THE RETRIEVE MICROSATELLITE TETHER DEORBIT EXPERIMENT

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Abstract.

We have designed and built prototype hardware for a very small electrodynamic tether device for deorbiting a microsatellite at the end of its mission. This experiment is intended to fly as a secondary payload on a microsatellite mission. It is designed to present no risk to the spacecraft's primary payloads, remaining completely dormant until the spacecraft has completed its mission. At the end of the spacecraft's mission, the tether device will deploy a 2 km long interconnected-multiline conducting tether upwards from the microsatellite, and will use passive electrodynamic drag to lower the orbit of the microsatellite. To minimize the mass of the device, we developed a new tether deployment mechanism in which the tether deployer ejects itself away from the spacecraft and becomes the tether endmass ballast. Laboratory testing of this deployment mechanism indicates that it can successfully deploy a multiline tether at tensions low enough for successful deployment. We evaluated several plasma contactor technologies for this experiment, and selected a thermionic device based upon a COTS dispenser cathode for its minimal mass and technology maturity. With this tether hardware, a "barebones" experiment to deorbit a 100 kg microsatellite can be implemented with a total mass of less than 2.5 kg., which is less than the propellant required to fully deorbit such a microspacecraft using thrusters. A more capable experiment, with active control of tether dynamics and diagnostics on tether performance and dynamics, can be implemented with a total mass of 3.5 kg.

Introduction

Under funding from the Air Force Research Laboratory, Tethers Unlimited, Inc. (TUI) and its subcontractors, General Dynamics-Space Propulsion Systems and the University of Michigan's Space Physics Research Laboratory (SPRL), have developed a prototype of a very small electrodynamic tether drag system designed to deorbit a microsatellite at the end of its mission. This development effort sought to meet two seemingly incompatible objectives: first, to develop an electrodynamic tether experiment that will achieve several meaningful advancements of space tether technologies, and second, to perform this experiment on a 100 kg microsatellite platform with a total mass impact on the spacecraft of "less than zero." Despite these challenges, the design effort was successful, developing mission concepts and prototype hardware for a simple passive-drag, passively-stabilized electrodynamic tether deorbit device with a total mass of less than 2.5 kg. Because completely deorbiting a 100 kg-class microsatellite from a mid-LEO orbit using onboard thrusters would require over 5 kg of propellant, this tether experiment could have a negative mass impact on the microsatellite. Moreover, because this experiment would be flown as a secondary payload on an operational microsatellite, the experiment must be designed to present no credible risk to the primary mission of the spacecraft. This experiment was named the "RETRIEVE" experiment because it was initially envisioned as a demonstration of a capability for retrieving resident space objects for servicing or disposal; during the course of the project the experiment design evolved into an experiment to demonstrate controlled end-of-life spacecraft proposal, but we have retained the RETRIEVE moniker for the sake of continuity. In this paper, we will discuss the objectives of the experiment, present the experiment design and its impact upon the host microsatellite, and then discuss the results of tests performed on the prototype hardware. We will conclude by briefly describing an experiment option that would demonstrate active control of tether dynamics with an additional mass impact of only 1 kg.

Experiment Objectives

To be worthwhile, the tether experiment must provide a significant advancement in technology over previous tether missions. Previous missions, including the NASA Tethered Satellite System (TSS) and Plasma Motor Generator (PMG) Experiments, have demonstrated the ability of electrodynamic tethers to generate significant currents through their interactions with the Earth's magnetic field and ionosphere. They have also, in principle, demonstrated some level of propulsive capability, but no detailed measurements of thrust or propulsive performance were obtained by these flights. NASA's upcoming ProSEDS experiment will, within the year, have demonstrated the ability of a bare wire tether to provide an efficient mechanism to collect electron current from the ionosphere, and it will have demonstrated that a tether can lower the orbit of a LEO spacecraft.

For an electrodynamic tether propulsion system to be useful for USAF, NASA, and commercial space needs, however, a number of additional capabilities must be demonstrated.[1] These prior missions have not demonstrated a tether structure capable of surviving the orbital debris environment for a long duration mission. They have also not demonstrated the capability to actively control the dynamics of the tether, nor to perform controlled orbital maneuvering with the tether. Accordingly, we sought to identify a mission concept and mission objectives suitable for demonstrating these key capabilities in a small, inexpensive secondary payload experiment.

To address the outstanding tether technology issues, we developed the four primary goals for the mission.

1. **Demonstrate that the lifetime and performance of an electrodynamic tether can meet or exceed the goals of the Air Force's IHPRPT program.**

The Air Force's IHPRPT program is seeking to achieve a significant improvement in performance and lifetime of in-space propulsion capabilities for its spacecraft. Electrodynamic tether systems have strong potential to meet these goals because they can provide highly efficient propulsion in LEO with low or zero propellant usage. The tether experiment should demonstrate that an electrodynamic tether can survive the orbital environment and provide propulsive capability for an extended length of time. The objective success criteria will be the survival of the tether for a duration determined as a function of the systems thrust capability and mass in accordance with IHPRPT goals. The method for validation will be observations of tether intactness through ground based radar/optical measurements and telemetry from the satellite to provide propulsion performance data.

2. **Demonstrate control of tether librations.**

Because tethers are long, flexible structures, and because electrodynamic tethers will generate thrust forces that vary over time, the dynamics of electrodynamic tethers are complex, and coupling between the varying forces and the oscillatory modes of the tether can lead to instabilities in long-duration missions. The proposed baseline tether experiment will demonstrate passive stabilization of the tether instabilities. The enhanced mission option would demonstrate active feedback damping of the tether libration modes using modulation of the tether current. The success criteria for this objective will be the maintenance of the in-plane tether libration amplitude to less than 45°. Validation of these goals in the baseline experiment would be accomplished using postprocessing of spacecraft telemetry. In the enhanced mission option, validation would be accomplished through onboard measurements of the tether libration angle and through ground-based tracking of the tether endmasses.

3. **Demonstrate controlled orbital maneuvering using an electrodynamic tether.**

The direction and magnitude of the forces generated by an electrodynamic tether vary constantly due to fluctuations in ionospheric density and changes in the angle between the tether and the geomagnetic field. Consequently, performing propulsion with an electrodynamic tether is more akin to sailing a yacht than standard spacecraft thrusting with rockets. For an electrodynamic tether propulsion system to be useful on an operational spacecraft it must have the capability to adjust the tether thrust levels over the period of one or more orbits to properly achieve the desired orbital maneuvers. The proposed experiment would demonstrate this capability by modulating the tether current to circularize an initially elliptical orbit. The success criteria for this goal would be the capability to lower the microsatellite's orbit apogee and perigee independently, with the ability to vary the ratio of apogee to perigee deboost rates by 33%. Validation of this goal would be obtained using the microsatellite's onboard orbit sensing capabilities and ground tracking of the system. Additional maneuvering capability could be demonstrated by performing a simulated “avoidance” maneuver to validate the capability of tethered systems to avoid collisions with other space objects.

4. **Demonstrate deployment of a multiline conducting tether.**

Although multiline space tether structures have been successfully deployed from SEDS and other tether hardware in ground experiments,[2] they have not yet been tested in space. Consequently, one significant goal of the proposed experiment would be simply to demonstrate that a survivable conducting tether can be successfully deployed in space. Validation of the deployment and tether survival will be obtained using ground-based measurements of the separation between the microsatellite and the endmass.

Experiment Design

Mission Concept: Achieving the experiment goals detailed above within the tight mass allocations available on microsatellites was a challenging endeavor, and required several design iterations. The resulting experiment design is for a very small, simple electrodynamic tether system with minimal instrumentation and avionics. It is designed to accomplish the deorbit experiment concept illustrated in Figure 1, shown as a secondary experiment on the upcoming AF XSS-11 microsatellite mission. To minimize risks to the primary mission, the tether experiment would be completely dormant during the entire primary mission, with the tether stowed, the avionics unpowered, and the deployment mechanism fully safed. Only after the spacecraft completes all of the objectives of its primary mission, and it is time to deboost the spacecraft to comply with space debris mitigation guidelines, would the tether experiment be activated. Upon command from the host spacecraft, the tether system would eject its tether deployer upwards from the spacecraft. Once the tether is fully deployed, the avionics would activate an electron emission device on the satellite end of the tether, enabling current to flow through the tether. This current would interact with the Earth's magnetic field, lowering the orbit of the spacecraft. During the first phase of the experiment, lasting approximately 4 months, the tether system would deboost the spacecraft at the maximum rate possible within the bounds of tether stability. Once the tethered system's perigee reaches an altitude of approximately 420 km, the experiment would modulate the tether current so as to circularize the orbit of the spacecraft within about 1 month. After the circularization maneuver, the tether experiment would again maximize the deboost rate, deorbiting the system within approximately one month. In the subsections below we describe the components of the hardware for this experiment.

Tether

In the proposed tether experiment, a 2 km conducting tether will be deployed above the microsatellite. In order to provide a very high probability that the tether will survive the LEO micrometeorite/orbital debris (M/OD) environment intact for the 6-month duration of the experiment, we chose to construct the tether using the multiline, failsafe Hoytether™ design developed under a NASA SBIR effort several years ago.[3] For this experiment, the tether design must meet a number of challenging criteria: It must be a good conductor, must provide tensile strength capable of withstanding all possible tension excursions that could be caused by deployment or tether dynamic behavior, must have a sufficiently high ratio of thermal emissivity to solar absorptivity so as to prevent overheating by ohmic and solar heat sources, must resist degradation or oxidation by atomic oxygen, and must be very flexible so that it can deploy with millinewton deployment forces. To

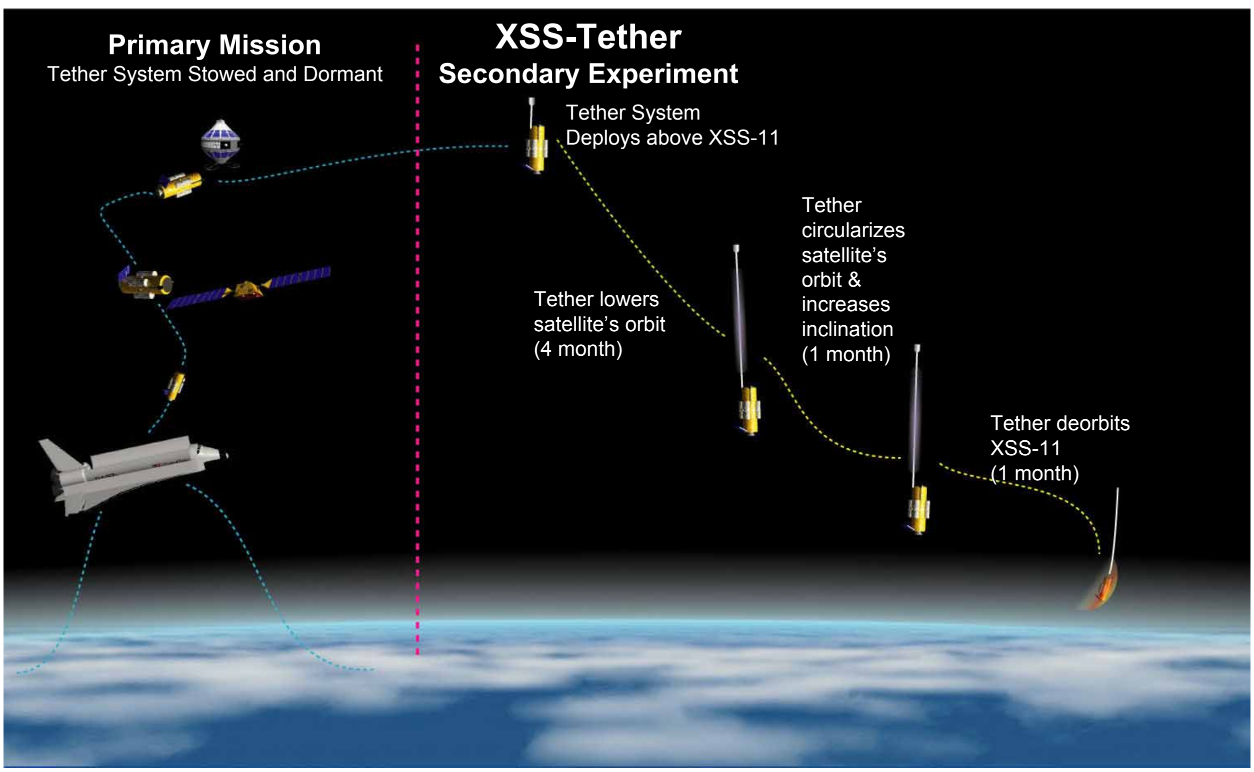

FIGURE 1. The proposed Microsatellite Tether Deorbit Experiment concept.

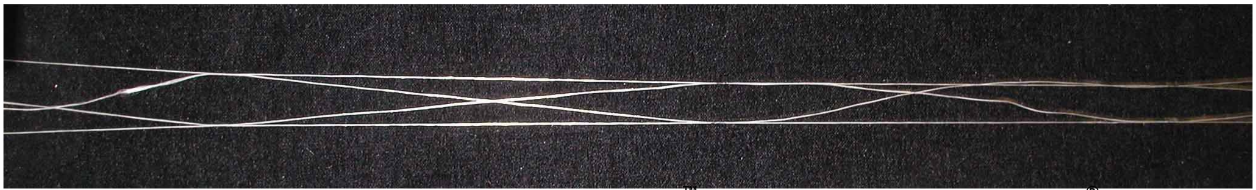

Figure 2. A section of conducting Hoytether™ constructed of metalized Kevlar.®

meet all of these criteria, we developed a multiline Hoytether™ using a metallized Kevlar® yarn. This yarn has a base of 200 denier Kevlar® fiber onto which copper is electroplated. A thin flash of Nickel is plated on top of the copper. The Nickel coating provides excellent resistance to oxidation. Furthermore, the surface of this Nickel has a microscale roughness that provides adequate thermal emissivity characteristics. We developed an in-house capability for fabricating long lengths of this tether. In this process, every single joint is inspected manually to ensure quality control. A photo of a short length of this tether is shown in Figure 2. The tether has a linear density of 0.3 g/m, giving it a total mass of 600 g for the two-kilometer length. We carried out a detailed survivability analysis of this tether structure and found that it will have a 99.935% of surviving the M/OD environment for the expected 6 month duration of the experiment. Nearly all of this relatively low risk is due to the unlikely event of a strike by a large piece of orbital debris greater than 1 meter in size, which could cut all of the tether lines at once. The probability of surviving multiple cuts by M/OD impactors smaller than 5 cm in diameter is 99.9999%. In extended operations, the tether survival probability will remain above 99% until almost 4 years of exposure.

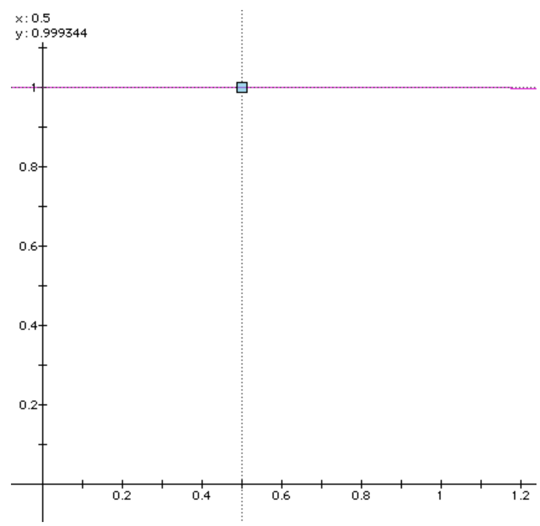

Figure 3. Survival probability of the tether in the LEO M/OD environment.

Deployer

Because the forces acting on an electrodynamic tether are always perpendicular to the tether, and thus tend to push the tether towards a horizontal orientation, the system must include a mass at the end of the tether to provide gravity-gradient forces that will counteract the electrodynamic torque on the tether and keep the tether oriented vertically. In the TSS, PMG, and ProSEDS experiments, the deployer remained on the host spacecraft while a subsatellite was ejected at the end of the tether provided this ballast mass. In the RETRIEVE experiment, however, the extremely tight mass restrictions prevent us from using non-functional mass to provide ballast to the tether. For this reason, the deployment system for the microsatellite tether system is designed rather differently than other tether deployment systems. In the RETRIEVE experiment, the deployer itself will eject itself away from the host spacecraft, deploying the tether as it goes, and the spool, shroud, and other deployer components will serve as the tether ballast endmass after the tether is deployed. To eject itself, the deployer utilizes a small ejection mechanism designed for TUI by GD-SPS. The ejector uses only a NASA-standard initiator to provide the ejection impulse. The ejector is designed so that all of the products of the initiator are contained to prevent contamination of the cathode or spacecraft. The details of the design of this tether deployer are proprietary and the subject of current patent applications, so they will not be detailed in this paper. The deployer mass, including mounting bracket, cabling, shroud, spool, and ejector is 0.9 kg. The deployer canister is shown in Figure 4. Testing of the deployer will be discussed below.

Avionics

The baseline experiment design is intended to meet the AFRL's desire for a "barebones"-mass tether deorbit experiment. Therefore, in the baseline experiment design the avionics have been kept to a minimum in terms of both complexity and mass. The functions of the avionics are to:

- Power and control the electron emission device;
- Measure the tether current;
- Turn the tether current on and off at the command of the spacecraft;

The electron emission device, a thermionic emitter, requires approximately 15 W of heater power at 6 V. The avionics convert the 28 V spacecraft bus power to 6 V in a manner that enables the avionics to vary the heater power so as to achieve the gentle warm-up required by these devices and also to vary the emitted current if desired. The total mass of the avionics, including enclosure, is 0.56 kg. The brassboard-level prototype avionics developed and tested in this effort are shown in Figure 4. Significant size reductions can be achieved for the flight unit.

Electron Emitter

In designing the RETRIEVE experiment, we evaluated several different plasma contactor options, including hollow cathodes, FEACs, and thermionic emitters. In most electrodynamic tether systems, thermionic emitters are not a favored choice because of their relatively high power requirements. However, for the proposed experiment, the currents desired are very low (approximately 18 mA average), and this can be accomplished by thermionic emitters operating at less than 20 W, which is commensurate with the power levels available from the host microsatellite. Furthermore, low mass and high technology readiness are the key requirements for this application, and so the thermionic approach was chosen as most suitable. The RETRIEVE electron emission device is based upon a COTS dispenser cathode device. Under a subcontract effort, the University of Michigan's Space Physics Research Laboratory has developed a design for this device based upon TUI's specifications, and performed preliminary performance testing *in vacuuo*. Because the dispenser cathode devices are susceptible to degradation due to exposure to oxygen and other chemicals, the design incorporates the cathode into an enclosure with a spring-hinged lid. During integration and launch this enclosure will be filled with a tenth of an atmosphere of dry nitrogen to mitigate contamination. The lid is designed so that it is held closed by the tether deployer; when the deployer is ejected, it releases the lid, allowing it to swing open and expose the cathode to space. The electron emitter device, including cabling, has a CBE mass of 0.17kg.

Passive Stabilization

The baseline "barebones" tether experiment design does not include mechanisms for sensing tether dynamics and performing feedback control on the tether dynamics. Rather, the baseline experiment will use passive means for limiting the growth of tether dynamics. This stabilization will be accomplished through two methods. First, although the tether system could conduct currents as high as 100 mA under some conditions, the tether current will deliberately be limited to less than 35 mA. This prevents rapid growth of certain librational instabilities. Second, the tether itself is designed with a significant amount of longitudinal damping. This longitudinal damping drains energy from the unstable modes as the tether oscillates. Without active damping, the tether dynamics do become significant, reducing the potential deboost performance of the tether, but extensive numerical modeling indicates that these passive means can keep the tether dynamics within acceptable bounds. If some level of orbital data and computational capability on the microsatellite is available to the tether experiment, active feedback control can be performed using satellite orbital data as the input. This feedback control will not be as effective as feedback based upon tether dynamics sensing data,[4] but will be an improvement over just passive stabilization.

Figure 4. The prototype RETRIEVE avionics and deployer.

Impacts to Host MicroSatellite

The total (CBE+Uncertainty) mass of the baseline "barebones" tether experiment is less than 2.5 kg. Because this mass must be carried around by the host spacecraft during its primary mission, its total mass impact on the spacecraft must also include the mass of the propellant required to carry that mass around during the primary mission. On the XSS-11 spacecraft, which will perform approximately 700 m/s of ΔV during its primary mission, this mass penalty is approximately 40%. The adjusted mass impact of the tether experiment is thus 3.5 kg. This spacecraft, however, is required by DoD/NASA orbital debris mitigation guidelines to ensure that it has less than a 25 year final orbital lifetime. To fully deorbit the microsatellite from an estimated mid-LEO slightly elliptical orbit would require over 5 kg of propellant. Thus, for full deorbit, the tether experiment could actually reduce the spacecraft's mass requirements by 1.5 kg. Most likely, however, the spacecraft will be designed to carry a certain quantity of fuel, and will be fully loaded regardless of deorbit method. The tether experiment could, in that case, allow the spacecraft to perform additional ΔV maneuvers, increasing the payoff of its primary mission.

Other impacts to the spacecraft include the experiment's requirements for power, volume, telemetry, and attitude control. The avionics and electron emitter are expected to require less than 18 W in total. To initiate tether deployment, the ejector will require a feed from the spacecraft's pyro initiation system. The deployer has dimensions of approximately 10 cm dia x 25 cm length, and the avionics and electron emitter will together require roughly 600 cm^3. The command and telemetry requirements for the experiment are minimal. In the simplest implementation, the experiment would require only that the spacecraft turn on its power. In slightly more capable implementations, the spacecraft would read current measurements from the experiment for downlink, and could provide on/off or analog current variation inputs to the experiment. The only attitude control requirement for the experiment is that the spacecraft should orient itself before tether deployer ejection so that the deployer will be ejected approximately 25° ahead of zenith.

Deployment testing and simulation

Deployment Drag Measurements

The Microsatellite Tether Deorbit experiment will utilize a tether deployment mechanism in which an ejection mechanism will propel the tether deployer canister upwards from the microsatellite, and the canister will pay tether out as it moves away from the satellite.

The deployment canister's initial velocity will be provided by a small ejection mechanism developed for TUI by General Dynamics-SPS. The ejection mechanism is integrated with the tether spool and the hardware for mounting the deployer to the spacecraft. The ejection mechanism is powered by a NASA-standard initiator, which, when activated, first releases the deployer from its mechanical hold-down and then provides the impulse to push the deployer canister away from the microsatellite.

As the canister moves away, its speed will gradually decrease due to friction between the tether and the canister shroud. Because all of the deployment energy is provided impulsively, and the gravity gradient forces on the system will be only a few millinewtons at full tether deployment, it is important to ensure that the canister is ejected with sufficient initial velocity that it will fully deploy the tether before the drag brings it to a halt. It is also important to not eject the deployer with too great an initial velocity, or it could rebound if it reaches the end of the tether while still moving with a subtantial velocity. For this reason, we assembled a test capability for accurately measuring the millinewton-level drag forces the deployer canister experiences as it pays out the tether. In this test facility, the deployer canister is suspended on a long-arm pendulum.

We have used this deployment test assembly to measure deployment drag at a wide range of deployment rates, with a variety of different tether spool diameters, shroud diameters, and shroud configurations. To minimize the deployment drag, it is desirable to minimize the contact between the tether and the shroud. For this reason, it is desirable to design the tether spool with as small a diameter as practical, because the smaller the spool, the less the tether "slings" outward as it deploys and rubs against the shroud. Figure 5 shows test data from a deployment test conducted using a tether constructed of metalized Kevlar® yarns, deployed from a spool with a 1" OD, and a smooth cylindrical shroud with an inner diameter of 3.5". The drag appears to depend primarily upon the square of the deployment speed, which is to be expected for frictional effects. Note that these drag tests were performed in atmosphere. Because aerodynamic effects can play an important role in the dynamics of the deployment of light tethers such as this one, additional testing in vacuum is desirable.

Deployment Simulation

To evaluate the feasibility of deploying the tether using this impulsive ejection method, we simulated the deployment of the tether using both the TetherSim™ numerical code and an Excel spreadsheet model, using the drag dependence given in Figure 5. In the simulation, the endmass was ejected with an initial velocity of 5 m/s, and the model took into account the varying gravity gradient force, the orbital dynamics, and the payout of the tether from the canister. Figure 6 shows the simulation results for the length of tether deployed as a function of time compared to the results obtained with the spreadsheet model. The two methods agree quite well, both indicating that the tether will be fully deployed within about ten minutes. The discrepancy between the numerical model and the spreadsheet model at the very end of the deployment is due mainly to the fact that the spreadsheet model does not include effects due to orbital mechanics and tether dynamics. The numerical simulation indicates that with an initial velocity of 5 m/s, the canister still has about 1 m/s velocity when it reaches the end of the tether. It will be necessary to provide some passive braking at the end of the deployment to ensure that the tether does not rebound. This will be achieved by winding the last section of tether to deploy with a light adhesive, as was done in the Plasma Motor Generator experiment.[5]

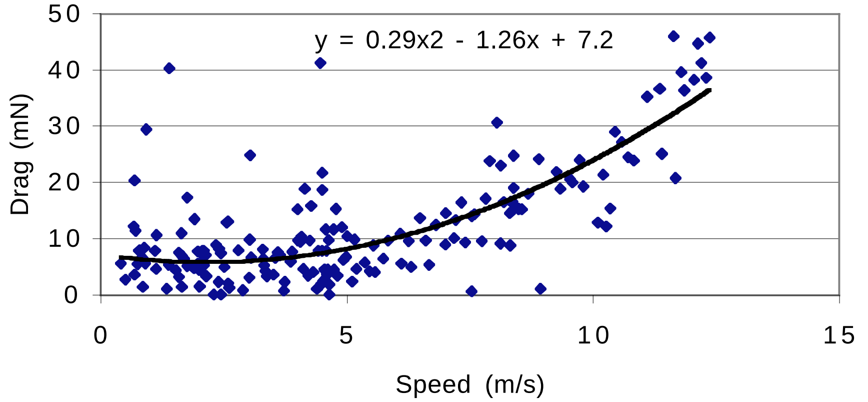

Figure 5. Deployment Drag vs. Deployment Speed for a tether constructed of metalized Kevlar®, deployed from a 1" diameter spool, 3" winding OD, with a smooth 3.5" ID shroud.

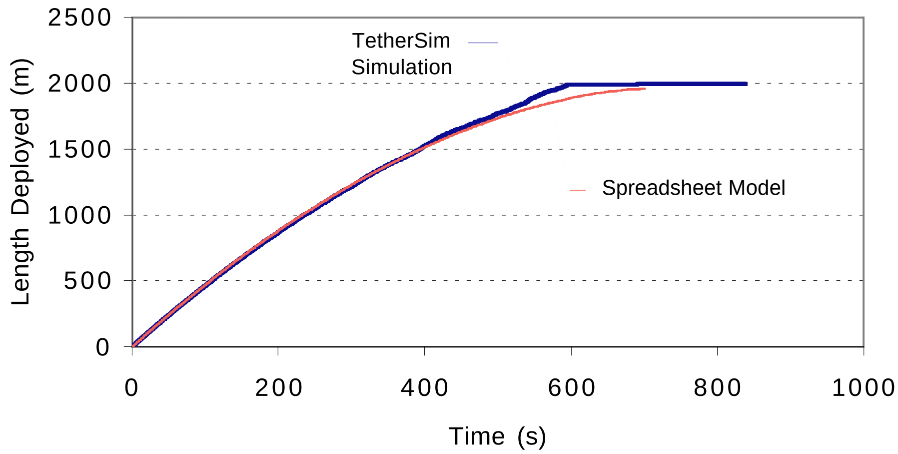

Figure 6. Results of a deployment simulated using TetherSim and the drag vs speed characteristics given in Figure 5 with an endmass ejection velocity of 5 m/s.

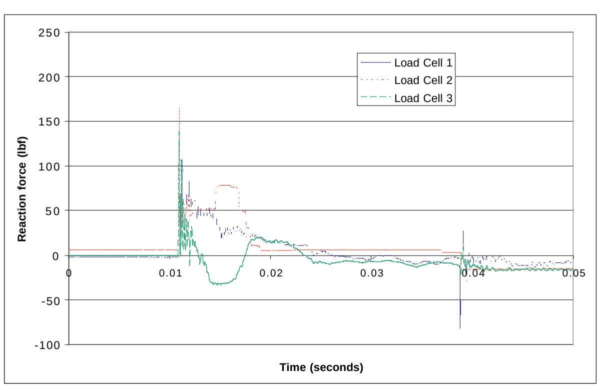

Figure 7. Reaction force data measured by the three load cells

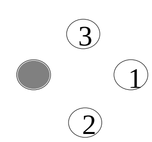

Figure 8. Load cell layout.

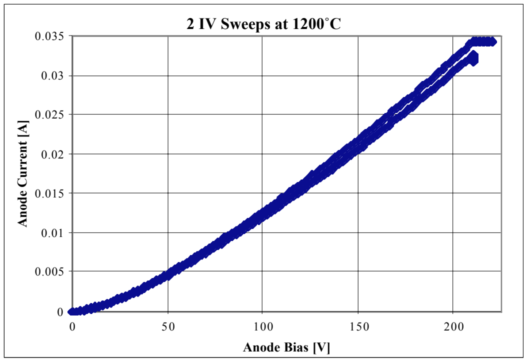

Figure 10. Current-Voltage characteristics of the thermionic emitter, without accelerating structures.

Deployer Ejection Testing

In order to verify the operation of the ejection mechanism and the method of tether deployment TUI and GD-SPS conducted a series of test deployments in a high-bay facility equipped with high-speed video. The specific purpose of these tests were to:

1) demonstrate that the ejection mechanism works reliably and provides the expected ejection velocity;
2) demonstrate that the endmass/deployer can successfully deploy the multiline conducting Hoytether at high speed and low tension;
3) evaluate methods for securing the tether prior to ejection and releasing it at ejection;
4) measure reaction force and torques imparted to spacecraft by ejection mechanism.

The ejector mount was secured to the test stand by four bolts, with the deployer canister oriented 45° from vertical. Figure 9 shows photos of one of the deployment tests. In all five tests conducted, the GD-SPS ejection mechanism performed flawlessly. The tests also demonstrated that the multiline tether deploys successfully from the deployment canister, and examination of the deployment videos indicate that the tether deploys at low tensions and the dynamics of deployment helps to spread the multiple lines in the tether apart.

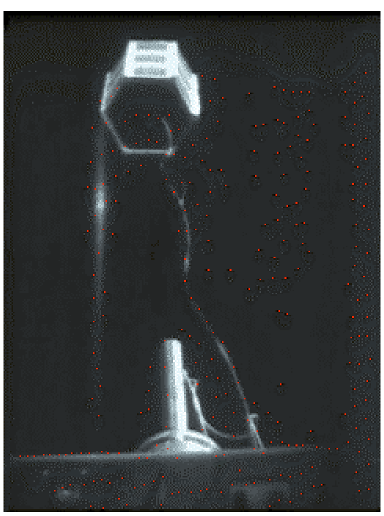

Figure 9. A frame from a high-speed video of a deployment test, viewed from the satellite-end of tether.

For all five tests, load cell data was captured at the mounting interface at three of the four bolts, with a solid aluminum spacer on the fourth position. The locations of the load cells for the tests are shown in Figure 8 (looking down at the mounting fixture). Example load cell data for an ejection test are shown in Figure 7. The load cell data show an initial impulse that occurs when the NASA-standard initiator is ignited, followed by a second negative impulse associated with the ejection mechanism. When corrected for zero drift and and integrated over the pulse duration, the load cell measurements gave an average primary impulse magnitude of 12 N-s. Even with a worst-case mounting configuration, the host propulsion should easily be able to counteract any moment generated by this launch impulse. In all cases, the peak instantaneous launch force imparted was less than 250lbf, meaning that the launch impulse will not present a meaningful challenge to mounting fasteners.

Electron Emitter Testing

The University of Michigan's SPRL has performed preliminary testing of the thermionic emitter in a vacuum environment. These initial tests examined the current-voltage characteristics of the dispenser cathode device emitting current with no extra accelerating structures. The IV characteristics of the thermionic emitter are shown in Figure 10. Even without an accelerating grid, the emitter produces roughly 15 mA of current at 100 V of bias relative to the anode. Since the RETRIEVE tether system is predicted to carry an average current of 18 mA, and will have tether-*EMF* voltages of 100-600 volts, this device would be adequate even without accelerating structures. Future work will investigate the performance improvements that can be attained using accelerating grids or other structures.

Enhanced Mission Options

Active Stabilization of Tether Dynamics

Because electrodynamic tether systems can exhibit instabilities that can degrade the thrust performance of the tether or lead to loss of control of the system, it is highly desirable to develop and demonstrate a capability for actively controlling the dynamics of the tether. The TSS-1R mission demonstrated some level of active feedback control on tether dynamics. However, in the

TSS system, this was accomplished by maneuvering the Shuttle Orbiter with its onboard thrusters, which consumed propellant. Under a recent Phase I NASA SBIR contract effort, TUI successfully developed methods and prototype hardware for sensing the dynamics of space tethers and performing feedback control by varying the tether current to stabilize the tether dynamics.[4] Such a capability could be demonstrated by augmenting the baseline proposed experiment with sensors for observing the relative motion of the tether endmass. Our initial prototyping efforts indicate that this important capability could be demonstrated with an additional mass requirement of approximately 1 kg.

Retrieval of Tether for Orbital Debris Investigations

Because theorists' ability to accurately predict the survival probability of tethers and other large, gossamer structures in space is currently severely limited by the paucity of real data on the interaction of tether structures with the M/OD environment, it would be greatly advantageous if the experiment could return data on the rate and nature of damage of the tether by M/OD. Two potential methods for accomplishing this would be to either retrieve the tether after extended exposure for study on the ground, or to scan the tether and transmit data back to Earth. Current models of the rate of damage of tether materials indicate that approximately 16 of the 4,000 individual line segments in the RETRIEVE tether would be cut by M/OD impacts during the experiment duration. To demonstrate the feasibility of these concepts, we developed and demonstrated a small, simple, low-cost mechanism for retrieving the tether after exposure and storing it in a small canister. A potential option for scanning the tether would be to pass it through a sensitive linear scanner such as is used on fax machines, and transmit the data to ground stations.

Retrieval of Resident Space Objects

A capability to retrieve or dispose of resident space objects (RSO) would be highly advantageous for orbital debris mitigation and servicing of on-orbit space assets. The proposed tether experiment could serve as a basis for a low-cost microsatellite-based capability for capturing RSO's and lowering their orbits to altitudes where they could be retrieved by a Shuttle orbiter or disposed of by immolation in the upper atmosphere. To retrieve spacecraft from mid- to high-LEO altitudes using propellant-based thruster systems would require such a large mass of propellant that it would not be feasible on a microsatellite platform. Because the tether does not require propellant to perform maneuvering, it can provide a very low-mass means for deboosting RSO's. Such a system would also require the capability to capture disabled or uncooperative spacecraft. To meet this need, TUI recently developed and tested a proof-of-concept prototype of a simple, lightweight deployable-net based mechanism for capturing spacecraft. We estimate that this additional capability could be implemented with an additional mass of less than 1.5 kg.

Orbit Raising of Shuttle-Launched Microsatellites

Although RETRIEVE experiment hardware was designed to provide a "barebones" deorbit capability for microsatellites, the design of its components was also chosen so that it could readily be enhanced to provide orbit-raising or stationkeeping propulsion for a microsatellite. A particularly suitable application would be raising microsatellites deployed from the Shuttle SHELS platform to higher, longer-life orbits. Currently, safety issues associated with chemical rockets present significant impediments to their use for orbit raising SHELS-launched microsatellites, and the rocket systems that can meet the safety requirements have low Isp's and thus require that a significant fraction of the SHELS mass capability be used for fuel. TUI is currently designing a small power-processing unit and associated hardware that will enable the microsatellite to provide high-voltage power to the tether system so that it can provide orbit-raising thrust. Our initial design efforts indicate that this "Microsatellite Propellantless Electrodynamic Tether (μPET) Propulsion System" can be implemented with a total mass of less than 5 kg (not including solar arrays), and the system could raise a 125 kg microsatellite from a 350 km Shuttle orbit to a 700 km operational orbit within 3 months.

Conclusions

Designing an electrodynamic tether experiment able to demonstrate new technologies while fitting within the tight mass constraints of a secondary payload on a microsatellite proved to be a very challenging task. Nonetheless, the team of TUI, GD-SPS, and U.M.-SPRL succeeded in developing a design for a very small, simple tether deorbit experiment that will demonstrate ΔV-per-mass performance exceeding the AFRL's IHPRPT goals, demonstrate deployment and long-duration operation of a multiline conducting space tether, accomplish passive stabilization of tether dynamics, and demonstrate controlled orbital maneuvering using a tether. We have developed prototypes and engineering models for the components of the experiment, and are confident that the experiment can be accomplished with a total hardware mass of less than 2.5 kg. Because this experiment would accomplish the required end-of-mission deboost of the microsatellite with lower net mass requirements than a chemical-thruster based system, the experiment could have a net negative mass impact on the microspacecraft.

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