

Innovative and Cost Effective Remediation of Orbital Debris

TEAM MEMBERS: Christopher S. Keranen, Patrick A. Lobo, Jason A. Douglas, Stephaney N. Saari

Team Advisor: Lt Col. Thomas B. Joslyn (PhD)

United States Air Force Academy

Introduction

More than a million objects, large enough to threaten operational spacecraft, are believed to reside in low Earth orbit (LEO) and this value is expected to increase significantly in the next decades.¹ The resulting hazard to operational spacecraft could render certain LEO altitudes unusable, particularly above 600 km where atmospheric drag is ineffective for removing orbital debris. Certain objects, such as spent rocket stages and large defunct satellites, have the potential to create thousands of smaller bodies through impacts with other objects, some too small to track.² The United States is particularly vulnerable to the loss of space assets because its economy is so dependent on international commerce and its military forces are so widely spread across the planet.

Researchers from the National Aeronautics and Space Administration (NASA) Orbital Debris Program Office prioritized the hazard posed by thousands of large objects in orbit as a function of object mass and collision probability. Their study concluded that the breakup of just three of the 500 highest priority objects could lead to collisions with other objects and debris population growth that would render certain altitudes too hazardous for satellite operations. NASA researchers also determined that the removal of just five high-priority objects from orbit each year would likely prevent anticipated growth in the LEO debris population.³

The growing population of orbital debris poses a real and growing threat of impact with active spacecraft that has caused and will increasingly cause millions of dollars in damage to operational spacecraft. In the coming decades debris impacts are also likely to degrade national security, adversely affect the economy, and threaten lives on manned spacecraft. Population growth in the next 50 years could be gradual or could be abrupt and could yield concentrations high enough to render parts of Low Earth Orbit (LEO) unusable, and transit through these regions hazardous. Of particular concern is the region of LEO between 600 and 1000 km where numerous large and fragile rocket bodies reside. At these altitudes, objects incur very little atmospheric drag and can remain in orbit for centuries. These rocket bodies are effectively ticking time bombs that, when hit, can create thousands of projectiles, each of which could potentially impact other rocket bodies.

In an effort to mitigate the threat posed by orbital debris, researchers at the United States Air Force Academy (USFA) have developed the StreamSat concept for removal of objects from LEO. StreamSat is an innovative spacecraft that projects small clouds of liquid droplets into the path of on-coming debris for impact and transfer of momentum. Droplets are vaporized during the impact and the object is slowed and its orbit perigee lowered, causing the object to incur more atmospheric drag and shortening its orbital life. A single StreamSat can remove dozens of objects from orbit with little or no maneuvering between intercepts. StreamSat technology also has the ability to alter the trajectory of an object nearing reentry to affect a controlled reentry that avoids impact with populated areas. Such a capability provides a method for avoiding damage or loss of life on the ground for which the nation that launched the object is liable.

Other proposed orbital debris remediation methods are designed to either go after multiple small objects or a single large object. Methods targeting large object require a separate intercepting spacecraft that must rendezvous and often attach to an uncontrolled object. Because uncontrolled objects often have rotational

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motion, grappling or attaching to them is very difficult, and has not been demonstrated. Moreover, since each hazardous object is in a different orbital plane, a single spacecraft cannot maneuver to de-orbit more than one object without consuming a significant amount of propellant. Another proposed method, called Orion, calls for a ground-based laser that can lower the orbits of objects through ablation of surface material that slows objects. A system like Orion is likely to face international opposition because it could be used offensively to disable spacecraft.⁴

Technical Analysis

Most of StreamSat's spacecraft subsystems do not require any technical advances. In particular, communication, data handling, thermal control, power generation, and spacecraft structure can be satisfied with off-the-shelf components. StreamSat will need a relatively high degree of pointing control and knowledge. Placing droplets on a 1m² target over a distance of 20 km requires a pointing accuracy of 10.3 arc seconds. Existing small satellite reaction wheel control systems have demonstrated this accuracy in-flight. Electrospray thrusters, demonstrated at the Air Force Academy and elsewhere, can also produce the impulse bit needed to maintain such pointing accuracy. Droplet streams can be produced from separate sites on the surface of a spacecraft in a manner that minimizes the amount of disturbance torque imparted to the spacecraft. Analysis of a very small spacecraft (3U CubeSat) producing dozens of high-speed streams simultaneously show that existing attitude control systems provide slow rate to compensate for a malfunctioning stream generator located as far from the spacecraft center of gravity as possible (15 cm). Larger spacecraft will respond more slowly to a disturbance torque of this nature and can also be controlled within 10.3 arc seconds with existing attitude control systems.

Essential to the prospect of intercepting objects with droplets is accurate projection through space. There are several sources of pointing error including the control fidelity of the projecting spacecraft, knowledge of targeted object position, environmental forces, and limitations in machining droplet stream generators. Researchers at the University of Southern California looked at the accuracy of droplet stream generators in the 1980s as part of a program called the Liquid Droplet Radiator (LDR).⁵ They demonstrated droplet dispersion of less than 1 micro radian for some generators and devised an instrument for measuring the dispersion accuracy of generators in a long vacuum chamber prior to flight in space.⁶ The ability to test the natural dispersion angle of droplet generators prior to flight allows for selection of flight hardware with demonstrated accuracy better than 1 micro radian. Spacecraft attitude control introduces more pointing accuracy error, but can be nearly two orders of magnitude better. Taken together, attitude control and droplet generator pointing error can be limited to less than one micro radian using existing technology and techniques.

During transit, external forces will alter the path of droplets and could cause the target to be missed unless models can accurately predict these forces and compensate for them. Forces acting on droplets include Coulomb forces, drag, solar radiation pressure, and Lorentz forces. Coulomb forces are directly proportional to the charge developed by droplets and exponentially proportional to the distance between droplets. A computer simulation showing droplet impact points is presented in Figure 1 that shows droplets with very little spacing that repel one another during transit and produce the impact pattern on the left. Droplets on the right were spaced more optimally and produced an impact pattern that fits within the small circle superimposed on the left image.

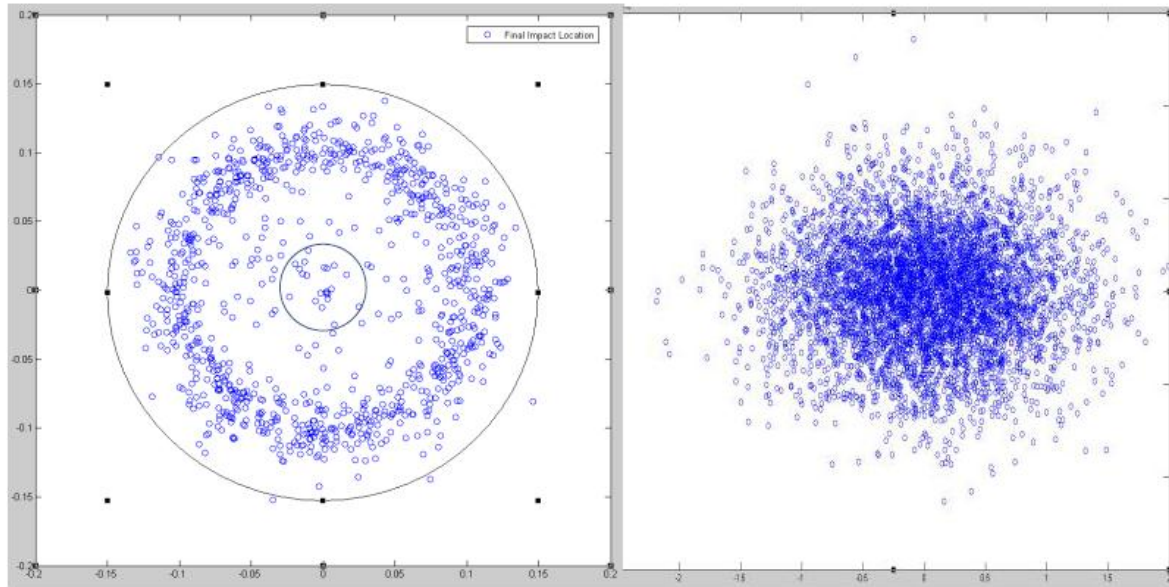


Figure 1. Impact patterns for droplets with close and more wide lateral spacing (showing effect of Coulomb charge repulsion during transit)

It is necessary for neighboring droplets to have known size so that the magnitude and effects of coulomb forces can be predicted and corrected for. If charge can be predicted accurately, clouds of droplet streams can be generated in a manner that optimizes mass density of the cloud at impact with the target. In addition to extremely low vapor pressure, the ionic liquid BMIM-BF₄ is proposed as the momentum transfer liquid because of its relatively high conductivity and low predicted charge. Computer modeling of droplet charging in space has been performed at the University of Colorado and partially validated by experiments in vacuum. This modeling indicates that space charging will not be a significant impediment to droplet stream transfer except during strong geomagnetic events happening during solar maximum, roughly every 10 years.⁷

If droplets miss the target, they will tend to drift apart due to the action of electrostatic forces between charged droplets. Thus, if a droplet cloud misses the intended target, the cloud will expand with time, reducing the mass density of the cloud to significantly lower levels. The effect of an unintended impact of a small number of widely spaced droplets with an operational spacecraft would be to impart a relatively insignificant amount of momentum to that spacecraft. Testing of high velocity impacts with Aluminum at the USAF Academy has shown no significant effects on this material and that the droplets are vaporized during the impact. Long term exposure of BMIM-BF₄ to Gamma radiation has been shown to cause an increase in absorptivity and is expected to eventually lead to evaporation due to solar heating.^{8,9} If radiation exposure does not lead to droplet evaporation fast enough, droplets can be doped with Carbon nanoparticles, that have been shown to increase absorptivity of ionic liquid.¹⁰

As a precursor to an operational StreamSat spacecraft, a demonstrator spacecraft called StreamDemoSat is proposed that will measure the effectiveness and determine the limitations of droplet streams to transfer momentum through a series of experiments. In these experiments, droplets will be transferred from the end of a boom, through an electric field, and to an impact location sensor on the spacecraft. Results will be used to refine algorithms that predict forces due to drag, solar radiation pressure, Earth's magnetic field, and Coulomb forces that will alter the path of transiting droplets. StreamDemoSat could also conduct technology demonstration experiments with Electrospray thrusters to evaluate their attitude and

orbit control capabilities. Electrospray thrusters can use BMIM-BF₄ as propellant and can use the same supply of liquid used for momentum transfer as fuel for the orbit and attitude control system.¹¹ StreamDemoSat could also include an optical or infrared sensor for use in detecting objects and refining their orbit more accurately than is possible with ground-based sensors alone.

The mission of StreamDemoSat could also be performed by a secondary payload on an operational spacecraft. Calculations and testing indicate that by refining droplet flight path predictive models, the risk of missing a one square meter circle of known position can be limited to less than a single miss per one million droplets transferred. It is possible to proceed directly to momentum transfer to on-coming objects in space without first conducting charging or drag measurement experiments in space. This is particularly true if the targeted object has the ability to detect small changes in its velocity and relay this information. However, if many droplets miss in such an experiment, it will be difficult to quantify the forces that caused droplets to miss the spacecraft. For this reason, a precursor mission, or experiments flown on other operational spacecraft is considered desirable before proceeding with production of operational StreamSats.

The effectiveness of StreamSat is significantly enhanced by timely updates of targeted object orbit information from ground based and space-based sensors. Routine control of StreamSat could be performed by the U.S. Air Force Academy (USAF) ground station or a similarly equipped ground station. During actual debris intercepts, other ground stations may be needed to provide StreamSat with timely object orbit information prior to the intercept. Such timely updates could be provided by ground stations in other nations or U.S. stations located around the world. For this reason international involvement in the program is desirable.

Market Analysis

Although StreamSat has potential commercial value as a method of protecting operational spacecraft, the main customers are expected to be domestic and foreign government agencies since they operate some of the most critical spacecraft and self-insure their spacecraft. In addition, government space agencies are generally the most concerned with preserving the LEO environment for future use. The market for space debris remediation is small and not yet fully developed. There are currently no companies that have a demonstrated method of remediation; however, the European Space Agency (ESA) has made a request for proposals from companies interested in performing remediation missions.¹² Several organizations have responded, however, none of their proposed remediation methods can remove hazardous large objects from orbit as efficiently as StreamSat.

Another possible source of funding to support the development of StreamSat is the commercial satellite insurance industry, which has a vested interest in preserving LEO for spacecraft operations and limiting the number of claims caused by debris impacts. Records indicate that in 2008 the annual average of satellite insurance premiums was \$20 million. A system that reduces future claims and costs only tens of millions of dollars is likely worth the investment to this industry that is dominated by a single insurance company, Lloyds of London. Insurance company investment is even more likely if it is made in tandem with government support or in tandem with telecommunications companies who stand to benefit from reduced replacement costs that would result from active remediation of orbital debris.

This is a quickly emerging market. At least one company, Clean Space One, claims that their system will be ready for launch and in-space tested as early as 2018.¹³ 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. The first company to enter the market also has more high priority objects to remove from orbit. Governments are most willing to pay for the removal of high priority large objects and each

StreamSat could remediate dozens of objects. Table 1 shows a self-assessment of timeliness for entry into the debris remediation market and the potential in 10 year. The collision of a U.S. Iridium spacecraft with a Russian spacecraft in 2009 at 800 km altitude has both increased awareness of the risk and increased the risk of collision to large objects below 800km. The Chinese anti-satellite test in 2007, also at 800km, also increased the risk of operating at this altitude. Debris from the 2009 collision forced astronauts to take shelter on the International Space Station during a close pass in 2012.¹⁴ These events make NASA's call to remediate large objects above 600km even more urgent and future collisions certain to build more support for active debris remediation.

Market Timeliness Assessment		
Factor	Currently	Potential in 10 yrs
Willingness of customers to pay for remediation	Moderate	High
Momentum of the market	Moderate	High
Need for a new debris remediation technology	High	High
Extent to which business and environmental trends increasing market demand	High	High

Table 1. Analysis of Timeliness of Entry into the Orbital Debris Market

In the United States, the Department of Defense (DoD) is charged with tracking objects in space and NASA is tasked with evaluating methods for ameliorating the orbital debris problem. The target market is government agencies that operate spacecraft. Table 2 shows a Target Market Attractiveness Assessment. This table suggests that this product has moderate potential at this time, but good potential for a limited number of competitors when the market fully emerges. Companies with the best methods of debris remediation will be well positioned to exploit funding opportunities when this occurs.

Target Market Attractiveness Assessment		
Factor	Currently	Potential in 10 yrs
Number of competitors in target market	4-5	Probably limited
Methods for generating revenue	Limited	Many
Ability to create "barriers to entry" for competitors	Quite Possible	Limited
Degree to which customers feel satisfied by the current technologies	Dissatisfied	Satisfied

Table 2. Market Attractiveness Assessment

Industry Analysis

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. 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. The need for orbital debris remediation was assessed and it was concluded that the need is both of interest to the industry at large and being pursued by companies and government agencies in several countries. This assessment is summarized in Table 3.

Industry Attractiveness Assessment		
Factor	Currently	Potential in 10 yrs
Number of Competitors	Few	Moderate
Growth Rate of Industry	Moderate	High
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

Table 3. Assessment of Industry Attractiveness

Overall, advances in electronics and launch technologies are leading to a new class of smaller, cheaper, and lower-flying satellites. This trend makes it less costly when a spacecraft suffers a collision with orbital debris, but it also increases the number of spacecraft in orbit and the likelihood of collisions with large hazardous objects. As more governments and companies become spacecraft operators, the demand for a solution to the growing problem of orbital debris remediation is likely to grow as well. The first one or two companies to emerge with a successful remediation system will have a significant advantage over competitors by being able to target the most hazardous objects in LEO for remediation. Such missions will likely garnish national and even international support because they benefit all humanity and preserve LEO for the use of future generations.

StreamSat has significant advantages over competitors because of its ability to target many objects with a single spacecraft. The relative simplicity of the design and lack of a need to rendezvous with objects give StreamSat significant advantages relative to competing designs. CleanSpace One proposes a small satellite that will rendezvous with a small object, physically capture the object, and then use rocket propellant to lower the orbit. The Phoenix Program proposes building a maintenance satellite that fixes “manfunctioning” satellites for further use. Sling-Sat proposes attaching to objects and then pushing them to lower altitudes, temporarily exposing them to more atmospheric drag and lowering the average altitude of the object’s orbit. All of these competitors, except Orion, require rendezvous and attachment to targeted objects which is costly in terms of propellant and complicated due to the difficulty of attaching to an uncontrolled object. Moreover, these competitors can only remove one object without substantial maneuvering. Table 4 shows the advantages of StreamSat relative to industry competitors in the remediation market.

Factor	StreamSat	CleanSpace One	Phoenix Program	Sling-Sat	Orion
Efficiency	Advantage	Disadvantage	Disadvantage	Disadvantage	Disadvantage
Complexity	Advantage	Disadvantage	Disadvantage	Disadvantage	Advantage
Production cost	Advantage	Disadvantage	Disadvantage	Advantage	Advantage
Launch & Ops cost	Advantage	Disadvantage	Disadvantage	Disadvantage	Advantage
Political Barriers	Possible Disadvantage	Advantage	Advantage	Advantage	Disadvantage
Hazards to satellites during remediation	Possible Disadvantage	Advantage	Advantage	Possible Disadvantage	Possible Disadvantage
Feasibility	Advantage	Disadvantage	Disadvantage	Disadvantage	Advantage

Table 4. Analysis of Competitors in Orbital Debris Remediation Market

A potential disadvantage to the StreamSat concept is international opposition to a system that could be used to “attack” foreign operational spacecraft. Analysis shows that StreamSat would not have the capability to destroy or even damage a spacecraft, but this may be difficult to prove on the world stage. Any system that can remove objects from orbit has the potential to be used to remove an operational spacecraft from orbit so any competing system would face similar political hurdles. Because of the potential for international opposition, it will probably be useful to gain the support of international partners to help quell concerns of use of the system to alter the orbits of operational spacecraft.

Recommendations

A successful Stream DemoSat mission would pave the way for deployment of StreamSat orbital debris remediation spacecraft that would significantly reduce the risk of future space operations. This risk reduction can be realized at a cost that is a fraction of the cost of just one of the many high-value spacecraft expected to be lost without orbital debris remediation. The need is relatively urgent as the

breakup of any of the hundreds of high-priority hazardous objects in LEO could lead to a chain reaction in which other objects are destroyed and an altitude band of LEO rendered permanently unusable. StreamSat would pioneer a profitable technology while preserving the space environment for future generations and reducing the cost of operating in space for everyone.

USAFA received an \$8,700 grant from NASA that was used for StreamSat technology development and testing. Funding is currently being sought for development of hardware for use in a demonstration mission, either as a stand-alone spacecraft, or as a payload on a host spacecraft. The cost to build a free-flying nanosatellite that could refine models of droplet charging and then demonstrate remediation of an object is estimated at \$2 million. This estimation includes \$1.3 million for equipment, \$700,000 for labor, but no launch costs. The cost to build a secondary payload to accomplish these objectives on a hosting spacecraft is estimated at \$1.5M. Due to current budget limitations in the U.S. government and the international nature of the StreamSat mission, it may prove useful to seek foreign government collaboration and support. Officials within the space programs of Brazil, Chile, and Singapore have expressed interest in collaborating in the development of this technology and visiting researchers from Singapore have already performed research related to the StreamSat program.

Design, development, assembly, integration and most testing could be conducted at the Air Force Academy which has already built and operated 5 spacecraft and is currently building 2 more. However, USAFA already has a full schedule for development of other spacecraft. To begin development of StreamSat in a timely manner, collaboration with another company, university, or organization is desired. Collaboration on StreamSat hardware has already occurred at the University of Colorado in Boulder and analysis work has been performed at the Colorado Springs campus. CU Boulder has experience with producing small satellites and currently operates one. StreamSat hardware development has also been carried out by Enventa Corp. of Boulder, CO.

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. A StreamSat spacecraft is expected to operate for 2-3 years before depleting its supply of ionic liquid. A StreamDemoSat spacecraft is expected to operate intermittently for many years to evaluate charging conditions under many different solar and geomagnetic conditions. Once fluid is depleted, the StreamSat can still provide object tracking information to the space operations community (if so equipped). It could also be used to perform some ancillary scientific or communications mission. 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 Electrospray thrusters or a drag enhancement device.

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