Sail Material, Inspection Imager, and Deployment Analysis for an End-Of-Life Disposal Drag Sail

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ABSTRACT

The increasing congestion of spacecraft in low Earth orbit has amplified concerns that on orbit collisions will damage operational satellites and propagate a chain reaction of debris generation. Furthermore, as nano (sub-10 kg) and micro (sub-100 kg) spacecraft continually decrease the cost and entry barriers to low Earth orbit access, there is a growing concern that uncontrolled small satellites will pose a threat to their operational neighbours at the end of their operational lives. The small satellite community is therefore beckoned to remedy this matter, but must do so in a manner that does not jeopardize existing merits with which small satellites have excelled; that is, low cost and high performance. In seeking a solution, this paper discusses portions of the design and testing of the gossamer drag sail disposal system developed at the Space Flight Laboratory to be qualified on the CanX-7 3U CubeSat. Contrary to existing drag sails, the system discussed herein requires less than 1U of volume, needs no control or operations after deployment, and has extended use with larger spacecraft (larger than 3U form factors) due to its segmented sail design. This paper presents the design of the sail and onboard imaging system, and concludes with a discussion on testing performed with flight representative drag sail modules to characterize the deployment times expected in the low Earth orbit environment.

1 INTRODUCTION

Worldwide interest in micro and nano class satellites is rising due to their rapid design cycles and high performance capabilities. As these small spacecraft evolve from technology demonstrators to astronomical, Earth observation, and communication missions, they are being placed into long duration high altitude orbits to increase their mission potential. This regime shift toward higher altitudes brings an increased concern for end of life disposal. The current count of objects larger than 10 cm—both debris and functioning spacecraft—is around 16,000 [1]. This number has recently grown due to weapons testing and cascading collisions of satellites and their debris. Publications from the Inter-Agency Space Debris Coordination Committee (IADC) have indicated that the debris growth rates are unwavering and expect collision rates to increase [2]. Objects in Low Earth Orbit (LEO) below 1000 km altitude are therefore recommended to deorbit within 25 years after mission completion to release the space to future satellites. Alone, this mitigation strategy is not expected to correct the orbital debris problem, but is a necessary first step prior to active deorbiting of non-cooperative targets.

Unaided, a small satellite such as a 3U CubeSat (i.e. CanX-7) could take up to 60 years to deorbit from 600 km and 500 years to deorbit from 800 km [3]. There has yet to be any proven deorbit methods or technologies available for nanosatellites, and microsatellites without propulsion systems are similarly out of luck. Compounding this concern is that small satellites are designed for lifetimes shorter than some deorbit maneuvers, thus requiring a deorbit system that functions without an operational bus and any active control.

The CanX-7 mission is a deorbit technology demonstrator focused on the development and validation of a deorbit device for nano and micro satellites. An aerodynamic drag sail was selected as the deorbit device for this mission. This class of device deorbits a spacecraft by augmenting the drag forces with an additional sail structure.

1 Deorbiting has been performed at the nanosatellite scale before with NanoSail-D and RAIKO, however neither of these devices demonstrated a deorbit platform for a fully operational nanosatellite with commercial or scientific mission objectives.
experienced through the deployment of a large structure. The increased drag continuously works against the satellite’s motion, thereby reducing the overall energy of the satellite, leading to a drop in altitude. Once low enough, the satellite safely burns up in the atmosphere. This deorbit system is designed to work on satellites as small as CubeSats without compromise to their primary mission [4]. The system itself is comprised of multiple drag sail modules, each of which is a standalone device capable of deploying a 1 m² sail. Use on future satellites is simple as each module only requires a connection for power and communications [5].

This paper presents the challenges overcome in completing multiple aspects of the drag sail module design, beginning with sail material analysis and selection. Multiple aspects of the low Earth orbit environment are considered for sail material selection. After examining the thermal environment, the atomic oxygen fluence, and micrometeorite and debris damage over the maximum deorbit lifetime, an appropriate sail can be selected. The deployment confirmation and sail inspection imaging system on CanX-7 is then presented. This camera system allows for unambiguous deployment confirmation along with continued sail monitoring through the course of deorbiting. The imaging system captures over 50% of the fully deployed sail area through the use of a triad of small cameras that focus on key features of the fully deployed sail. Lastly, this paper provides a summary of deployment testing that has allowed for characterisation of deployment dynamics as an alternative to modeling the complex deployment dynamics. This has established confidence in the mechanical design prior to final testing and flight. Moreover, it has been shown that the drag sail module can safely and repeatedly deploy between −40°C and 80°C.

2 DESIGN OVERVIEW

The focus of this paper is the design, analysis, and selection of the sail membrane material and coatings, the design and testing of the camera inspection system, and system level deployment testing. The following preamble will provide context to how this work has contributed to the development of a fully functional and flight ready deorbit system.

The full drag sail system consists of four triangular modules that each deploys a thin film sail. Each module operates independently, with unique booms, electronics, and sail to deploy one quarter of the full drag sail. The major components of the drag sail module are shown in Figure 1. The modular design allows for integration onto non-standard nanosatellite busses—in particular with the Space Flight Laboratory’s (SFL) Generic Nanosatellite Bus and Nanosatellite for Earth Monitoring and Observation Bus [4]. The design of the drag sail module focused on deorbiting a 15 kg host satellite from 800 km altitude, which requires a 4 m² sail [6]. Therefore, each drag sail module must deploy a sail of at least 1 m² area, and maintain this area until the host satellite has been sufficiently lowered into the atmosphere.

Figure 1 – Major component view of the drag sail module

The drag sail module primary structure is Windform XT 2.0, a carbon fiber reinforced polyamide that is additively manufactured via a laser sintering process. This has allowed for high volumetric efficiency as well as complex features in the structural design that would otherwise be too costly to manufacture. The structure houses the onboard electronics, two tape spring booms, the sail, and supporting mechanical components. The sail cartridge provides 31 cm³ for the sail, which necessitates a sail thickness below 30 μm to meet the 1 m² deployed area requirement. Overall, each drag sail module fills half of a 10 cm x 10 cm x 3 cm volume when fully assembled, as shown in Figure 2. On CanX-7, the four arranged drag sail modules consume 10 cm x 10 cm x 8 cm, which is less than 1U of the 3U bus.

Figure 2 – Assembled drag sail module

Validation of deployment will occur through two independent systems on the CanX-7 mission. The primary system is from onboard telemetry, which monitors the rotational motion of the reel where the tape spring booms are mounted. Rotation of the reel is
indicative of boom motion, and high speed telemetry allows for estimates of deployment rates and deployed lengths of the booms. However, this measurement cannot assess the quality of sail deployment, where sail deployment is quantified as the percentage of the 1 m² target area achieved. The system used to unambiguously determine the quality of sail deployment is a triad of small cameras that are mounted within CanX-7’s deployable boom. Images of the sails after deployment will be captured by this system for download, and ultimately used to confirm the reel telemetry and deployment success.

In order to meet the deorbit goals, there must be established confidence in the deployment system, while the sail itself must be designed to withstand the rigorous environment of LEO. Programmatically, CanX-7 exists to prove the system’s design works and to provide flight heritage for the drag sail module; however, there is opportunity for analysis and deployment testing to serve as pathways to reduce risk prior to flight. The following sections detail the work performed on the CanX-7 mission to meet its objectives in qualifying a drag sail deorbiting system for nano and microsatellites.

3 SAIL ANALYSIS AND SELECTION

To predict the performance of the sail during its deorbit operation, a reference deorbit profile must first be established. As the drag sail module is being designed for use on spacecraft more massive than CanX-7 from altitudes of 800 km, the resulting design will have large margins on deorbit rate and survivability for this mission. The material selection attempts to be as conservative as possible, such that the most robust design permitted within the available mass and volume is developed. After first attempts to complete the design with commercially available thin film materials and coatings, thermal and atomic oxygen degradation were identified as competing factors in coating selection. For thermal purposes, transparent materials are ideal, while atomic oxygen erosion is mitigated with metallized coatings such as aluminum. For the analysis presented, Mylar, Kapton, Upilex, CP-1, and CORIN XLS were considered, with commercially available coatings such as aluminum and silicon oxides (Note: Shorthand is used henceforth to identify coatings. This is presented as a prefix and suffix to membrane materials; for example Al-Kapton would be single-side aluminized Kapton). Additionally, considerations are given to the inclusion of a tear mitigation strategy (a rip-stop solution) by considering fracture mechanics with an evaluation of loads and expected damage.

3.1 Atomic Oxygen Erosion

Atomic oxygen (AO) erosion depths can be estimated using information about material and orbital properties. Polyamide and polyimide materials have extensive use in spaceflights, with numerous derivatives of each film having been characterized on the LDEF and MISSE missions [7], [8], [9]. Coatings must also be considered, as single and double sided coatings can be added to reduce or eliminate erosion.

The deorbit trajectory is the key orbital property in the analysis of AO erosion for a drag sail. Estimates of time at altitude are necessary for determining the AO fluence to use in the analysis, which is directly proportional to erosion. It is also important to note that AO concentrations with altitude have been measured and tabulated based on solar activity. Spacecraft attitude is also important for this analysis if single sided coated sails are considered. For the worst case analysis, it is assumed that the spacecraft starts at 800 km and maintains a random tumble until 500 km altitude, at which point it will aerostabilise [6]. This stability allows for the use of single side coated sails that are oriented to protect the ram side of the sail after stabilization.

Finally, the cumulative depth of atomic oxygen erosion can be summarised by Equation (3.1), where \( d_{AO} \) is the erosion depth, \( \rho_{AO}(h, S) \) is the AO concentration (atoms/cm³) as a function of altitude, \( h \), and solar output, \( S \), \( \psi_{orbit}(h) \) is the orbital velocity, \( t_{deorbit} \) is the time to deorbit, \( \gamma_m \) is the measured AO erosion rate for the material (cm³/atom), and \( \phi(h, m) \) is the erosion reduction factor based on altitude and coating. Erosion reduction factors are taken as: 1 for an uncoated sail; 0.6 for a single-side coated sail above 500 km [10]; 0.07 for a single-side coated sail below 500 km [10]; 0 for a double-side coated sail.

\[
\begin{align*}
  d_{AO} &= \int_{t_{deorbit}}^{\infty} \rho_{AO}(h, S) \cdot \psi_{orbit}(h) \cdot \gamma_m \cdot \phi(h, m) \cdot dt \\
  \text{(3.1)}
\end{align*}
\]

To simplify this analysis, a conservative discretization of the cumulative erosion is determined by summing the erosion depths for a range of altitudes, as shown in Equation (3.2), where subscripts identify the altitude range in question.

\[
\begin{align*}
  d_{AO, total} &= d_{800-700} + d_{700-600} + d_{600-500} + d_{500-400} \\
  \text{(3.2)}
\end{align*}
\]

The altitude profile over the deorbit period of CanX-7 has been estimated for a wide range of initial orbital conditions with the current sail size, allowing for lifetime degradation analysis of the sail material [6]. This profile, shown in Figure 3, allows for time dependent analysis at various orbital altitudes for atomic oxygen erosion. By extracting dwell times from this analysis and using Equation (3.2) with tabulated worst
coupled with time and temperature, requiring time dependent analysis to predict mechanical degradation. On orbit, thin film sails are subject to the radiative thermal environment of low Earth orbit, with contributions from the sun, Earth, and deep space. With external factors constant, optical properties of the sail are the driving factors for steady state temperatures. Steady state temperature is found by balancing the radiative thermal energy equations shown in (3.3) and (3.4) [11], where \( Q \) is energy input/output, \( q \) is energy flux (\( W/m^2 \)), \( \alpha \) is the solar absorptivity of the sail, \( \varepsilon \) is the infrared emissivity of the sail, \( A_{sail} \) is the sail area, \( F \) is the sail-to-Earth view factor, which varies with altitude and sail orientation, \( \sigma \) is the Stefan-Boltzmann constant, and \( T_{space} \) is the background temperature of the universe (4 K).

\[
Q_{in} = \alpha q_{solar} A_{sail} + \alpha q_{IR} A_{sail} F + \varepsilon q_{IR} A_{sail} F 
\]

(3.3)

\[
Q_{out} = \varepsilon \sigma A_{sail} (T_{sail}^4 - T_{space}^4) 
\]

(3.4)

It should be noted that a steady state assumption for this system is applicable as the thin film sail has very low thermal mass (i.e. temperature changes occur quickly). Combining Equations (3.3) and (3.4) with WCH and WCC geometries gives a solution for the extreme temperatures. For WCC, the sail is in eclipse and the thermal energy balance becomes Equation (3.5), as solar and albedo inputs are reduced to zero. As this equation is independent of sail properties, all sails will experience the same WCC temperature of \(-130^\circ C\).

\[
q_{IR} F = \sigma (T_{sail}^4 - T_{space}^4) 
\]

(3.5)

WCH temperatures are achieved when the sail is between the sun and Earth and oriented perpendicular to the sun vector. This results in maximum solar heating on one face and albedo input on the other. WCH temperatures are tabulated in Table 2, for double-side aluminum coated sails. Variations in temperature are due to variations in each manufacturer’s application of the coating.

Table 2 - WCH temperature for drag sail

<table>
<thead>
<tr>
<th>Base material</th>
<th>WCH Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mylar</td>
<td>211</td>
</tr>
<tr>
<td>Kapton</td>
<td>260</td>
</tr>
<tr>
<td>Upilex</td>
<td>267</td>
</tr>
</tbody>
</table>

At this WCH temperature, Mylar is nearing its melting temperature, rendering it unusable, while Kapton and Upilex have maximum recommended operating temperatures of 240°C and 270°C respectively from...
their manufacturer. As both materials are near maximum operating temperatures, thermal aging effects must be considered. Over a 25 year deorbit lifetime, a conservative assumption can be made that half of this time (12.5 years) will be in a WCH scenario. Over this time, Kapton is expected to become more brittle than Upilex according to their respective manufacturers. The maintenance of sail ductility is important as it reduces the severity of damage caused by debris. Therefore, Upilex was selected as the base material for this design.

3.3 Collision Analysis and Tear Propagation

During the deorbit operation, the large sail will be subjected to impacts from natural (micrometeorite) and unnatural debris. This will inevitably cause damage to the sail, and could lead to loss of a sail if the damage were to propagate edge to edge and sever one of the four connection points. Combining probabilistic models of debris impact rates with estimates from impact and fracture mechanics enables a quantitative estimate of whether a sail will catastrophically fail.

3.3.1 Impact Probability

The probability of impact by a given particle size can be found by applying a Poisson’s distribution to a particle fluence prediction, as shown in Equation (3.6) [12], where \( P_n \) is the probability of a number of impacts, \( N \) is the cumulative particle fluence for a given debris size “bin”, and \( n \) is the integer number of impacts.

\[
P_n = \frac{N^n}{n!} e^{-N}
\]

To determine the probability of any impacts for a given particle size, the probability of zero impacts is calculated and subtracted from 100%. A confidence margin of 95% is applied, where it is assumed that any particle with a 5% chance or greater will impact the sail.

The cumulative particle fluence is determined using publicly available debris models. For this work, the European Space Agency’s MASTER 2009 software was used. The debris distribution in LEO varies with altitude and inclination; however, a constant orbit solution was sought due to the decoupled nature of the debris software and the deorbit trajectory. A synchronous orbit at 800 km altitude was found to incur the most debris, and was used to determine the debris fluence at the spacecraft from the model [13]. A plot of particle fluence against debris size is shown in Figure 4 for a 1 m² sail over 25 years. Using Equation (3.6) with the modeled debris fluence, the probability of impact of one or more particles is determined as shown in Figure 5. From this analysis, a 1.5 mm diameter particle is expected to cause the largest impact.

![Particle flux](image)

**Figure 4 - Debris fluence over 25 years at 800 km altitude**

3.3.2 Loading and Fracture Mechanics

The primary concern with damage accumulation is the severing of one (of four) corner attachment points of the drag sail. Knowing the largest impact will be from a 1.5 mm particle, the long term damage can be estimated from hypervelocity impact trends for polyimides and fracture mechanics. Testing by [14] and [15] have shown that the ratio of particle size to film thickness is related to damage size in hypervelocity impacts. It has been shown that for a 1.5 mm particle passing into a 12.5 µm sail, the hole diameter is assumed to be the same size as the particle, or 1.5 mm. This is only true for non-brittle materials, which drives the desire to keep the sail membrane material from undergoing a glass transition. Brittle materials suffer from crack growth at impact sites, which increases damage size in an unpredictable way.

![Impact probability](image)

**Figure 5 - Impact probability for 25 year exposure**
It is assumed for this analysis that the sail has no damage prior to deployment. This can be accomplished with thorough quality assurance and rejection of any sails showing damage. This process will mitigate the failure of sails during the deployment sequence. After the sail is deployed, the instantaneous loads on the sail are quite small. The worst case load identified was for a drag induced roll by a single sail at 300 km altitude acting on a single base attachment point. Drag and centripetal loads were combined, giving a 5 mN worst-case load. This loading system can be idealised as shown in Figure 6. This system is a purely tensile “mode I” fracture mechanics system and can be analysed accordingly. A single attachment point was assumed for conservatism and a width of 5 mm was selected to represent the diameter of grommets used at each attachment point.

The fracture mechanics model in Equation (3.7) [16] predicts the stress required to propagate a tear, where $\sigma_c$ is the critical stress required to initiate tear propagation, $K_I$ is the critical stress intensity factor for the material for mode I tearing, $a$ is a function of crack length, and $F$ is a geometric factor that is a function of crack position and sample geometry.

$$\sigma_c = K_I \left( \sqrt{\pi a F} \right)^{-1} \quad (3.7)$$

The results of the fracture mechanics analysis for a 12.5 $\mu$m thick sail are shown in Figure 7. For the expected 1.5 mm damage from debris impact, a load of approximately 1500 mN is required to propagate the tear. The 5 mN expected loads are therefore insufficient to cause damage growth, and as a result, the sail design requires no additional reinforcement against tear propagation.

![Critical crack length](image.png)

Figure 7 - Loads required causing damage propagation for the idealised sail geometry

### 3.4 Flight Sail Design

After thermal, atomic oxygen, debris, and damage analysis, the sail material can be selected. Based on the previously discussed analyses, a double-side aluminized Upilex sail (Al-Upilex-Al) with a 12.5 $\mu$m membrane thickness will meet all requirements for the CanX-7 and reference missions. The final sail is 1.06 m², providing a total drag area of 4.25 m² for deorbiting.

### 4 SAIL INSPECTION SYSTEM

Confirmation of sail deployment will be performed by the onboard reel telemetry system that monitors the rotational motion during the uncoiling of the booms. For the inaugural flight of the drag sail modules, the telemetry system must be qualified as a method of sail quality measurement, which indicates that a direct confirmation method is required. An inspection camera system was selected as an unambiguous way to directly measure deployment percentage such that the telemetry recorded by the drag sail module can be confirmed.

The system implemented makes use of the small volume available at the end of CanX-7’s deployable
boom. In a package that measures just 20 mm x 30 mm x 10 mm, a triad of small cameras are housed, capable of capturing over 50% of the fully deployed sail as shown in Figure 8. This system is entirely independent, requiring only power and communications from the bus. This arrangement allows for imaging of portions of each sail, but focuses on major features—booms and sail baselines—that allow for assessment of sail deployment quality.

Figure 8 - Camera triad field of view of fully deployed sail

The system consumes 120 mW when active (imaging with a single camera), and less than 60 mW when idle. Imaging is performed one camera at a time, as the cameras are multiplexed to a single controller and memory bank. Automatic, semi-manual, and fully manual exposure and gain control are available to operators. Through risk reduction testing, the controls available have shown sufficient range to capture images in orbital lighting conditions. Software and hardware development on an engineering model has been performed, as well as image testing in a dark room environment to simulate the conditions expected in orbit. Figure 9 shows the engineering model of the camera motherboard, with the single perpendicular facing imager.

Figure 9 - Engineering model of the CanX-7 imager board

Shown in Figure 10 is an image captured during representative testing of the imaging system during a sun-stare reflecting off of the drag sail. This image was captured using fully automatic control. Incident light from the Sun is one of the worst case imaging cases due to over exposure, but the edge of the sail is still visible for deployment quality analysis. Manual control can offer better performance in this situation, which will be pursued in future work. It is expected that the image quality will increase in non-incident scenarios with either solar or albedo irradiance upon the sail. The primary goal of this imagery is locating the edge—or corner; camera dependent—of the sail, as it will give operators a measure of how far the sail deployed. This measure will then be used to quantify how well the reel telemetry system performed during deployment. This imaging system has the potential to be used for performance monitoring of the sail during the deorbit and, in particular, to assess any major damage that the sail may incur.

Figure 10 - Dark room image testing reveals deployment quality can be quantified with camera system

5 DEPLOYMENT TESTING

Fundamental to the deorbit payload’s development is ground-based risk reduction testing. Performing representative deployment tests can reveal any subtle design flaws while simultaneously characterising the deployment dynamics of the system. Understanding the dynamics prior to flight allows for deployment confirmation on orbit by comparing on orbit deployment telemetry with ground-based deployment telemetry.

Deployment testing is performed on a custom built deployment table. The deployment table mimics the triangular shape of the deployed drag sail, providing supports for both the booms and sail. Figure 11 shows
an example of a fully deployed sail on the deployment ground support equipment.

Figure 11 - Successful test performed on the deployment table

For testing expediency, the majority of test deployments are performed without the sail. This is critical as it allows for reduced turnaround times on deployment tests by removing the inspection and repacking aspects of sail arming. Results of module testing are not jeopardized however, as deployment tests with the sail are performed at temperature extremes to confirm deployment functionality. Of most importance is testing with the sail at cold temperatures, as this condition offers the highest resistance to motion from the reel assembly. If deployment with the sail is successful at cold extremes, then inclusion of the sail is unnecessary for room temperature and elevated temperature testing. Following this testing rationale, over 200 deployment tests of the drag sail module have been performed to date.

5.1 Deployment Dynamics

Deployment energy is provided by two coiled tape spring booms. These booms, as well as the folded sail, are restrained by a Vectran cord that is severed on command. Deployment accelerations can be determined by considering the rotational rates of the reel. The balance of driving and resisting torques is shown in Equation (5.1), where \( I_{\text{reel}} \) is the reel assembly inertia, \( \alpha_{\text{reel}} \) is the rotational acceleration of the reel assembly, \( \tau_B \) is the torque generated by the booms, and resisting torques: \( \tau_b \) from the bearings, \( \tau_f \) from internal friction, \( \tau_s \) from sail unfolding, and \( \tau_{B,e} \) from the elongated booms inertia.

\[
I_{\text{reel}}\alpha_{\text{reel}} = \tau_B - \left[ \tau_b + \tau_f + \tau_s + \tau_{B,e} \right] \tag{5.1}
\]

A coiled tape spring exerts a constant moment that can be determined based on the bend orientation and tape spring geometry. Equal and opposite steady end moments can be calculated using Equations (5.2) and (5.3) respectively [19]. These equations can be used knowing geometric and material properties, where \( v \) is Poisson’s ratio, \( \theta \) is the subtended angle of the tape spring, \( E \) is Young’s modulus, and \( t \) is thickness.

\[
\tau_{\text{same}} = (1 - v) \left[ \frac{E t^3}{12 (1 - v^2)} \right] \theta \tag{5.2}
\]

\[
\tau_{\text{opposite}} = (1 + v) \left[ \frac{E t^3}{12 (1 - v^2)} \right] \theta \tag{5.3}
\]

Of the two booms coiled in the drag sail module, one is coiled in the same sense and the other is coiled in the opposite sense. To calculate the total driving torque, the individual torque values are summed. For the copper beryllium booms used in the drag sail module, the combined moments create a theoretical driving torque of 60 mNm.

The challenge for modelling this complex system is determining accurate models for the resisting torques. Reel and elongated boom inertia can be modeled as time varying values to account for the geometric changes that occur during deployment, while internal friction can be estimated as metal on nylon contact. However, without accurate temperature and velocity dependent models for bearing and sail unfolding resistances, the model cannot be readily used to predict deployment performance. For this reason, testing is favoured over analytical predictions in this risk reduction campaign for the drag sail module.

5.2 Room Temperature Deployment Testing

The majority of deployment tests have been performed at room temperature (17°C to 20°C) to understand the dynamics and repeatability of deployment. During deployment, rotational motion is measured by a Hall Effect sensor telemetry system integral to the module. These measurements can be used to determine overall deployment time and deployment speed, to estimate deployment completion (i.e. how much the booms deployed). This telemetry provides all the information required for test comparison and characterisation of the system.

Most recent tests comparing deployment performance with changes to components of the reel assembly have shown deployment timing consistency, with a standard deviation of 1.1%. The results of these tests are shown in Figure 12. This testing is important due to the segmented design of the drag sail module. As only one module is currently being tested, consistency across modules can be demonstrated by varying the reel assembly as it is the primary moving component of the system. Understanding the deployment extremes is critical as each module must safely operate independently. Altogether, room temperature testing has shown that the average deployment time is 1546 ms ± 68.6 ms (1-σ).
As the drag sail module has no integrated soft stop mechanism, the stopping force is provided by the booms and the housing. If this action is too violent due to high deployment speeds, damage can occur. This does not pose an immediate concern for single-deployment use in space, but each module must be able to survive a number of deployments prior to flight to ensure they are fully functional. Through extensive testing, it was found that stopping a 500 ms deployment test caused no visible damage to any components. Therefore, if deployment times are maintained above 500 ms, the deployment lifetime is deemed sufficiently long to last all pre-flight and in-flight deployments. The room temperature deployments presented in Figure 12 meet this requirement.

5.3 Temperature Effects

The temperature of the module greatly affects the speed of a given deployment, with hot conditions resulting in faster deployments and cold conditions resulting in slower deployments. It has been found that when deployed without the sail, hot deployments are twice as fast and cold deployments are half as fast as room temperature deployments. The change in speed is predominantly from a change in bearing and damping resistance, with minor effects from variations in sliding friction. Representative data gathered from the reel telemetry system is shown in Figure 13 for cold (−40°C), room temperature (20°C), and hot tests (80°C). This data has been smoothed with a low pass filter for clarity. While faster, the hot deployment tests are still above the 500 ms deployment time safety requirement.

Cold deployments performed with the sail are the limiting case for the torque resistance that the module will experience and the final step in risk reduction testing. It has been shown that the module will successfully unfurl the sail to its full area over multiple deployments at −40°C. Reel telemetry has shown that deployment times are significantly longer and have periodic decelerations due to unfolding resistance.

The next step in the qualification of the module is thermal vacuum (TVAC) testing. The drag sail module will undergo deployment testing in a TVAC chamber capable of housing the fully deployed sail. Supporting hardware has been developed to simultaneously test six modules in a stacked configuration, and allows each to deploy its sail without interference. The predicted hot, cold, and, average on-orbit temperatures will be used to test and qualify this system.

6 CONCLUSIONS

Disposal technology is currently unavailable for nano and microsatellites, but is required to help mitigate the increasing congestion of low Earth orbit. As these small satellites become more popular for high performance missions at higher altitudes, natural deorbit lifetimes approach and grow beyond the recommended 25 years from the IADC. Deorbiting into Earth’s atmosphere is one suggested method of disposal, which can be achieved by exploiting the thin atmosphere of the LEO environment. An aerodynamic drag device, in the form of a thin deployed sail, is being developed by the Space Flight Laboratory to reconcile this challenge for small satellites.

Sail material selection has been performed such that drag area will be maintained until disposal is accomplished. This has required analysis of the many
environmental stresses experienced in LEO, which includes atomic oxygen, thermal, and debris exposure. This process has revealed that Upilex is the ideal choice for the sail membrane, to resist thermal degradation, with aluminum coatings on both sides to protect against atomic oxygen erosion. At just 12.5 µm thick, this drag sail is capable of surviving the rigors of space for up to 25 years.

To confirm sail deployment, two systems will be operational on CanX-7: the onboard reel telemetry system, and the inspection camera system. The camera system hardware and software has been developed up to its operational state for use in confirming reel telemetry by evaluating the area of sail deployed, as well as for lifetime monitoring of the sail to understand damage accumulation that may occur. This standalone system consumes a mere 6 cm³ of spacecraft volume, but provides a necessary service to this and future satellites. Further control development and testing is required prior to flight in order to determine the resolution of sail deployment measurements taken from these images.

The desire to reduce risk associated with new technology involves analysis and testing, but the complexity of the drag sail module deployment dynamics has led to a reliance on testing. An extensive test campaign was performed to understand the dynamics and identify any design issues. Deployment times at room temperature averaged 1546 ms, and showed consistency with a standard deviation of 68.6 ms. Hot deployments at 80°C remained 33% above the safe deployment timing margin of 500 ms. Finally, cold deployment tests performed with the sail proved that the deployment system is capable of deploying in its worst case conditions with maximum resisting loads. Due to this work, new drag sail modules can now be qualified by comparison with deployment data without the sail, drastically saving on validation time.

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8 REFERENCES


