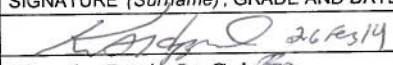


**STAFF SUMMARY SHEET**

	TO	ACTION	SIGNATURE (Surname), GRADE AND DATE		TO	ACTION	SIGNATURE (Surname), GRADE AND DATE
1	DFx	sig	 Timothy Pettit, Lt Col <i>for</i>	6			
2	DFER	approve	<i>SOLTY, AD-22, 27 Feb 14</i>	7			
3	DFx	action	Jason Belvill, Capt, Originator	8			
4				9			
5				10			

SURNAME OF ACTION OFFICER AND GRADE	SYMBOL	PHONE	TYPIST'S INITIALS	SUSPENSE DATE
JASON BELVILL, 0-3	USAFA/DFM	719-333-2315	JEB	20140228

SUBJECT	DATE
Clearance for Material for Public Release USAFA-DF-PA- <i>132</i>	20140226

**SUMMARY**

1. PURPOSE. To provide security and policy review on the document at Tab 1 prior to release to the public.

2. BACKGROUND.

Authors: Stephaney Sarri, Jason Douglas, Patrick Lobo, Chris Keranen

Title: Orbital Debris Written Submission for NSIC

Circle one: Abstract    Tech Report    Journal Article    Speech    Paper    Presentation    Poster  
 Thesis/Dissertation    Book    Other: 5 page written submission to NSIC

Check all that apply (For Communications Purposes):

- CRADA (Cooperative Research and Development Agreement) exists
- Photo/ Video Opportunities     STEM-outreach Related     New Invention/ Discovery/ Patent

Description:

Written submission for NSIC, 25 April

Release Information:

This is a mandatory submission requirement to apply and compete at the National Security Innovations Competition.

Recommended Distribution Statement: Distribution A: approved for public release, distribution unlimited

3. DISCUSSION.

Written submission attached.

4. RECOMMENDATION. Sign Coord block above indicating document is suitable for public release. Suitability is based solely on the document being unclassified, not jeopardizing DoD interest, and accurately portraying official policy.

  
 JASON BELVILL  
 Instructor of Management

Attachment:

- 1. Written Submission



DEPARTMENT OF THE AIR FORCE  
THE DEPARTMENT OF MANAGEMENT  
UNITED STATES AIR FORCE ACADEMY

## ORBITAL DEBRIS

### Introduction

Pollution is an issue that isn't often taken seriously; it is chronic and continually worsening. The reason for this is that pollution does not have an immediate effect on the environment or society. It takes time to see depletion of the ozone, bacterial contamination, or decreased air quality. Due to the lack of immediacy, society assumes that the issue doesn't warrant immediate attention. Unfortunately, these issues will rise in importance and become urgent, time critical, or in need of a solution. A type of pollution that we don't often consider is space pollution; specifically, orbital debris. There are millions of unwanted objects in space, many of which come from decommissioned spacecraft or broken parts. The debris travels in constant orbit at various altitudes and constantly poses the threat of impact with active spacecraft; which could potentially generate millions of dollars' worth of structural damage, compromise life, destroy communication systems, etc.

Therefore, Lieutenant Colonel Joslyn of United States Air Force Academy's Department of Aeronautics, in addition to many students and researchers, contributed to the development and testing of the analysis and experimentation of the StreamSat concept and product. StreamSat is a revolutionary spacecraft that utilizes the propulsion of clustered liquid droplets directed at debris that will cause the unwanted debris to lose momentum, deorbit, and burn up in the atmosphere. StreamSat uses mounted solar panels and rechargeable batteries to enable self-sufficiency and reduce maintenance needs. StreamSat also requires very limited communication in order to carry out its functions.

This product is pulling customers to the business by targeting potential decision makers and consumers. In regards to space, the target consumers are essentially any entity with assets in space to include countries with active spacecraft, wireless network providers, television companies, weather companies, etc. This technology can be used to eliminate immediate hazards posed to "high-value operational spacecraft" by shortening the orbital life of debris. This product has the potential of targeting dozens of objects while utilizing a single orbit, and hundreds more objects with controlled orbital transfer capability, thus saving entities involved in space millions of dollars on a yearly basis.

Although this product will be available to individual consumers, the main customers are expected to be government space agencies since they hold the majority of the realty in space, maintain some of the most critical operational spacecraft, and monitor the launch portal to space. In addition, government space agencies are generally the most fiscally capable groups concerned with the effects of space debris on their assets. The market for space debris remediation is small and not yet fully developed. There are currently no companies that have made it to the finish line and solidified their product. However, this is a quickly emerging market. Like StreamSat, the competitors in this market of space debris remediation are not in the production stage yet. However, there are no other spacecraft that achieve the same mission in such an effective, efficient, and economical manner.

### Technical Analysis

#### SPACECRAFT SUBSYSTEMS (section will be expanded pending cooperative agreement)

##### Attitude Control System

In order to refine the known position of other spacecraft, and project droplets accurately, StreamSat will need a relatively high degree of pointing control and knowledge. Placing droplets on a  $1\text{m}^2$  target over a distance of 20 km requires a pointing accuracy of 10.3 arc seconds. Existing NanoSat reaction wheel control systems have demonstrated this accuracy in-flight. Electro spray thrusters demonstrated at the Air Force Academy, and elsewhere, can also produce the impulse bit needed to maintain such pointing accuracy.

Analysis shows that optical and infrared sensors that will fit within a 3U CubeSat envelope can detect large objects at a range of over 50km. The IR optics system studied for this project is an uncooled micro bolometer array. The goal of the IR sensor analyzed is not to find other spacecraft in a static image but to detect spacecraft

motion against a relatively unchanging background. Optical systems, studied for StreamSat, would focus on a predetermined field of view at a distance where the object is expected to come into range and then refine the known position of the object in two dimensions. An additional optical observation at closer range could be used to refine the objects position in the third dimension.

### Communications required for Stage I: In-flight Testing

A hypothetical StreamSat pair with a leader-follower separation distance of 10 m and an inclination of 82° was analyzed using Satellite Toolkit (STK) to determine the frequency of contacts with the USAFA ground station. The classical orbital elements for this hypothetical orbit are shown in the Table 1. Over the course of a month, the hypothetical StreamSat contacted the USAFA Astro Lab ground station 154 times with an average duration of 40.5 minutes. This amount of contact time is sufficient to perform necessary data transfer to carry out the initial phase of testing to refine StreamSat pointing algorithms over the course of 12 weeks.

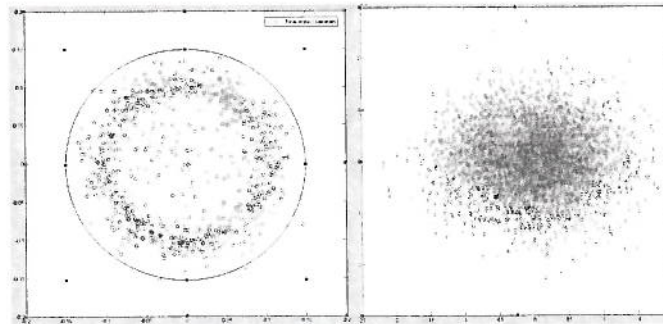
**Table 1: Classical Orbital Elements of Notional StreamSat**

Semi-major Axis	7078.14 km
Eccentricity	0
Inclination	82°
Right Ascension of the Ascending Node	0°
Argument of Perigee	0°

StreamSat will transmit sensor information, droplet impact data, and satellite health telemetry to one or more ground stations. Additional ground stations on other continents will be useful to more rapidly acquire results of experiments. Additional ground stations are particularly useful during the commissioning and intercept demonstration phase of the mission. Prior to an intercept it will be necessary to provide StreamSat with the latest ground-based radar update of the location of the object that is being targeted. Providing the most updated target position information will probably require the use of a ground station outside of North America, but for a very short period of time and very infrequently.

### Droplet Stream Production

Silicon oils and ionic liquids have very low vapor pressure and are liquid at the temperatures expected during droplet transit. The ionic liquid BMIM-BF<sub>4</sub> has a wide range of temperatures at which it remains a liquid and is chemically stable, even when exposed to high energy particles and other forms of radiation. This fluid has undergone testing at USAFA showing it will not evaporate in vacuum until reaching at least 300°C. USAFA testing has also shown BMIM-BF<sub>4</sub> to be an effective Electrospray thruster propellant. There is no limit to the size or speed of droplets however; to date they have only been produced in vacuum between 0.25mm and 3.5mm with speeds of up to 100m/s. At this speed the travel time to intercept a target with a cross range distance of 20km is over 3 minutes. It will also be necessary to account for the interactions between individual droplets in the droplet stream. If the droplets are fired too closely to one another, Coulomb forces between droplets will repel each other and decrease the precision of impacts on the target.



**Figure 1: Single stream without adequate spacing (left) and with adequate spacing (right)**

Once charge can be accurately predicted, Coulomb forces between droplets can be mitigated with sufficient spacing between droplets. Analysis shows that free-flying droplets will not freeze during typical LEO eclipse periods. Liquid droplets are less likely to damage a spacecraft than solid droplets are since they flatten and distribute their force of momentum over a larger area than solid droplets. Liquid droplets that impact spacecraft at speeds greater than 1200m/s are expected to vaporize during the impact. In the event that droplets miss the targeted object they are predicted to evaporate over the course of a few years (depending on absorptivity changes) and pose little threat to operational spacecraft. The ballistic coefficient of free-flying droplets is much lower than typical spacecraft and atmospheric drag will de-orbit droplets more quickly than larger objects. Research indicates that droplets can be darkened to increase solar heating and raise droplet temperatures above their evaporation point and shorten their expected life to less than one month.

### Optional Optical Sensor

Analysis shows that visible and infrared sensors that will fit within a 3U CubeSat envelope can detect large objects at a range of over 50km. Optical systems, studied for StreamSat, would focus on a predetermined field of view at a distance where the object is expected to come into range and then refine the known position of the object in two dimensions. An additional optical observation at closer range could be used to refine the objects position in the third dimension. More analysis is needed to determine the necessity of in-space sensors for determining object location. The position of many objects is believed to be known with sufficient accuracy to permit droplet stream intercept with low probability of missing the target.

### Implementation Readiness Analysis

This is a quickly emerging market. Some companies have projected that their product will be ready for launch and in-space tested as early as 2015. Essentially, the company that emerges at the forefront of this market will enter the market in a timely manner, be comparatively more affordable, and more efficient. StreamSat has not yet tested the product in space, but has a fully developed product, currently under revision to improve accuracy for droplet projection. StreamSat utilizes outside engineering manufacturing companies to develop the product, and in house engineering for final design specifications. Facilities at the United States Air Force Academy are currently being used to test this product in vacuum chambers to simulate the space environment as best as possible. Prospectively, this product has moderately high potential, as seen in the below assessment table.

Industry Attractiveness Assessment		
Factor	Value	Potential
Number of Competitors	Few	Moderate
Age of Industry	Young	High
Growth Rate of Industry	Moderate	Moderate
Average Net Income of Firms	N/A	N/A
Degree of Industry Concentration	Fragmented	High
Stage of Industry Life Cycle	Growth Phase	Moderate
Importance of product/service	High	High
Extent to which trends are moving in favor of industry	Medium	Moderate
Number of new products emerging in the industry	Medium	Moderate

Long-term Prospects	Strong	High
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### Target Market Attractiveness

In the United States, the Department of Defense (DoD) is charged with tracking objects in space. The effectiveness of StreamSat would be significantly enhanced by timely updates of high-priority object orbit information from the DoD's network of tracking sensors. Routine control of StreamSat can be performed by the U.S. Air Force Academy (USAFA) ground station or a similarly equipped ground station. During actual debris intercepts, other ground stations may be needed to provide StreamSat with the most updated object orbit information prior to the intercept. Design, development, assembly, integration and most testing could be conducted at the Air Force Academy; however, USAFA has limited experience with CubeSats and has a full schedule for development of FalconSAT 6 and 8. Therefore, we would seek international relations to assist in this process. To begin development of StreamSat in a timely manner, collaboration with another company, university, or organization is required. As our target market is government and space agencies, please review the Target Market Attractiveness Assessment below, which ultimately suggests that this product has moderate potential; however, once the market fully emerges we believe that many of the "moderate" categories will become "high potential" categories.

Target Market Attractiveness Assessment		
Factor	Value	Potential
Number of competitors in target market	Few	Moderate
Growth rate of firms in the target market	N/A	N/A
Average net income for firms in target market	N/A	N/A
Methods for generating revenue	Clear	High
Ability to create "barriers to entry" for competitors	May or may not be able to create	Moderate
Degree to which customers feel satisfied by the current offerings	Dissatisfied	High
Potential to employ low cost guerilla and/or buzz marketing techniques	Moderate	Moderate
Excitement surrounding new product/service offerings	Moderate	Moderate

### Market Timeliness

Development is estimated to take 36-42 months using the same development schedule currently used for other spacecraft produced by USAFA. This schedule could be accelerated considerably with a management system that is not tied to a semester system where the workforce turns over every year. The spacecraft is expected to operate for 2-3 years before depleting its supply of ionic liquid. Once fluid is depleted, the StreamSat can still provide object tracking information to the space operations community (if so equipped). At the end of its operational lifetime the spacecraft will use a reserve of ionic liquid as propellant to expedite its own deorbit with on-board Electropray thrusters (if so equipped).

A successful StreamSat mission would pave the way for larger orbital debris remediation spacecraft that would significantly reduce the risk of space operations. This risk reduction can be realized at a cost that is less than the cost of just one of the many high-value spacecraft expected to be lost in the coming years, if high priority objects are not removed from orbit.

The profitability of space for communications, GPS, television, and other technological trends is another reason why the removal of space debris affects many government and private companies. NASA's Orbital Debris Program Office conducted a study of hazardous objects in orbit in terms of size and probabilities of collision. This study showed that the breakup of several of the 500 highest priority objects would lead to debris concentrations considered too hazardous for spacecraft to travel through or operate in low earth orbits. The debris would render the

area needed for companies to conduct operations useless. With the improvements in satellite costs and manufacturing, more satellites will inevitably be launched and add to the clutter that already exists. These NASA simulations indicate that even with planned end-of-mission (PMD) of 90% of future spacecraft, there will still be a large amount of growth in overall space debris. Five high priority objects must be removed to maintain current numbers of debris. Thus we can conclude that this is indeed a need project and the sooner it can be produced and on the market, the better. This conclusion is supported by the assessment below.

Market Timeliness Assessment		
Factor	Value	Potential
Buying mood of customers	Moderate	High
Momentum of the Market	Moderate	Moderate
Need for a new firm with your offering	High	High
Extent to which business and environmental trends are moving in favor of the target market	High	High
Recent or planned entrance of large firms	Large firms entering the market	Low

Overall, advances in electronics and launch technologies are leading to a new class of smaller, cheaper, and lower-flying satellites. If government and private space agencies wish to pursue capabilities to launch more satellites, they need to support this product. The first one or two companies to emerge with a successful product will come out on top of this market.

### Major Competitors

StreamSat has advantages in fuel conservation, operational cost, and safety because of the concept of using charged liquid droplets as the fuel source. A current disadvantage is that the precision of the droplet projection needs to be refined to be more accurate; however, even with low accuracy, meaning increased number of droplets to be deployed, the droplets are extremely inexpensive. Another disadvantage is the political barriers due to space laws and the perception of "blasting" other satellites to decommission them. Due to the complexity of the design, StreamSat stands above the competition with its current stage of development, mission requirements, and cost efficiency.

Competitor Analysis						
Factor	StreamSat	CleanSpace One	Phoenix Program	Terminator Tape	Sling-Sat	ORION
Fuel Conservation	Advantage	Disadvantage	Even	Advantage	Advantage	Advantage
Complexity	Even	Even	Disadvantage	Even	Disadvantage	Disadvantage
Cost (material worth)	Advantage	Disadvantage	Disadvantage	Even	Advantage	Advantage
Cost (operation)	Advantage	Disadvantage	Even	Advantage	Disadvantage	Advantage
Political Barriers	Disadvantage	Advantage	Advantage	Advantage	Disadvantage	Advantage
Safety	Advantage	Even	Even	Even	Even	Disadvantage
Feasibility	Even	Advantage	Advantage	Disadvantage	Disadvantage	Disadvantage

### Recommendations

The global satellite industry is currently a \$189.5 billion industry with a growth rate of 10% since 2001. The average satellite costs \$99 million with an average launch cost of \$51 million. Companies that utilize satellites in space spend millions to insure their satellites with the average coverage costing 8%-15% of the total cost of the satellite. Therefore, Phase I to bring the Orbital Debris Remediation project to market is on-ground research and

development. Lieutenant Colonel Joslyn received \$100,000 in grants from NASA and AFSOR to be utilized for ground research, testing, and development of StreamStat technology. Lt. Col. Joslyn has completed this phase of testing and has a patent pending on the StreamStat technology. Our competitors have only completed ground testing as well. Our competitors have a wide range of costs. CleanSpace One, has a cost of \$11 million to deorbit a similar piece of debris. The Japanese space tether costs anywhere from \$5 - \$10 million. The only alternative that comes close to the price range of the proposed system is the laser broom which is estimated to cost \$1 million but has not been proven as a feasible idea.

Phase II will be to undergo in-space research and development. The cost to build one orbital debris remediation satellite is estimated to be \$2 million. This estimation is due to \$1.3 million delegated to labor, \$500,000 to equipment, and \$100,000 to launch. With the satellite 50% accuracy StreamStat has enough liquid to deorbit 25 pieces of debris. Therefore, each piece of debris will only cost \$80,000 to deorbit using this system in a span of 2-3 years.

Phase III, is to have an operational satellite. There are two avenues available to successfully complete this phase. We estimate that this will require \$2 million in capital. One of the avenues we could take to fund this phase is to target NASA, AFOSR, and the Department of Defense. Due to the current fiscal limitations in the U.S. government, it would be in our best interest to reach out to international government investors as well. Currently, Lt Col Joslyn is in contact with the space programs of Brazil and Chile who have expressed interest in a joint venture using this technology. Not only would this help financially, but it would also improve the legal standing of this endeavor. Unless the government decides to fund the program, we will pursue the second avenue available to use. This is a commercial application for this satellite. The target market for this satellite would be satellite insurance companies. We have targeted this market as a successful avenue because records indicate that in 2008 the annual average of satellite insurance premiums was \$20 million. The customers of the insurance companies would benefit from having a system that could prevent a collision causing satellites to be put out of commission indefinitely. Therefore these customers would bear the cost burden of the service our product would provide in space, therefore increasing the profitability of the insurance companies.