft computers and sensors, in most cases permanently.

Similar indiscriminate degradation could be accomplished with non-nuclear means. Kessler syndrome suggests the possibility of collisions or debris on-orbit will create cascade effect in which each additional collision generates a larger debris field that increases the likelihood of the next. Eventually, there will be so many objects in low earth orbit that it is rendered inaccessible. Triggering this effect would merely be a matter of creating a large enough debris field, either by destroying an on-orbit asset or by launching sufficient numbers of midsize space debris.

Indiscriminate weapons are well suited for use by countries that do not have robust space programs and can be used as an “equalizer” by denying access to space for all forces. They are not particularly complicated, as they do not require accurate guidance or even orbital flight. Any space-faring country would be capable of creating such a weapon. Exhibit 3 shows a list of countries with space capabilities, the number of spacecraft each country currently has (the smaller the number, the more likely the country is to use an indiscriminate weapon), and whether or not the country possesses nuclear warheads. There are several countries that have minimal space footprints that would benefit from indiscriminate space denial.

Country	Satellites	Nuclear
United States	1551	Y
Russia	1497	Y
China	251	Y
Japan	168	N
India	84	Y
France	69	Y
Israel	17	N
North Korea	8	Y
Iran	1	N

Exhibit 3: List of space-faring countries capable of indiscriminate attacks.[4]

Directed

Directed weapons are weapons capable of targeting and neutralizing individual spacecraft. Directed weapons typically fall into three categories: kinetic impactors, proximity weapons, and directed energy weapons. A mission profile of a typical directed attack is shown in Exhibit 4.

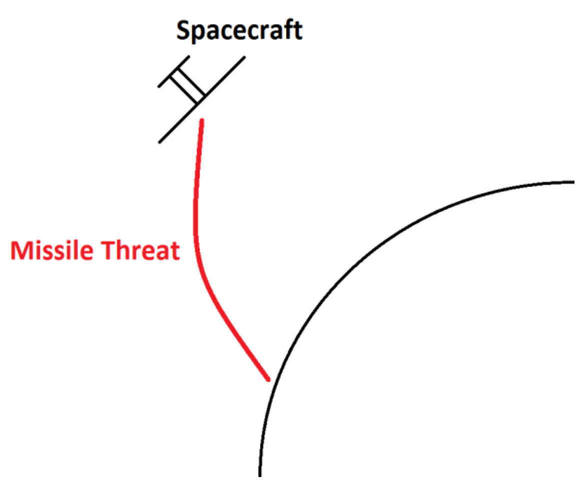

Exhibit 4: Mission profile of direct attack.

Kinetic impactors are ground-launched weapons that use high-velocity impacts to degrade or destroy a spacecraft by damaging critical components. They can have dedicated impact “warheads” or just use the launch vehicle itself as the impactor. Kinetic impactors are launched on trajectories that cause them to intercept the target spacecraft. They can be launched at any point the spacecraft is overhead/expected to be overhead but require a very high-resolution understanding of spacecraft position and orbit. Kinetic impactors also create large debris fields, which can be a hazard to other spacecraft.

Fused warheads are launched using very similar mechanisms as kinetic impactors, but instead of directly impacting the target spacecraft with a solid mass, they carry an explosive warhead. The missile is designed to explode in proximity to the targeted spacecraft and degrade/destroy critical components with small high-velocity particles generated by the explosion. While the kill-mechanism is similar to the kinetic impactors, fused warheads have lower accuracy requirements as their explosion covers a larger area. Like kinetic impactors, fused warheads also create large debris fields which can be a hazard to other spacecraft.

Directed energy weapons use energy beams traveling at the speed of light to damage or destroy spacecraft. This category includes lasers and high-powered microwaves. Due to the high intercept speed, directed energy weapons have minimal targeting requirements – they need to know where the spacecraft is in relation to whatever resolution their beam-spread is, but they do not necessarily need to know the spacecraft's orbit. This makes them easier to field, especially against a spacecraft capable of maneuvering. Directed energy weapons are also scalable. They can create issues ranging from temporary blindness to complete system failure. They generally do not create significant debris fields when used. They are less effective in varying atmospheric conditions, and their capability is not fully refined.

There are several examples of tested/fielded directed anti-satellite (ASat) weapons. The primary countries that have tested or proposed such systems are the US, Russia, and China.

United States

The US has developed several directed ASat systems:[5] There are four main public programs, several of which have been demonstrated operationally.

- *ALMV*: The “Air-Launched Miniature Vehicle” was a two-stage missile intended to be air-launched by an F-15. It had a kinetic warhead on board. It successfully destroyed a satellite in October 1985. The debris from this incident persisted until 2002.
- *KE-ASAT:* An army program that was created in the late 1980s which was never tested on a satellite. It also used a kinetic impactor.
- *MIRCAL*: A directed energy weapon utilizing a high energy laser, last tested in 1997.
- *SM-3 Missile*: An SM-3 missile from a Ticonderoga Class Guided Missile Cruiser successfully destroyed a satellite in low earth orbit in 2008.

Russia

According to recent reports, Russia has developed a successful direct ascent ASat weapon, the PL-19 Nudol. As of December 2016, the system had been tested five times. Each time it was launched from a base in central Russia.[6]

China

China has conducted several high-profile ASat demonstrations. Most of these demonstrations have used the Dong Neng Missile. The Dong Neng program is a high-earth orbit interceptor that destroys spacecraft with a kinetic impactor. Its development was based on the results of the 2007 Chinese ASat missile test.[7]

Co-orbital

Co-orbital space weapons enter the same orbit as their target before engaging. Co-orbital spacecraft can range from basic spacecraft packed with explosives that rendezvous with the target, to advanced space robots capable of conducting intelligence investigations on targets prior to disabling/destroying them. These spacecraft take a variety of forms and have equally varied kill modes. A possible mission profile of a typical directed attack is shown in Exhibit 5.

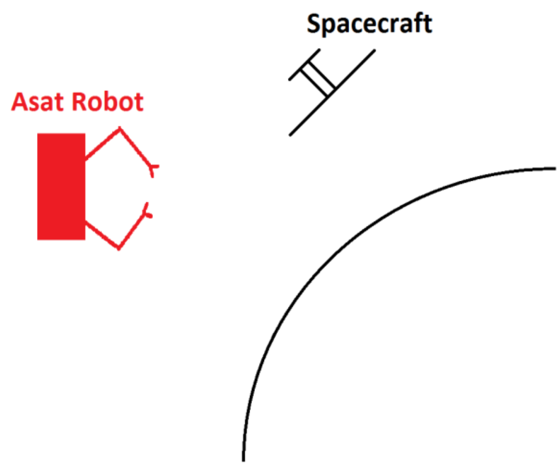

Exhibit 5: Mission profile of co-orbital attack.

A co-orbital kinetic kill is very similar to the directed weapon systems, except instead of just intercepting the target at a point of orbit, the kill vehicle must join the same orbit. From an accuracy standpoint, this is easier to achieve, but it severely limits launch opportunities and dramatically increases engagement time.

A co-orbital weapon can rendezvous with and conduct proximity operations on a target. It can selectively disable or degrade individual components, and, depending on the target, may be able to do it undetected. Such degradation could be as minor as repositioning an antenna or even applying a layer of dust to an optic. Effective targeted kill modes can emulate natural satellite failure, making the attribution of damage to hostile action challenging.

There are several highly public efforts around the world to produce “satellite servicers” intended to repair and refurbish on-orbit vehicles.[8] While many of these spacecraft may have additional applications, this paper focuses on those rumored to be dedicated ASat vehicles.

Russia

Russia has developed the Kosmos-2499, a yet unnamed on-orbit proximity operations spacecraft launched in December 2013. That spacecraft is rumored to be an anti-satellite robot. It conducted close-in rendezvous operations with its launch vehicle to demonstrate intercept capability.[9]

China

China has also launched similar capability, the Aolong-1. It is a SmallSat officially designed to perform space debris mitigation missions by using a small robotic arm to grapple satellites and launch them back towards earth.[10] Assuming the SmallSat is capable of approaching non-cooperative targets, this mission could clearly be dual-purpose, as the capability to deorbit spacecraft is a weaponizable technology.

SYSTEM VULNERABILITY ASSESSMENT

The system vulnerability assessment examines the likelihood a spacecraft will be damaged/destroyed given that it is impacted by one of the kill vehicles. The first step is to locate which systems are vulnerable. All of the systems contained in the body of the spacecraft are mission critical. These are reproduced below:

- *Command and Data Handling System*: Without the C+DH system, the spacecraft components will have no way of aggregating or sending data.
- *Communications System*: While both communication systems are not required, one is necessary to maintain the ability to send data back to Earth. Given their close proximity, it is possible to count this as one system.
- *Attitude Determination and Control System*: The ADCS system is needed to provide pointing capability for the payload, and to maintain a communications link.
- *Electrical Power System*: The EPS is needed to power all of the above systems.

The following components are “less” necessary for basic spacecraft operations and may able to sustain some damage without crippling functionality. The degradation of these systems will affect operations, but may not prevent the spacecraft from completing its mission.

- *Frame*: The spacecraft frame is designed to support the spacecraft components during launch. Given launch loads are several orders of magnitude over orbital loads, much of the frame is non-essential after launch.
- *Scanning Antenna*: Minor damage to the antenna (such as small holes) would diminish the antenna gain but probably not cause a complete loss of operations
- *Solar Array*: The solar array would also be somewhat damage tolerant. While not redundant, the left and right solar array operate independently, and the loss of one could be compensated for by reducing operations based on available power.

Each weapon has its own damage mechanism, and thus the spacecraft's vulnerability analysis is unique to each weapon type. Analysis conducted on indiscriminate, directed and co-orbital attacks is explained in detail in the following subsections and summarized in Exhibit 6.

Indiscriminate

SmallSat are typically designed for low earth orbit (LEO). They are optimized for the relatively benign radiation environment found in LEO. They typically utilize commercial processors originally designed for terrestrial applications and rely on short mission life and low overall radiation exposure to avoid issues. Should a high-altitude NUDET occur, the assumption of short mission life and low overall radiation exposure would be negated, and the spacecraft would encounter much higher radiation levels. These higher radiation levels would put many electronic components at risk. There is insufficient radiation testing on current commercial off the shelf (COTS) processors to produce a full estimate as to the impact. Furthermore, there is significant variability in predicting what the increased radiation environment would be. Assuming the worst case in each scenario, and recognizing that minor radiation areas such as the South Atlantic Anomaly routinely disable spacecraft, it is safest to assume an indiscriminate nuclear attack would disable most SmallSat spacecraft within a month. It is also reasonable to assume that the spacecraft would continue operating for several days after a NUDET, perhaps minimizing the tactical impact of such an attack.

If attacked by a non-nuclear indiscriminate weapon, operating in LEO is an advantage. The constellation operates in the lower portion of LEO, where atmospheric drag is particularly high. As such, there is a smaller number of satellites and a smaller debris field than would be found at higher altitudes. This makes reaching the critical number of objects to generate a cascading Kessler effect very challenging and suggests that the constellation is not particularly vulnerable to such an attack.

Directed

Directed attack on spacecraft are likely to succeed. The average spacecraft frame is made out of 1.5 mm thick aluminum and is incapable of protecting the spacecraft against kinetic attack. Additional shielding would add weight, and sufficient shielding to protect against objects closing at orbital speeds would be cost prohibitive. The best mitigation to such attacks would be redundancy, but the small size of the spacecraft makes it challenging, if not impossible, to achieve sufficient component separation to provide protection.

Co-orbital

Like kinetic impacts, a co-orbital attack on the spacecraft is very likely to succeed should the vehicle be able to rendezvous. Once the spacecraft have rendezvoused, there are no defensive systems on the target spacecraft that would be capable of deterring attack, nor is there sufficient space to provide such apparatus.

Component	**Indiscriminate**	**Directed**	**Co-Orbital**
Comms	Y	Y	Y
ADCS	Y	Y	Y
EPS	Y	Y	Y
Frame	N	Y	Y
Antenna	N	Y	Y
Solar	Y	Y	Y

Exhibit 6: Component vulnerability to indiscriminate attack.

SYSTEM SUSCEPTIBILITY ASSESSMENT

The system susceptibility assessment examines the likelihood the spacecraft will be targeted and hit by one of the weapons systems. The susceptibility is unique to each type of weapon system.

Indiscriminate

A summary of the events leading to the successful irradiation of the target spacecraft is shown in Exhibit 7. It starts with the decision to attack spacecraft and ends when the spacecraft enters the radioactive plume.

#	**Essential Event**
1	Spacecraft flies into radiation
2	Warhead operates correctly
3	Missile guidance system functions
4	Missile motor functions
5	Enemy determines optimal altitude for deployment
6	Enemy willing to deny space to all users – including potential allies
7	Enemy determines space assets are in use

Exhibit 7: Indiscriminate essential events and elements.

There are few points in this sequence that are dependent on the spacecraft design. The indiscriminate attack is spacecraft agnostic and does not depend on tracking or even locating the spacecraft to produce harm. The best point of mitigation is perhaps through external influence, or some other form of deterrence, at point six. Spacecraft maneuvering would assist; however, the quick substantial orbital changes needed to escape a large plume are not possible with current technology. Ultimately, susceptibility to indiscriminate attacks is currently unmitigable at spacecraft level.

Directed

A summary of the events leading to a successful impact with the target spacecraft is shown in Exhibit 8. It starts with the decision to attack spacecraft and ends when the warhead impacts the target.

#	Essential Event
1	Impactor or fragments hit spacecraft
2	Warhead intercepts satellite
3	Missile guided to location the spacecraft is expected to arrive
4	Missile motor functions
5	Enemy determines the spacecraft orbit and the optimal location for interception
6	Spacecraft detected by a ground station
7	Enemy determines space assets are in use

Exhibit 8: Directed essential events and elements.

There are several locations in this sequence that are dependent on the spacecraft. The enemy must be able to detect the spacecraft, which is dependent on its optical or radar cross-section. They must be able to predict its orbit and be located in an area that the spacecraft will pass overhead to fire at it. Finally, the enemy must be able to provide terminal guidance to their warhead.

Co-orbital

A summary of the events leading to a successful disabling of the target spacecraft is shown in Exhibit 9. It starts with the decision to attack spacecraft and ends when the orbiter creates the damage.

#	Essential Event
1	Orbiter disables spacecraft
2	Orbiter intercepts satellite
3	Enemy asset enters orbit with spacecraft
4	Enemy launches/retasks orbiting asset
5	Enemy determines the spacecraft orbit and the optimal location for co-orbital interception
6	Spacecraft detected by a ground station
7	Enemy determines that space assets are in use

Exhibit 9: Co-orbital essential events and elements.

Like the directed approach, there are several locations in this sequence that are dependent on the spacecraft. The enemy must be able to detect the spacecraft, which is dependent on its optical or radar cross-section. They must be able to predict its orbit, and they must be able to maneuver their on-orbit spacecraft to intercept. Once in the same orbit, it must be able to detect, track and rendezvous with the target.

These attacks are all driven by spacecraft features. For the attacks surveyed, three key spacecraft susceptibility drivers were identified: 1) the spacecraft's detectability, 2) its orbit design, and 3) its ability to detect and deter aggression.

The largest spacecraft derived feature is its detectability. This governs when an engagement is possible. There are three main ways spacecraft are detected on-orbit:

- *Electro-optics*: Optical examination that looks for reflected sunlight from spacecraft features.
- *Radar*: Ground and space-based radar scanning for spacecraft.
- *Infrared*: A warm spacecraft will stand out against the ambient temperature of space.

The spacecraft's observability with electro-optics is dependent on reflective material and surface area. The surface area of the spacecraft is based on payload requirements and is unchangeable, while the reflective area of the spacecraft is normally dictated by the thermal design.

As with electro-optics, the spacecraft's radar cross section (RCS) is very much dependent on its attached equipment, and its large antenna provides a substantial radar return. An approximation of the radar cross-section is shown in Exhibit 10. The significant return from the antenna and the solar array is easily apparent, as is the smaller return from the sides of the spacecraft.

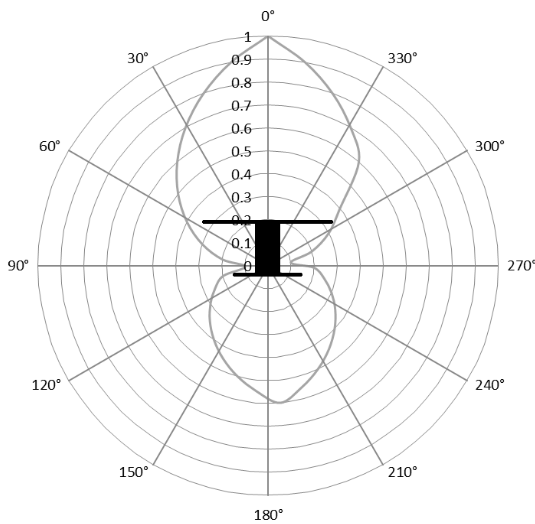

Exhibit 10: Approximation of the Spacecraft's Radar Cross Section

Infrared is dependent on both attached equipment and the temperature of its exterior surfaces. The ambient temperature in space is -454°F.[11] The spacecraft's temperature must be maintained between 32°F and 150 °F. Given this large temperature delta, infrared (IR) views would show a more significant heat signature from the center body section, where the majority of the electrical equipment is located.

The spacecraft's orbit further influences the spacecraft's detectability. The spacecraft's orbital design dictates when it will pass over ground sites that can track and potentially destroy it. In order to accomplish its mission of imaging the entire world, the spacecraft must, at some point, pass over the entire Earth.

Traditionally, there are two main factors driving orbit design: cost and access. The fewer planes the spacecraft are in, the fewer launches that are required, the lower the overall cost. Conversely, the more planes the spacecraft is in, the better the access times (time between passes), and the better the constellation performance.

The spacecraft is initially designed to be launched to an orbit with four orbital planes with nine spacecraft per plane. This costs an estimated $40M in launch fees and provides an image of any location on Earth approximately every 72 minutes.

In this orbit, if the enemy were to fire at every spacecraft that passed overhead, the constellation would stop meeting the 90-minute pass key performance parameter in a little under two hours. The entire constellation of 36 spacecraft would be destroyed in 11.2 hours.

The greatest enabler for any attack, however, is not based on technical capability. Satellites are vulnerable targets due to the difficulty distinguishing hostile damage from innocuous faults or natural phenomena. This difficulty attributing damage encourages the use of anti-satellite weapons, as it is conceivable the attack may be unnoticed. There is no situational awareness of the spacecraft's surroundings or exterior state, beyond basic spacecraft health information. Larger spacecraft can employ dedicated diagnostic vehicles, small robots embedded on launch that can spider around the exterior of the spacecraft and detect and possibly repair damage.[8] Small spacecraft do not have surplus mass and cannot afford such systems. Instead, they are left blind to threats and ground controllers must spend countless hours trying to attribute failure based on scant telemetry data.

SURVIVABILITY ASSESSMENT

In its current form, the hypothetical constellation of spacecraft is very susceptible and extremely vulnerable. From a strict survivability standpoint, at a per unit level there is no survivability – any form of ASat system will be able to destroy this spacecraft. Potential improvements were explored; improvements were focused on the two key factors contributing to spacecraft susceptibility.

Detectability

The first step is to reduce the spacecraft's detectability. If the spacecraft cannot be detected, it cannot be attacked. In its current form, the spacecraft constantly points its antenna at the ground, regardless of threat picture or tactical necessity. In order to gather data, the satellite must have its antenna deployed and Earth-facing, but there are, perhaps, high threat areas where the imagery gained may not be worth the risk. If this is the case, RCS can be minimized a number of ways.

If the spacecraft is flying over a hostile area and is not required to image it, the spacecraft can pivot such that it's thin body, rather than its large antenna, is oriented downward. This is shown in Exhibit 11. Adopting this flight profile reduces the cross section from 0.42 m^2 to 0.0693 m^2, an 83% reduction assuming the location of the radar site is known and the spacecraft can be dynamically positioned to track it. Depending on the enemy capability, this may or may not be sufficient to affect targeting, but regardless a decrease in cross section will decrease susceptibility.

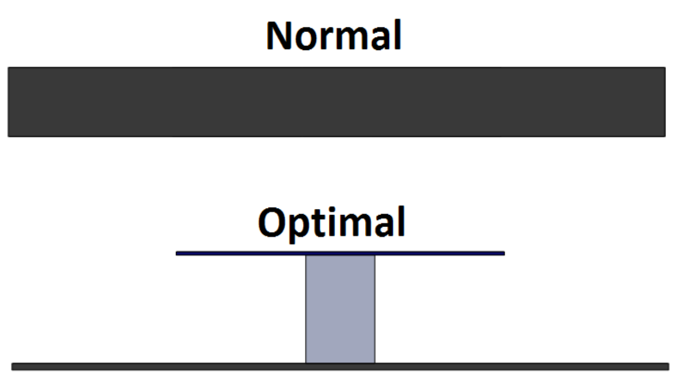

Exhibit 11: Comparison of flight profiles.

The antenna and solar array must have been folded for launch; by changing their deployment mechanism to allow for retraction, a similar performance increase to the orientation could be achieved. This change is superior to the orientation shift, as it allows the spacecraft to be viewed from any angle and still maintain a small cross section. Depending on the deployment mechanism, this could be a costly design change and introduces additional risk as the mechanism could break in the folded position. However, in high-risk scenarios, this could be sufficient to dissuade the enemy from attacking.

Deterrence

The flaw in the spacecraft's original design is it has no way of monitoring its external surfaces. This allows enemy spacecraft to approach without possible detection, and to create damage that may not be attributable to hostile action. Without the ability to attribute damage, there is no way to respond. If the damage was attributable, then a proportionate response (perhaps ground-based) could be mounted. This would deter future attacks.

A relatively simple way to add this attribution system is to add body cameras to the spacecraft. Four cameras, mounted on each face of the spacecraft, could form a 360-degree awareness zone and detect incoming hostile actions. An example of this system is shown in Exhibit 12.

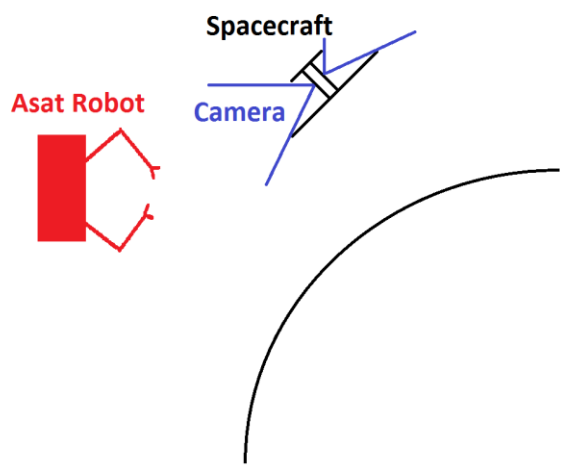

Exhibit 12: Mission profile of co-orbit attack with camera defense.

Orbit

The constellation was designed to be the cheapest option that still met the 90-minute revisit time requirement. An STK model was developed to examine the effect of adding additional orbital planes. The “Walker” constellation design was selected to evenly distribute the spacecraft across a set number of orbital planes. Three types of constellation were tested: four orbital planes, six orbital planes, and nine orbital planes. The threat was located near the equator. The revisit time representing constellation performance was determined based on the threat location. The spacecraft were assumed to be destroyed immediately after their footprint touched the threat location. Three factors were considered: 1) time to destroy each satellite; 2) time to diminish capability; and 3) number of spacecraft required to meet the requirement.

The time to destroy each spacecraft is shown in Exhibit 13. The figure demonstrates the relative uniformity of speed of destruction. Given this uniformity, the conclusion drawn is constellation design does not impact spacecraft attrition.

The time to diminish capacity is shown in Exhibit 14, which plots system revisit time compared to the total engagement time. The four-plane configuration lost mission capability after just 55 minutes, while the six-plane configuration retained required capability for 144 minutes. The nine-plane configuration provided the best capability and survived for 173 minutes. Past the point of loss of capability, the six- and nine-plane configurations provided similar performance, while the four-plane configuration was consistently worse.

The number of spacecraft that can be destroyed while the constellation still meets the requirement is represented in Exhibit 15. The four-plane configuration can tolerate the loss of five spacecraft, while the six- and nine-plane configurations can tolerate the loss of eight spacecraft.

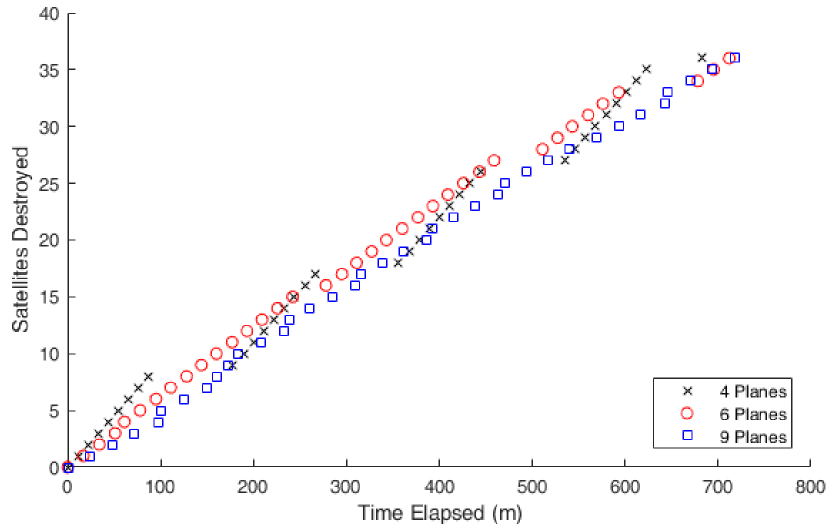

Exhibit 13: Graph of spacecraft destroyed vs. time.

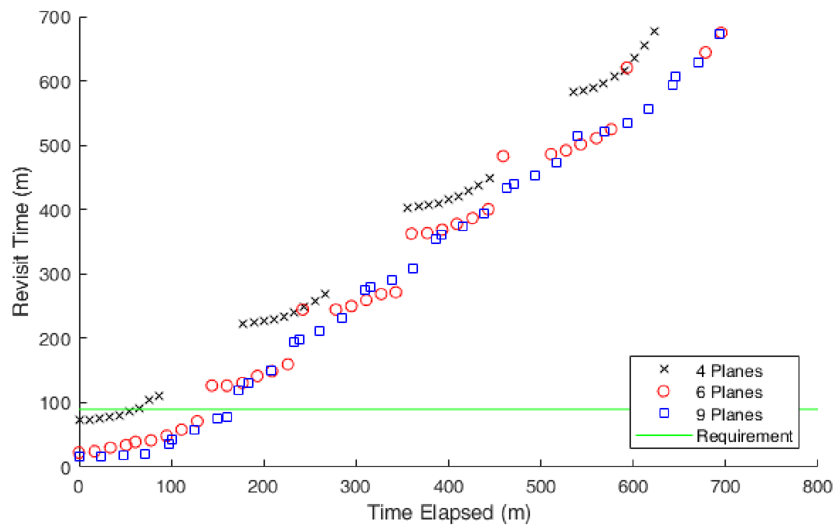

Exhibit 14: Graph of system revisit time vs. engagement time.

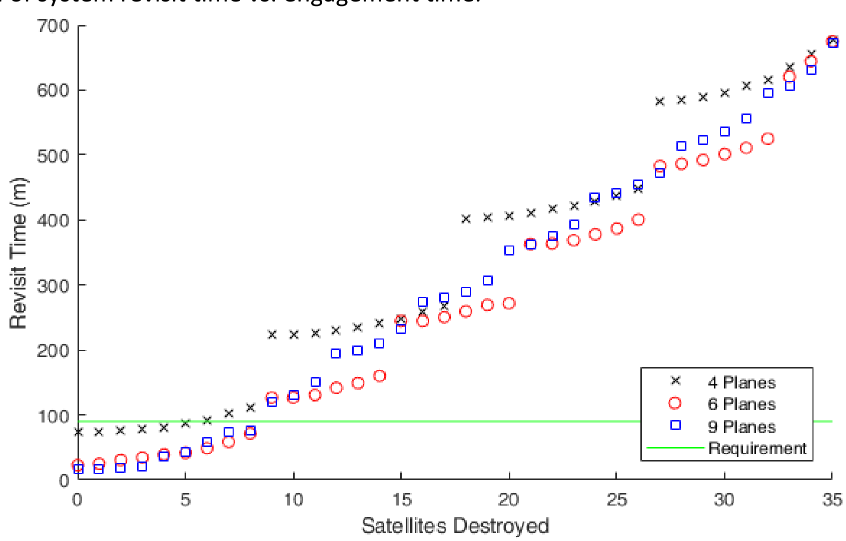

Exhibit 15: Graph of revisit time vs. satellites destroyed.

Overall, it is clear that the selected orbital pattern (four-planes, nine spacecraft per plane) is less survivable than the alternatives. While there is an additional expense as the number of orbital planes increases, the tolerance to spacecraft loss also increases. Exhibit 16 highlights the cost and effect of varying orbital planes. “Initial” represents the initial revisit time, and “degraded” is the 90-minute revisit time parameter. The cost estimate is based on a launch cost of $10M per launch. This launch cost is a conservative estimate-based analysis of the developing small launch market.[12]

Planes	**Cost ($M)**	**Initial (m)**	**S.C.**	**Time**
4	40	73	5	55
6	60	23	8	144
9	90	17	8	173

Exhibit 16: Summary of STK orbital analysis result.

Using six orbital planes instead of four would cost an extra $20M and increases the number of spacecraft attritable by three while increasing the survival time by 260%. Assuming the constellation comes under attack, this has the potential to save $30M in replacement charges and dramatically improves the ability to use the constellation as it is attacked.

Spending an additional $30M (50% above the six-plane configuration) to use nine orbital planes provides no improvement to the number of attritable spacecraft and a 20% improvement in survival time. There are no cost savings and only a minor improvement in survival time given the considerable capital expense.

There is additional benefit in multiple planes in defense against attack from co-orbit weapons. Orbital phase changes (moving between spacecraft in the same orbital plane) require very little propellant and can be accomplished relatively quickly. Inclination changes (traveling between planes) consume large amounts of propellant. It is unlikely that the co-orbit attack vehicle contains sufficient propellant to execute multiple plane changes – the more planes utilized, the more co-orbit attackers necessary.

CONCLUSION

Even with these improvements, the constellation is very vulnerable. However, the spacecraft does have a substantial advantage in that it is very easy to restore capability. By using SmallSats instead of large spacecraft, the cost of launch for one spacecraft is at approximately $1M. Furthermore, the time from start of launch contract to launch is much reduced, as there are more SmallSat launch providers available. The spacecraft itself is much less expensive and easier to build than a large spacecraft, which also maximizes its replaceability. Finally, the constellation is very flexible to different orbits, which means that a replacement spacecraft does not need to go to the same location the previous spacecraft occupied. This reduces launch constraints and increases the chances it can fly as a secondary payload.

Given the relatively low cost, in both time and dollars, of replacement, and assuming a per intercept cost of $10M, the cost of one SM-3 missile, the economics of attacking the constellation are questionable.

The recommended constellation consists of spacecraft deployed in six orbit planes, programmed with radar cross section reduction maneuvers in the event of anticipated hostile action, with a system of situational awareness cameras.

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