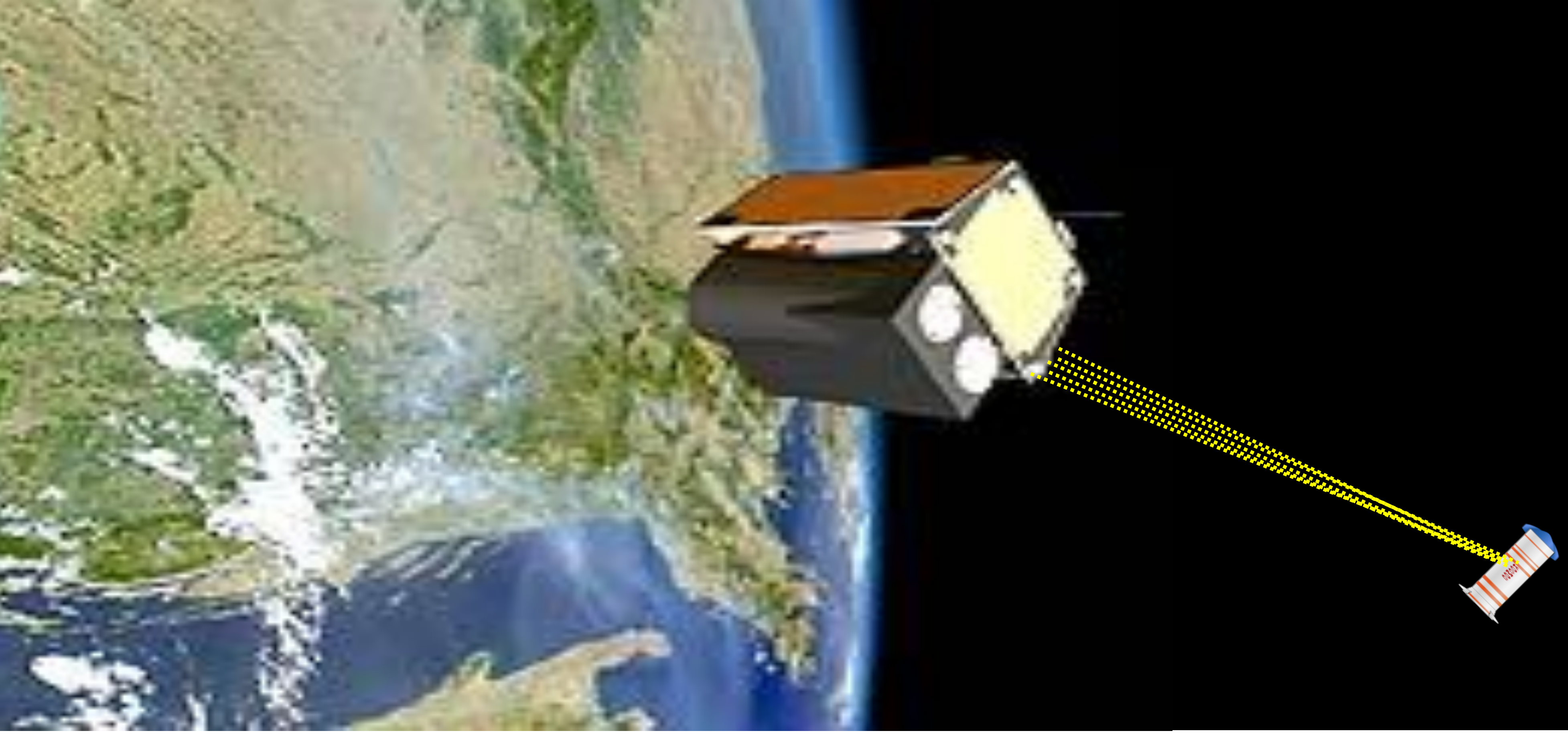

DebriSat: Orbital Debris Mitigation with Droplet Streams

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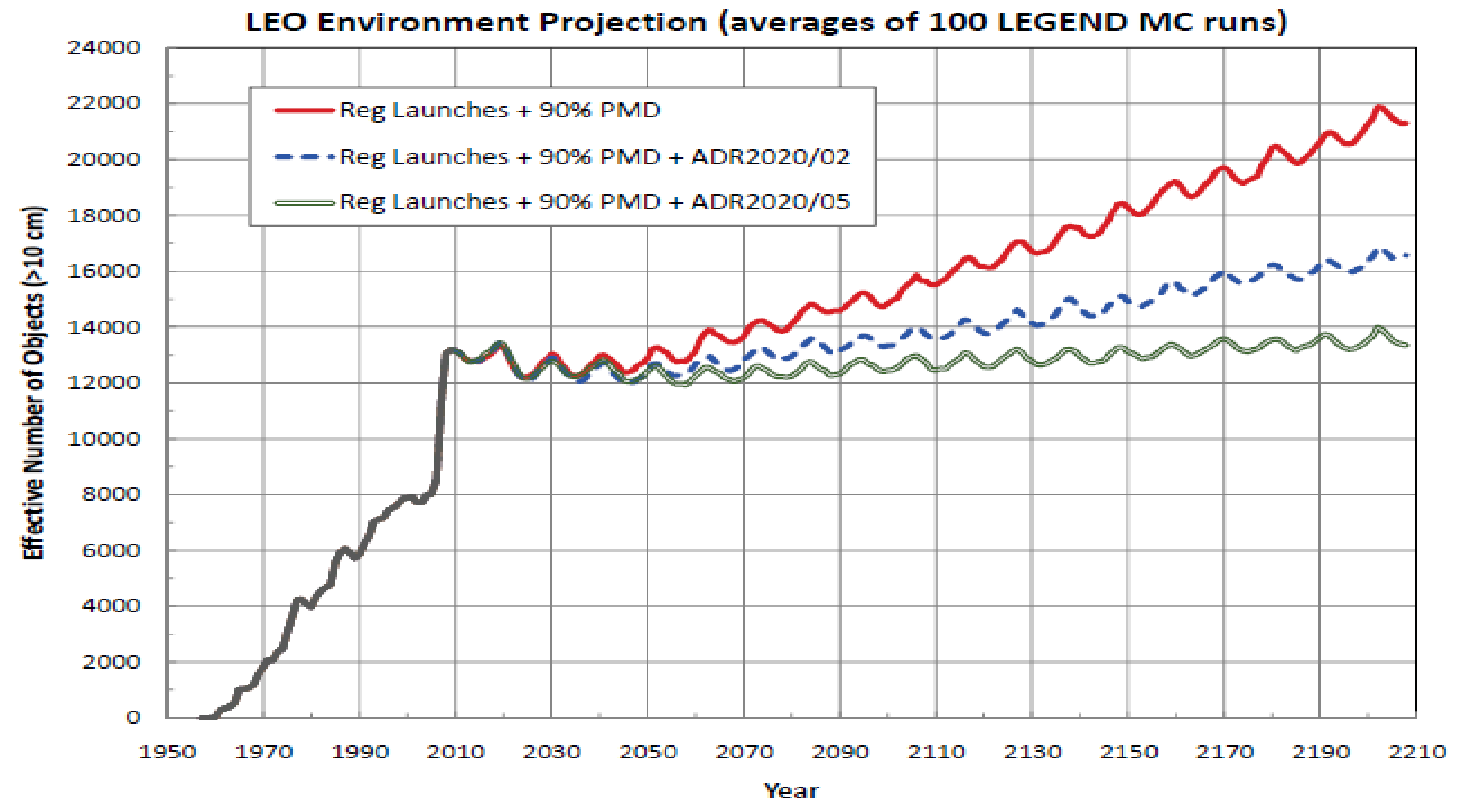
Overview:

Momentum is transferred via small liquid droplets from a small spacecraft to hazardous objects. The technique can be used to lower the altitude of high-priority derelict spacecraft and rocket bodies, expediting atmospheric de-orbit. Trajectory of objects that threaten operational spacecraft can also be altered to avoid collisions.

1. Introduction

The population of hazardous objects in low earth orbit is expected to increase exponentially in coming decades if active debris remediation efforts are not undertaken. The figure below shows NASA estimates of the orbital debris population with and without active debris removal (ADR). Removal of five objects per year starting in 2020 will help stabilize the population and make runaway population growth unlikely. A novel method of slowing objects and thereby reducing their orbital life is being studied at the United States Air Force Academy. This method consists of transferring thousands of small droplets into the path of an oncoming object. When droplets impact the object at relative speeds approaching 15 km/s the object's orbital velocity will decrease without breakup of the object. The momentum transfer will lower the object's altitude, hastening atmospheric reentry. Changing the object's orbit may also be performed to reduce the chances of impacting an operational spacecraft. In theory, liquid droplet streams can be transferred tens of kilometers with less than half a meter of dispersion. However, aiming streams requires very accurate modeling of atmospheric drag and droplet charging. More precise knowledge of object location than currently exists is needed to ensure successful momentum transfers without missing the intended object.

Small spacecraft operating in a leader-follower arrangement can pinpoint and then target a known hazardous object. The lead spacecraft would use an optical sensor to precisely locate the object with better than 1m accuracy and pass this information to the trailing spacecraft which then uses this knowledge to accurately aim droplets on an intercept trajectory. Before active intercepts of objects are attempted, in-space experiments involving transfer of droplets between two spacecraft operating in close proximity should be carried out to refine drag and charge prediction algorithms. Space plasma charging of droplets may limit how closely droplet streams can be to one another before Coulomb forces cause the streams to diverge from each other. Computer-based charge modeling indicates that charging of ionic liquids in space could limit the projection range of parallel streams significantly during high geomagnetic activity, particularly in polar regions and in high orbits like Geosynchronous.



Projection of estimated LEO debris population with commonly adopted mitigation measures and No active debris removal (red plot). Blue and green plots shows population with 2 or 5 objects removed per year starting in 2020. (Liou, *Adv. Space Res*, 2011)

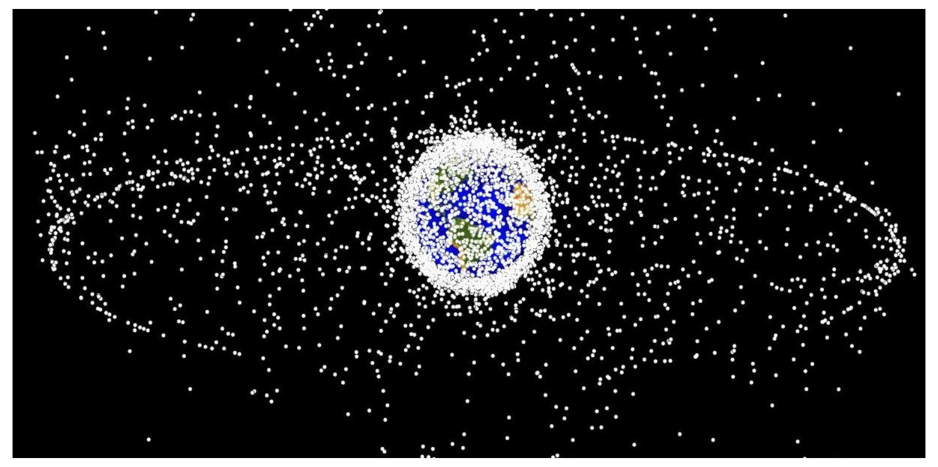
2. Applications of Droplet Stream Remediation

Protection of Operational Spacecraft

- Maneuvering and phasing of DebriSats in low earth elliptical orbits to allow high relative velocity intercept of hazardous objects that threaten operational spacecraft
- Slowing of objects to alter their trajectories and prevent impacts with high-value spacecraft like the International Space Station
- Removal of hazardous geosynchronous objects to preserve these valuable orbits

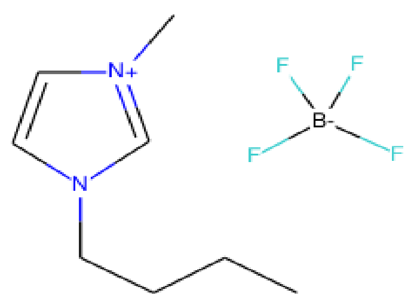
Large Scale De-orbiting of long-lived Orbital Debris

- Placement of DebriSats with hundreds of kilograms of liquid into orbits that can access large numbers of objects, particularly above 500km
- Alter the orbits of numerous objects to allow atmospheric degradation of their orbits and decrease the population of objects
- A single spacecraft pair weighting 1000kg can enable atmospheric de-orbit of more than 300 derelict spacecraft and rocket bodies that could otherwise breakup into to tens of thousands of hazardous objects

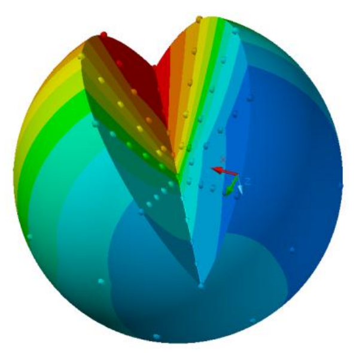


3. Technical Challenges and Analysis

There are several substances that are liquid at reasonable spacecraft temperatures, and have vapor pressures low enough to preclude significant evaporation in space. These include silicon oils such as Dow Corning 704 and 705 and several newly discovered ionic liquids. Ionic liquids are mixtures of cations and ions that do not bond chemically. Several ionic liquids exist that are good candidates for spacecraft momentum transfer; one in particular is BMIM-BF4. This fluid has a wide range of temperatures at which it remains a chemically stable liquid, even when exposed to high energy particles and other forms of radiation. It has undergone testing at USAFA and elsewhere that shows it to <u>also</u> be a very effective and efficient Electrospray thruster propellant.

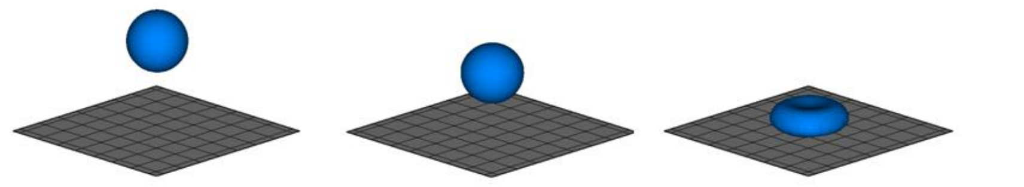


BMIM-BF4 Cation (left molecule) and Anion. Thermal Model of a Sunlit Droplet in Space (pictured at right)



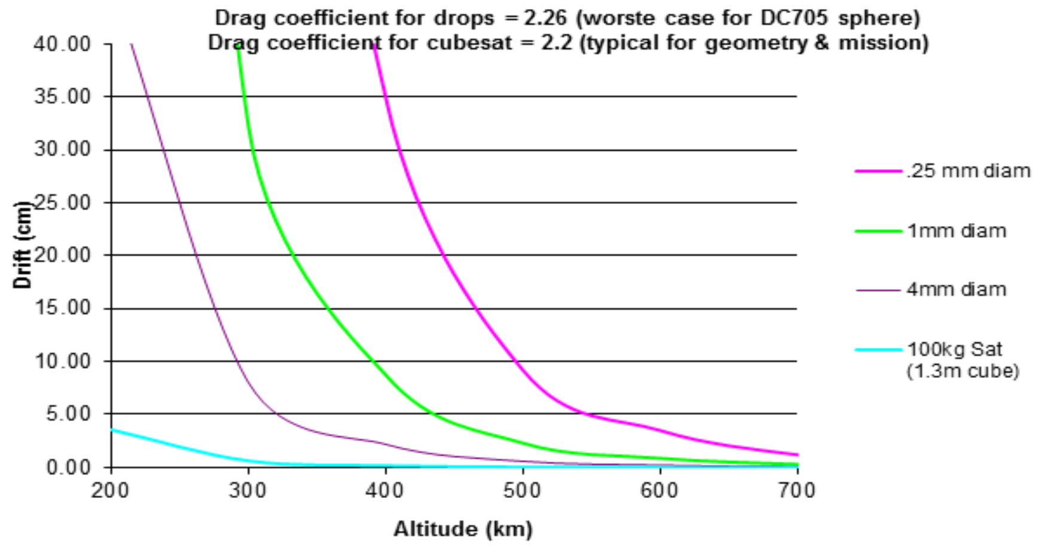
Testing shows that BMIM-BF4 will evaporate in vacuum at about 300°C which is in excess of the anticipated equilibrium temperature in space determined by heat transfer modeling using Thermal Desktop. There is no limit to the size or speed of droplets however; to date they have only been produced in vacuum between 0.25mm and 3.5mm with speeds of up to 100m/s. At this speed the travel time to intercept a target at a point 20km away is about 3 minutes.

In the event that droplets do not make contact with the targeted object, they are predicted to reach temperatures approaching 300°C and to evaporate over period of about 6 months. Research indicates that droplets can be darkened without altering their chemical makeup to increase solar heating and decrease their in-space lifetimes. Analysis shows that free droplets would not freeze during typical LEO eclipse periods making them unlikely to damage a spacecraft if a chance impact does occur. Liquid droplets that impact either intended or unintended targets are expected to distribute their energy over a much larger area than solid droplets would. Moreover, if relative velocities exceed 1500 m/s (as expected) droplets will heat sufficiently to vaporize the entire droplet, minimizing damage to spacecraft.



There is significant difference in drag forces between low and high solar activity levels, and accounting for this during actual orbit operations will be an important part of hitting an object over distances approaching 50km. The plot at right shows the relative effects of drag on droplets of different size and on a small spacecraft. These calculations assume elastic reflectance of neutral particles, and indicate that drag will slow the orbital velocity of droplets 2-3 times more than the orbital velocity of a 100kg spacecraft is slowed. The plot also reveals that these relative differences are increasingly negligible at higher altitudes. Predictions of drag should be validated by on-orbit testing and tandem, side-by-side flying spacecraft are particularly useful for quantifying this drag force since the drift from the intended path can be easily determined by fluid detection sensors covering the receiving face of each spacecraft.

Effect of Relative Drag Force Acting on Droplets and Spacecraft



4. Mission and Operations Concept

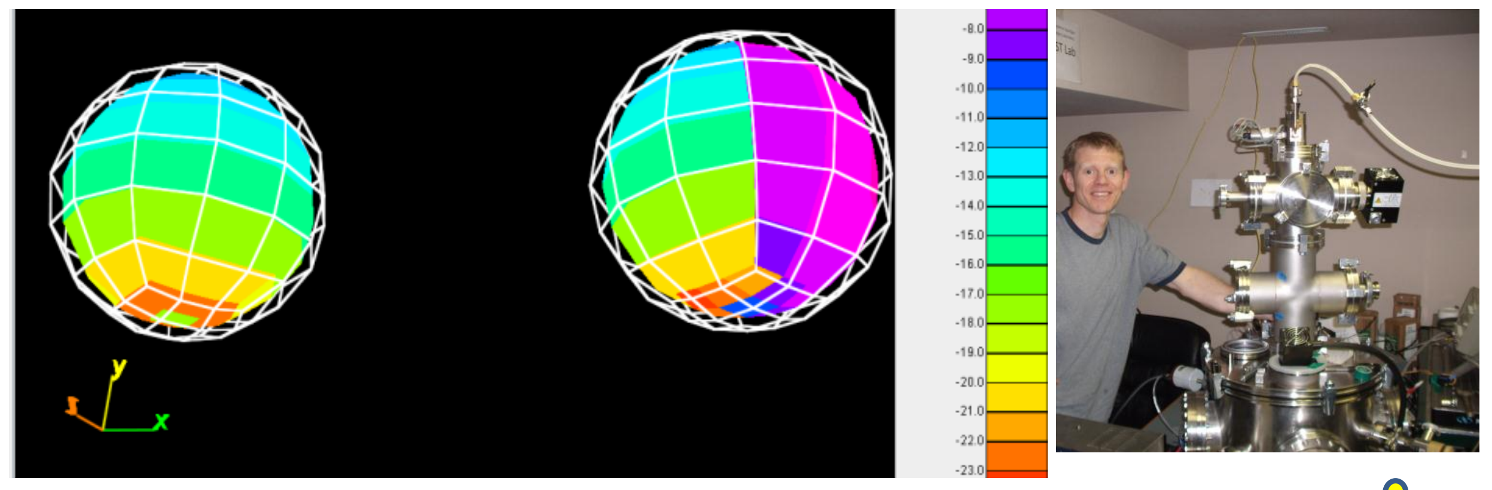
Two DebriSats are launched into orbit as a joined pair , the spacecraft separate from each other and autonomously maneuver to establish separation while maintaining precise relative attitude control with the same sides facing each other continuously. This face-to-face orientation is maintained with a laser pointing and tracking system and either reaction wheels or Electrospray thrusters. Spacecraft will use droplet streams to maintain a side-by-side formation for a brief period while monitoring the effects of drag on droplets that translate between spacecraft perpendicular to the direction of orbital flight.

Next the DebriSats move into a leader-follower formation and evaluate droplet projection accuracy at separation distances that grow with time. The two spacecraft maintain a constant relative orientation to each other. Impact location information is used to refine estimates of drag, droplet charging, solar radiation pressure, Lorentz forces and Coulomb forces.

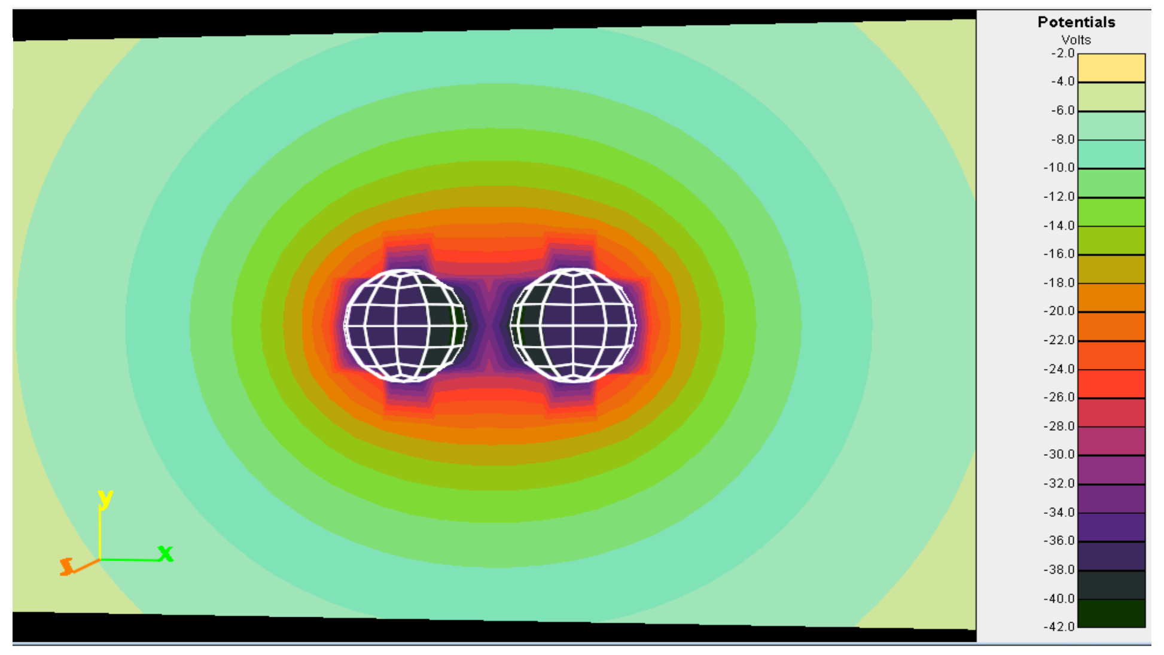
Once sufficient droplet transfer experimental data is collected, DebriSats will track each other with optical and infrared (IR) sensors, to compare actual detection distances and intensities to predicted. These observations will be conducted at various sun angles and in eclipse to better understand the effectiveness of optical and IR sensors under various levels of illumination. By comparing detected position with known position information the algorithms used to predict effective detection distance will be refined. Once detection algorithms are refined DebriSats will begin testing these algorithms on operational spacecraft that pass within the predicted detection range. This will allow mission planners to further refine the expected ability of DebriSat to detect objects of various size and temperature with different sun angles.

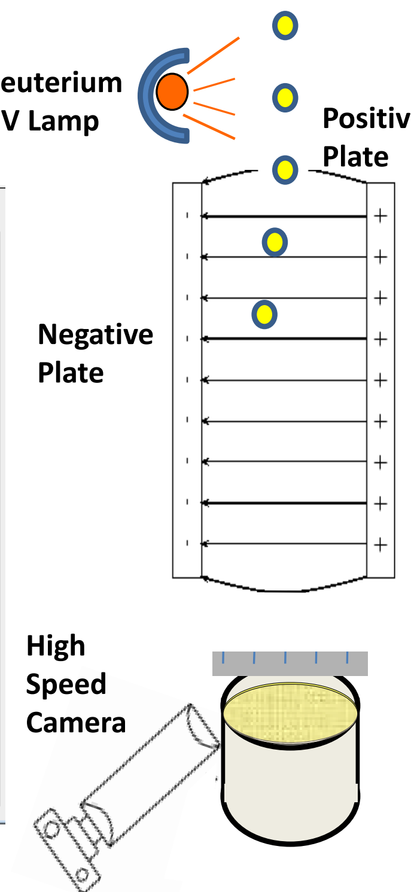
Once confidence in the droplet stream flight prediction models is gained one DebriSat will use Electrospray thrusters to maneuver into a phasing orbit in order to provide the other DebriSat with a target for detection and transfer of fluid to impact the second DebriSat. The impacted spacecraft will record the location of droplet impacts with fluid filled capacitor sensors covering one side of the spacecraft. Attitude sensors will record the disturbance torques and velocity change resulting from the impacting droplets. Several more fluid transfers between DebriSats will be conducted each with a greater relative spacecraft velocity and impact velocity than the last.

Following on-orbit testing DebriSat will continue to use onboard sensors to track known objects and detect unknown objects, too small for ground-based detection. With algorithms refined, Debris Sat is now ready for an operational test in which a lead DebriSat will update position information of an object and the trailing DebriSat will transfer thousands of droplets (200-500 grams) into the path of the object. Ground based and DebriSat sensors will be used to assess the effectiveness of momentum exchange with the object and look for damage to the object. Data from this and subsequent intercepts will be used to narrow the envelope of predicted post-intercept trajectories used to select future objects for intercept. DebriSat will retain enough ionic liquid to expedited it's own de-orbit with Electrospray thrusters.

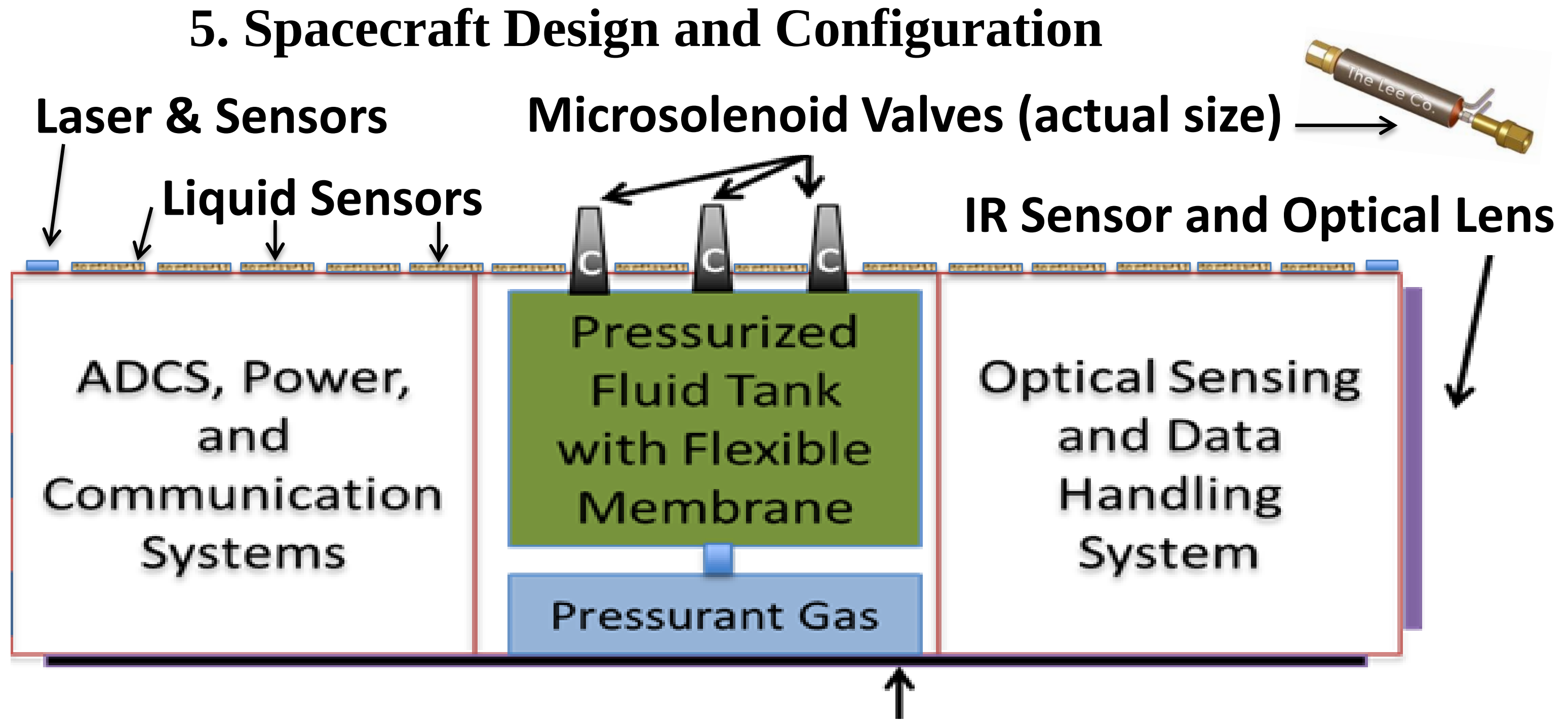


Droplet charging experiment (top and bottom right) used to validate part of the NASCAP predictive charge modeling results (shown above and below)



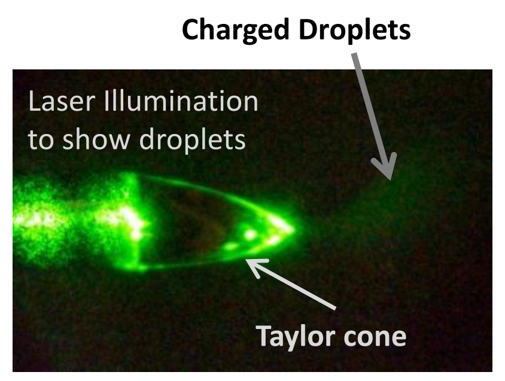


5. Spacecraft Design and Configuration

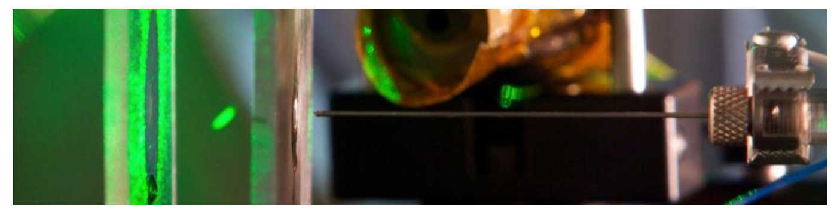


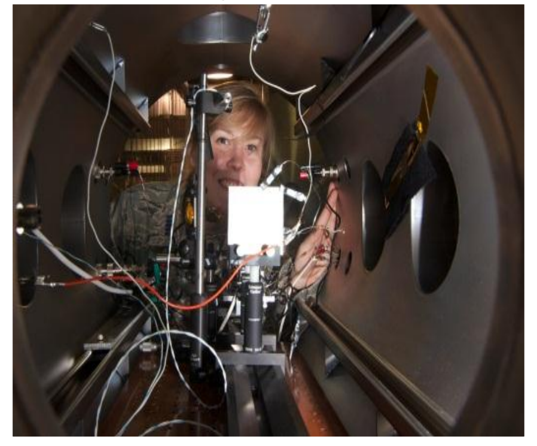
6U CubeSat with 3 Deployable Solar Arrays (arrays shown stowed)

DebriSat can fly as a pair of 3U CubeSats. This size is adequate to establish the viability of the droplet stream projection system and to perform several operational intercepts of objects. A larger 6U CubeSat DebriSat would allow for three times as many object intercepts with the added volume of fluid that can be stored. A 6U configuration also enables longer distance collection of droplets because of the larger size of two sides (30cm by 30cm). 6U DebriSats can fly both an optical telescope and an IR sensor to allow a comparison of the performance of each and increase object detection capabilities. For these reasons, and to reduce cost, a pair of similar 6U DebrisSats is believed to be the best combination of spacecraft for the initial DebriSat mission. Each spacecraft will have an array of solenoid valve droplet stream generators capable of performing experiments and actual object intercepts. DebriSat will use solar power and rechargeable batteries and its communications system will be quite similar to that of FalconSAT 7, a 3U remote sensing spacecraft built at the Air Force Academy. Attitude determination and control can be achieved with sufficient accuracy with a conventional reaction wheel system like that used on FalconSAT 7's Colony Two bus. It is expected, however, that Electrospray thrusters now in development in vacuum chamber testing at the Air Force Academy can provide attitude orbit control through Lorentz force acceleration of very small charged droplets of BMIM-BF4. Calculations show that such thrusters can serve both functions without exceeding the power available from a 6U CubeSat with body mounted and deployable solar arrays.



Electrospray thruster setup at right and below showing high-speed transit of charged droplets from the tip of a needle (shown below and left). Droplets are illuminated by a green laser.





DebriSat will have droplet impact sensors and a laser pointing and detection system to allow it to accomplish droplet transfer between DebriSats during the experimental phase of the mission. Droplet stream production will be accomplished with microsolenoid valves that can operate at frequencies above 100 Hz and produce any desired separation distance between successive droplets. Such valves can also produce single droplets which is useful during the experimentation phase of the mission.

In order to determine the droplet impact locations, the satellites will be equipped with fluid-filled capacitors which act as sensors. When droplets impact the sandwiched wire mesh capacitors they are trapped and the capacitance is altered. The change in capacitance alters a current signal, allowing the on-board processor to determine which area of the spacecraft was impacted. Initial spacecraft pairs will have one surface covered with these sensors to conduct pointing accuracy tests.

The top simulation at right show the impact points of droplets in a single stream without adequate spacing to prevent Coulomb forces, acting between droplets, from accelerating droplets away from the intended centerline path. The lower plot shows impact points for the same simulation with adequate spacing between droplets to prevent droplet dispersion. This effect is even more pronounced in parallel streams and requires further analysis to determine optimum stagger patterns to minimize dispersion.

Knowledge of droplet charge will be used to predict the effect of Lorentz and Coulomb forces on droplets and determine the allowable droplet proximity for various propagation distances. Charge knowledge will also allow the force of drag to be determined by removing the charge-induced Lorentz forces from the sum of forces determined by on-orbit tests.

A finite element charge modeling tool called NASCAP was used to predict the charge potential that droplets will reach in space. The solar-induced part of this predicted charge was then validated in a vacuum chamber experiment whereby droplets charged by an extreme UV lamp were passed through an electric field and their altered path quantified with high-speed imagery (depicted at left). Once charge predictive models are adequately refined by DebriSat testing, long distance droplet stream propagation is possible. This will greatly expand the number of objects DebriSat can intercept with a frequency of more than one per month in certain orbits.