The CanX-7 Drag Sail Demonstration Mission: Enabling Environmental Stewardship for Nano- and Microsatellites

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ABSTRACT

With an increasing number of single- and multi-small spacecraft missions, the need for environmental stewardship in space has never been more critical. As the 25-year deorbiting recommendations of the Inter-Agency Space Debris Coordination Committee (IADC) are adopted globally, there will be increased pressure on operators of both single-satellite and especially constellation missions to be able to deorbit their spacecraft in a cost-effective, expeditious way. Meeting the challenge of deorbiting satellites at end-of-life is particularly complicated by the fact that satellites cannot be relied upon to operate properly under such circumstances. Thus, the need for a simple, independent, and effective deorbiting technology—that does not itself increase risks to other low-Earth orbit spacecraft—is a problem of mortal significance for the small satellite community.

This paper discusses the CanX-7 technology demonstration mission, with a focus on the extensibility of its drag sail payload to micro- and nanosatellite constellations. The paper is divided into two parts. First, a general overview of the deorbiting problem is presented, and so-called "killer trades" associated with a variety of deorbiting approaches are discussed. A model is then presented that enables system designers to quickly choose the right deorbiting technology for a given spacecraft or constellation mission. The second part of this paper describes the CanX-7 deorbiting demonstrator. Expected to launch in 2014, CanX-7 will deploy a simple, modular, redundant, and adaptable drag sail technology for removing spacecraft from low Earth orbits at end-of-life. This technology, once demonstrated on orbit, can then be adapted to other LEO spacecraft to enable simple maintenance and EOL disposal in a simple and cost-effective way.

1 INTRODUCTION

As the number of objects in Earth orbit grows, the international satellite community faces a growing problem associated with orbital debris and space collision avoidance. In September 2007, the Inter-Agency Space Debris Coordination Committee (IADC) recommended that satellites deorbit within 25 years after the completion of their mission, or within 30 years of launch if they cannot be parked in less dense ("graveyard") orbits [1], [2]. Governments around the world are introducing procedures to implement the recommendations of the IADC, and consequently, this poses a significant programmatic risk for new space missions, especially those requiring rapid, responsive, short missions in low-Earth orbit (LEO). Unfortunately for nano- and microsatellites—which are ideally suited for responsive, short missions, as well as low-cost LEO constellations—no mature deorbiting technology currently exists that is suitable for a wide range of missions and orbits. Furthermore, there has not yet been a successful on-orbit demonstration of a suitable deorbiting device for both nano- and microsatellites.

The CanX-7 (Canadian Advanced Nanosatellite eXperiment-7) mission aims to accomplish one of the first successful demonstrations of a passive nano- and microsatellite deorbiting device[1]. Currently under development at the University of Toronto's Space Flight Laboratory, CanX-7 will employ a lightweight, modular, deployable drag sail to de-orbit a demonstrator nanosatellite. The sail payload design is highly compact, and able to fit onto even the smallest cubesat-based platforms, while still providing approximately $5m^2$ of sail area following deployment. CanX-7 will demonstrate the drag sail's customizability, modularity, stowability and effectiveness at meeting the deorbiting requirements of the IADC. This mission is funded by Defence Research and Development Canada (DRDC-Ottawa),

[1] This is contrary to Nanosail-D or IKAROS, both of which were solar sail missions. However, Nanosail-D (along with the RAIKO cubesat) has nevertheless successfully demonstrated the efficacy of a sail for deorbiting. CanX-7 will build on this by demonstrating a sail *for* nanosatellites, instead of a sail that just fits inside of one.

NSERC and COM DEV Ltd, with an expected launch in the mid-to-late 2014 timeframe. COM DEV and the Royal Military College of Canada (RMC) are also contributing a secondary Automatic Dependent Surveillance – Broadcast (ADS-B) receiver payload, which will be operated for six months prior to sail deployment in order to emulate an operational mission implementation of a deorbiting device.

This paper describes the CanX-7 mission, prefaced by a discussion of different deorbiting approaches for LEO small satellites, and an evaluation of the performance of drag sail based deorbiting for different sized satellites in the smallsat class.

2 DEORBITING METHODS

For most small satellites in low-Earth orbit, the only viable means of achieving end-of-life disposal is to deorbit. In some cases, the inherent characteristics of a satellite (i.e. its ballistic coefficient) and its altitude are such that the satellite will naturally deorbit within 25 years or less. However, in many cases, because of either high ballistic coefficient or relatively high altitude, deorbiting must be accomplished using a dedicated system. Several approaches to deorbiting exist, and can be broadly categorized as either *active* (i.e. requiring continuous operation, usually steering) or *passive* (i.e. requiring only deployment to effectively deorbit, with no attitude control needed).

2.1 Active Methods

Active methods of deorbiting require attitude control beyond the end of spacecraft life, by definition. Maintaining such attitude control either requires the satellite attitude control system to be functioning properly (which cannot be assured at end-of-life) or necessitates an additional (integral) deorbiting attitude determination and/or control system, which increases complexity and cannibalizes precious mass and volume (both of which are at a premium in small spacecraft). Examples of active approaches include propulsion systems and controlled (steered) solar and drag sails.

The most traditional active method for deorbiting is to use a propulsion system. However, the problem with propulsive deorbiting is that you must be able to point the thruster—which, as described, implies the ability to control (or at least determine) the attitude of the satellite, which cannot be assured beyond EOL. Notwithstanding this consideration, propulsive deorbiting also requires additional propellant, which drives spacecraft mass. For larger satellites that already require high-performance orbital maneuvering systems, the additional delta-V to deorbit may be a manageable penalty, but for smaller satellites the added mass, testing and handling complexity can be deal breakers.

Controlled solar or drag sails have been proposed [3], in which the sail orientation is constantly controlled relative to either the solar vector for steered sailing or the satellite velocity vector to maximize drag. These approaches have the same drawback as using propulsive techniques, in that they must be continuously controlled—however, in the case of active solar or drag sails, instead of needing to maintain attitude for several minutes to execute the deorbiting maneuver, continuous attitude control may be required for months or even years! This is a significant burden to impose on a mission—particularly a small space mission, whose operations budget may have long since been exhausted at end of mission.

For these reasons, active approaches that require post-EOL control are viewed less favorably than passive methods for single- or multi-smallsat missions.

2.2 Passive Methods

In contrast to active approaches, passive techniques do not require the satellite to remain operational during the deorbiting phase. Passive methods require no active control, relying only on natural perturbations and forces to accomplish deorbiting, and are therefore intrinsically much simpler than active methods. Examples of passive methods include drag sails, balloons, and ribbons or tethers. Passive systems are generally viewed here as preferable to active systems, given their "turn-key" characteristics—once a passive system is activated, it requires no long-term control or maintenance.

Tethers have often been advocated as promising deorbiting technologies for small satellites. However, such devices are usually extremely large when deployed (often hundreds of meters), have complex deployment (and deployed) dynamics, and have a demonstrated propensity to tangle and sever. Alternative concepts, such as inflatable balloons or inflatable drag sail devices, require the use of pressurized gas, which is problematic both for launch and for long-term leak-free storage. Inflatables can also be critically vulnerable to micrometeorite and orbital debris (MMOD) punctures, which is problematic for worst-case deorbiting durations. Techniques for rigidizing inflatables following deployment to address MMOD concerns have been proposed, but add complexity and testability challenges.

Contrary to the above options, passive, mechanically-deployed drag sails offer a promising approach to deorbiting. Such drag sails are passive, requiring no attitude control—decidedly preferable to active methods—and they can be deployed using only stored mechanical energy, without pressurants or pyrotechnics.

2.3 Deorbiting Device "Killer Trades"

A comparison of common deorbit approaches discussed for small LEO spacecraft is provided in Table 1, in which the so called "killer trades" of each option—the driving requirements, constraints and risks inherent in each—are summarized. Of the options presented in Table 1, mechanically-deployed drag sails are viewed as most promising for deorbiting nano- and microsatellites below a certain size, provided the orbit altitude is sufficiently low to allow drag-based deorbiting. Mechanically-deployed drag sails offer the benefits of small characteristic dimension, no attitude control requirements, and no pressurized gasses, instead using only their own stored mechanical energy for deployment. For these reasons, the development of a drag sail-based deorbiting technology has been selected by SFL for CanX-7, as well as future missions.

Table 1: Summary of Deorbiting Techniques for LEO Satellites

Deorbit Approach	Active / Passive	Killer Trades
Propulsion	Active	• Requires high total impulse (challenging for small satellites) • Requires active pointing / steering • Requires long-term propellant storage
Solar Sail	Active	• Requires active pointing / steering • Susceptible to jamming • Susceptible to MMOD degradation
Electrodynamic or Drag Tether	Passive	• Large characteristic dimension • Deployment complexity • Susceptible to jamming / tangling • Inclination-limited (electrodynamic tethers)
Inflatable Drag Device	Passive	• Requires long-term, leak-free storage of compressed gas • Altitude-limited • Susceptible to jamming • Susceptible to MMOD degradation / puncture
Mechanically-Deployed Drag Device	Passive	• Requires storage of mechanical energy • Altitude-limited • Susceptible to jamming • Susceptible to MMOD degradation

3 EVALUATION OF DRAG-BASED DEORBITING

To characterize the performance of drag sail-based deorbiting, and to understand its limitations, a series of lifetime analyses for LEO satellites were performed across a set of reference spacecraft. These results are summarized below.

3.1 Reference Spacecraft

In order to evaluate the efficacy and limitations of aerodynamic-based deorbiting for small satellites (and drag sails as a deorbiting technology in particular), we examine a series of reference smallsats that span the range of "useful" sizes and form factors. Each reference spacecraft is similar in characteristics to other small satellites used or proposed for operational single- or multi-satellite missions. These reference spacecraft are summarized in Table 2.

Table 2: Summary of Reference Spacecraft

Reference Spacecraft	Mass (kg)	Min. Area (m^2)
Triple Cube	3.5	0.01
GNB Nanosatellite	7.0	0.04
NEMO Nanosatellite	15.0	0.08
Microsatellite	100	1.0
Small Satellite	500	4.0

The first reference spacecraft is a "3U", or triple-cube spacecraft with a mass of 3.5 kg—this is representative of the CanX-7 nanosatellite, as well as the CanX-2 nanosatellite (operational since 2008) and a host of other current and near-term satellites.

The second reference spacecraft corresponds to the SFL Generic Nanosatellite Bus (GNB) form factor, which has a maximum mass of 7 kg in a 20cm by 20cm cubical form factor. The GNB form factor has been the basis for the NTS, AISSat-1, and UniBRITE / BRITE-Austria satellites currently on orbit, as well as the upcoming AISSat-2, BRITEs-Poland, BRITEs-Canada, CanX-4&5, and EV9 missions.

The third reference satellite, NEMO-class bus, also developed by SFL, straddles the border between nanosatellite and microsatellite, with a typical mass of 15 kg and a minimum ram area of 20cm by 40cm. The NEMO platform is currently being used by the NEMO-AM (ISRO) and NORSAT-1 (Norwegian Space Centre) satellites.

Lastly, two larger reference spacecraft—a 100kg, 1m cubical satellite, and a 500 kg 2m cubical satellite—are included to represent the larger end of the smallsat scale.

3.2 Methodology for Lifetime Analyses

In order to evaluate the efficacy of passive (aerodynamic) deorbiting of each reference spacecraft, a series of LEO altitudes from 400 km to 1000 km in 100 km increments are studied. In each case, the lifetime analysis tool in STK is used, with the input parameters summarized in Table 3. 100 km is taken as the altitude at which each satellite is considered to have successfully deorbited, though orbits at or below 300 km typically have lifetimes measured in hours to days. (Practically speaking, altitudes below 400 km are considered "deorbited", since life is short and—most importantly—spacecraft fly below the International Space Station.)

Table 3: STK Lifetime Analysis Parameters

Parameter	Value
Drag Coefficient (All Cases)	2.4
Atmospheric Model	NRLMSISE 2000
Decay Altitude	100 km
Solar Flux File	SolFlx_Schatten (June 2013)
Solar Flux Sigma Level	0
Start Date	10 June 2015

For commonality between each case, each LEO is specified as noon-midnight sun-synchronous, with the inclination equal to the sun-synchronous value at each altitude. While the SSO constraint does not by any means encompass the orbits of all missions in this spacecraft range, deorbiting performance from SSO is considered representative of other orbits. By way of illustration, Figure 1compares the deorbit time of the 100 kg reference spacecraft from 800 km with starting inclination at SSO, 52°, and 23.5°. In each case, the time required to deorbit is approximately the same.

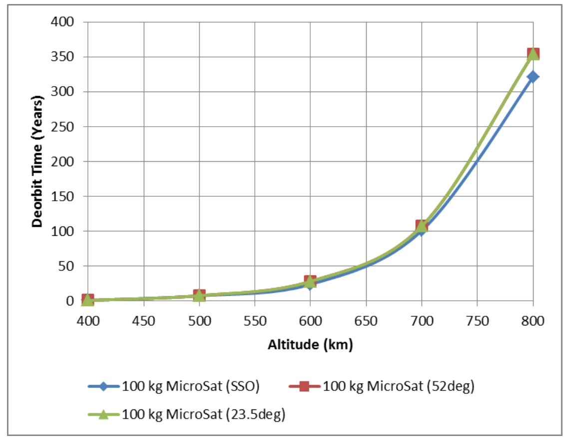

Figure 1: Comparison of Deorbit Times for 100 kg Microsatellite (1 m^2 Ram Area, SSO, 23.5° and 52° Inclinations)

For each reference spacecraft, three ram (frontal) areas are used to calculate deorbit times, corresponding to the minimum frontal area specified in Table 2; a total area resulting from the use of the SFL 5m^2 drag sail module described in this paper; and a 25m^2 drag sail, which is the practical limit of scalability for the SFL drag sail design presented in this paper. (Incidentally, this is also the expected area of the SSTL DeorbitSail [3], the largest dedicated drag sail for small spacecraft proposed in the open literature as of this writing—though the SSTL sail uses active steering throughout deorbiting, and is thus not strictly passive.)

It must be noted that deorbiting analyses are highly uncertain, with variance in results on the order of 10-20% of the predicted satellite lifetime. This is due to the large degree of uncertainty in atmospheric density integrated over life, which itself arises from uncertain solar activity predictions, since atmospheric density varies directly with solar flux. In each case studied here, either the nominal (minimum) spacecraft area or the full area of the sail (i.e. an aero-stabilized configuration) is assumed for deorbiting. While it is practically quite challenging to achieve aero-stabilization above altitudes of approximately 600 km, maximum-drag attitudes may be approached by minimizing disturbances arising from gravity gradient torques and geomagnetic torques—in the former case, by controlling satellite mass distribution across appendages, and in the latter case by reducing, eliminating, or compensating for the residual magnetic moment of the spacecraft during deorbiting, ideally accomplished passively using a trim magnet or compensatory dipole [4]. In the presence of these disturbances, the effective area available for drag can be reduced considerably, and must be accounted for in simulations.

3.3 Lifetime Analysis Results

Figure 2 through Figure 6 present the results of the deorbiting analyses for each reference spacecraft. In each figure, the time required to deorbit is plotted as a function of altitude on curves of constant ballistic coefficient, with the nominal (un-augmented) ram area, 5 m^2 CanX-7 drag sail, and 25 m^2 maximum-size drag sail evaluated.

Figure 2 presents results for the triple-cube reference spacecraft. Without a dedicated deorbiting device, the triple cube form factor has a relatively high ballistic coefficient, and can remain in orbit for some time. This is shown by the blue curve in Figure 2, which predicts lifetimes exceeding five decades as altitude approaches 600 km. however, when augmented with the baseline 5 m^2 drag sail, lifetimes are substantially shortened for all altitudes spanning the full range studied. At 1000 km, both the 5 m^2 and 25 m^2 sails satisfy the 25 year deorbiting period with ample margin. Thus, for the entire range of orbit altitudes considered, drag sails are a good means of disposing of spacecraft in this form factor.

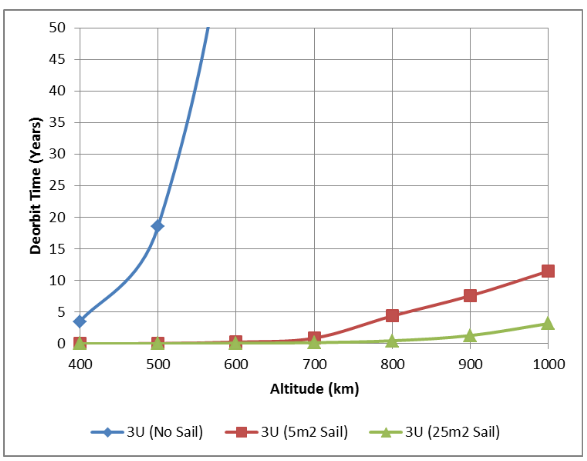

Figure 2: Deorbiting Times for Triple-Cube Reference Satellite

Figure 3 presents deorbiting results for the GNB reference spacecraft. As with the triple cube, the GNB form factor has a high ballistic coefficient in the absence of a drag sail, and lifetime on-orbit is long without any drag sails. However, as with the triple cube, the deployment of either 5 m^2 or 25 m^2 reference sail reduces satellite lifetime dramatically, to within the IADC guidelines. Thus, again, the drag sail technology being developed for CanX-7 is suitable for GNB-class spacecraft.

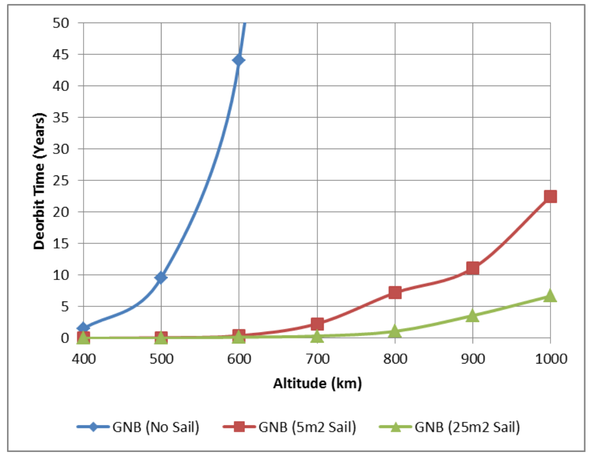

Figure 3: Deorbiting Times for GNB Reference Satellite

Figure 4 shows deorbiting results for NEMO-class missions. NEMO lifetimes on-orbit are similar to both triple cube and GNB missions in the absence of drag sails. The addition of the 5 m^2 sail achieves lifetimes within the 25-year IADC guideline up to altitudes of 900km; however, in the range of 900 to 1000 km, larger sails are required to achieve deorbiting within this period. Practically speaking, spacecraft of this class may have large residual magnetic moments, which (based on studies performed during the CanX-7 program) can decrease the effective area of drag sails to close to 50%, resulting in a “ceiling” of only 800 km for the 5 m^2 sail, above which larger drag sails are required. However, as can be seen from Figure 4, the 25 m^2 sail achieves the required deorbiting performance across the full altitude range studied.

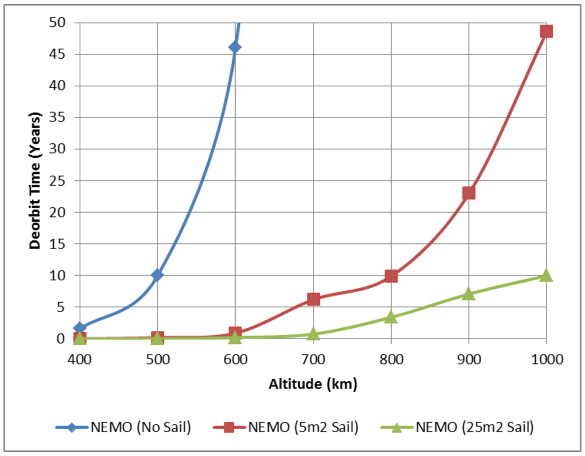

Figure 4: Deorbiting Times for NEMO Reference Satellite

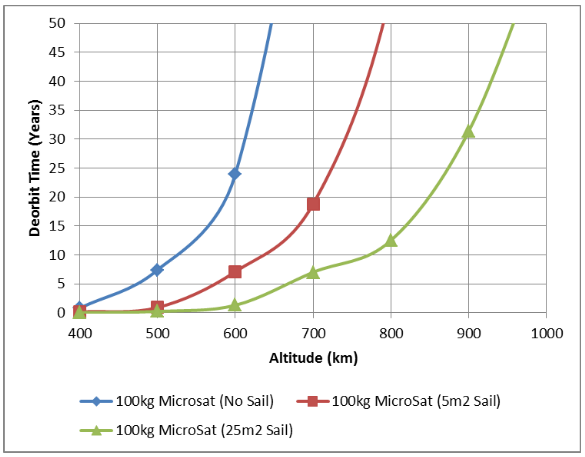

Figure 5: Deorbiting Times for 100 kg Reference Satellite

Figure 5 shows the deorbiting profiles for the reference 100 kg, 1 m^2 microsatellite. For the assumed mass and geometry, the baseline ballistic coefficient (without sail) is larger than the nanosatellites studied above, and the satellite is able to successfully deorbit within 25 years at altitudes up to 600 km without the need for a drag sail. For altitudes above 600 km, the CanX-7 demonstrator 5 m^2 sail is limited in effectiveness to just above 700 km, and the maximum-sized 25 m^2 sail is limited above approximately 860 km.

Lastly, Figure 6 shows lifetime results for the hypothetical 500 kg, 2 m^2 smallsat, the largest reference spacecraft studied. In this case, at altitudes below 600 km the smallsat may deorbit within the prescribed 25 year limit, but not above. Drag sails have diminishing effectiveness for this class of satellite—the 5 m^2 sail does little to reduce lifetime below that achieved without the sail, and the 25 m^2 sail loses effectiveness above approximately 725 km. Thus, for smallsats of this size, we begin to observe the limitations of drag sails for deorbiting.

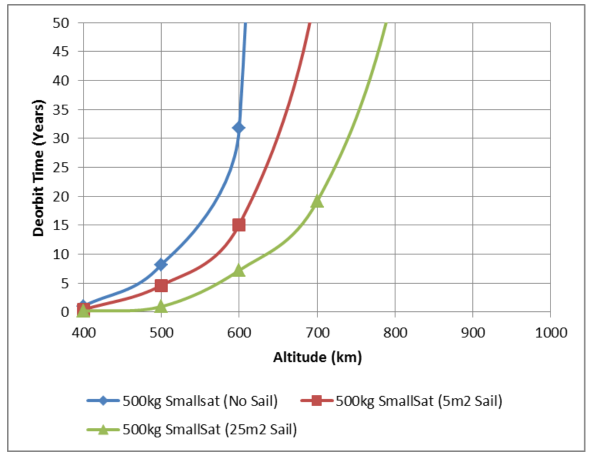

Figure 6: Deorbiting Times for 500 kg Reference Satellite

3.4 Discussion

The above figures illustrate the effectiveness of drag sails across a range of small spacecraft spanning low-Earth orbits up to 1000 km. Generally speaking, for nanosatellites and small microsatellites below 1000 km, small drag sails can be extremely useful in reducing satellite lifetime, while larger satellites require correspondingly larger sails to deorbit within the 25-year recommendations put forth by the IADC. As spacecraft size scales beyond 100 kg, the utility of drag sails (or at least, the drag sails considered here, based on scaling CanX-7 technology) begins to diminish. As well, for altitudes approaching 1000 km, the effectiveness of drag sails begins to diminish for any spacecraft, as there is simply very little atmosphere with which to generate drag (and atmospheric density also becomes more challenging to predict). Fortunately, 1000 km is also the typical ceiling for small spacecraft in single- or multi-satellite missions that have been proposed, since to venture above this altitude requires dealing with increased radiation flux in the Van Allen belts. Thus, for a practical range of low-Earth orbits, and for satellite sizes up to the 100kg class, drag sails are viewed as a good candidate deorbiting approach. For larger satellites (i.e. approaching ½ tonne) and LEOs above 1000 km, drag sails are probably not the right answer; but for nano- and microsatellites, drag sails are perhaps the best combination of deorbiting and cost effectiveness, without the need for continued operation of the satellite bus after deployment.

With the range of missions established for which drag sails can be useful as a deorbiting device established, we now turn our attention to describing the CanX-7 drag sail demonstrator, which will validate the core technology for future passive drag sails of the variety described above.

4 THE CANX-7 DEORBIT DEMONSTRATOR

The CanX-7 mission is intended to demonstrate a simple, modular, and passive deployable drag sail payload for spacecraft deorbiting. This drag sail, once operated successfully on-orbit, will serve as a pathfinder for an eventual standalone end-of-life deorbiting system for nano- and microsatellites.

The CanX-7 spacecraft itself is a simple nanosatellite in a triple-cube form factor. The satellite will deploy four identical drag sail modules in LEO, for a total sail area of approximately 5 m^2, and will quickly deorbit to demonstrate the efficacy of the drag sail technology. On-orbit performance will be used to validate the sail design as well as coupled attitude and deorbiting models. Once demonstrated in-flight, the drag sail technology and performance models can be adapted to suit a wide range of future missions, such as those described in earlier sections.

4.1 Spacecraft Overview

The CanX-7 spacecraft is a 3.6 kg nanosatellite with four drag sail modules comprising its main payload. This drag sail payload is intended to be deployed at the end of a six-month phase of secondary payload operation. Sail deployment will be initially confirmed via on-board telemetry and images, while deorbiting performance will be verifiable within weeks following deployment. In order to provide a path towards adaptation on multiple satellite platforms, the CanX-7 drag sail payload is designed to be modular and scalable, consisting of four individual drag sail modules, each deploying its own independent sail. A total sail area of approximately 5 m^2 is achieved with the full subassembly deployed.

The CanX-7 satellite is shown in

Figure 7 with its sails stowed, and in

Figure 8 with its drag sails deployed. In addition to the drag sail payload, CanX-7 also houses a secondary Automatic Dependent Surveillance-Broadcast (ADS-B) receiver, intended to monitor air traffic in the North Atlantic ocean, as well as a camera boom to capture images of sail deployment, consisting of three COTS imagers arranged to maximize visible sail area.

The CanX-7 bus is based on the CanX-2 triple-cube, in orbit since 2008. CanX-7 consists of an aluminum structure in a 10x10x34cm form factor. A single housekeeping computer (HKC) is used for command and data handling as well as attitude control. The attitude determination and control system (ADCS) is extremely simple, consisting of one three-axis magnetometer for determination and three orthogonally-mounted air-core magnetorquers for magnetic actuation. A UHF receiver provides a 4 kbps command uplink, while an S-Band transmitter provides downlink at 32 kbps minimum, 1 Mbps maximum. A centralized Power Distribution Unit (PDU) based on the SFL Modular Power System [5] provides switched power to spacecraft loads and collects power system voltage, current and temperature telemetry. Eight body-mounted solar strings (consisting of two cells per string) give an average power generation of approximately 2-6 W depending on attitude, while a single 4.8 Ah battery and battery charge/discharge regulator (BCDR) provide energy storage, eclipse power, and load-leveling during power-intensive operation. An exploded view highlighting the various CanX-7 components is shown in Figure 9, while Table 4 summarizes the high-level spacecraft specifications by subsystem. CanX-7 is designed to use the SFL XPOD-triple launch vehicle deployment system, as well as the SFL ground station in Toronto, Ontario, currently being used for the CanX-2, NTS, UniBRITE and MOST missions.

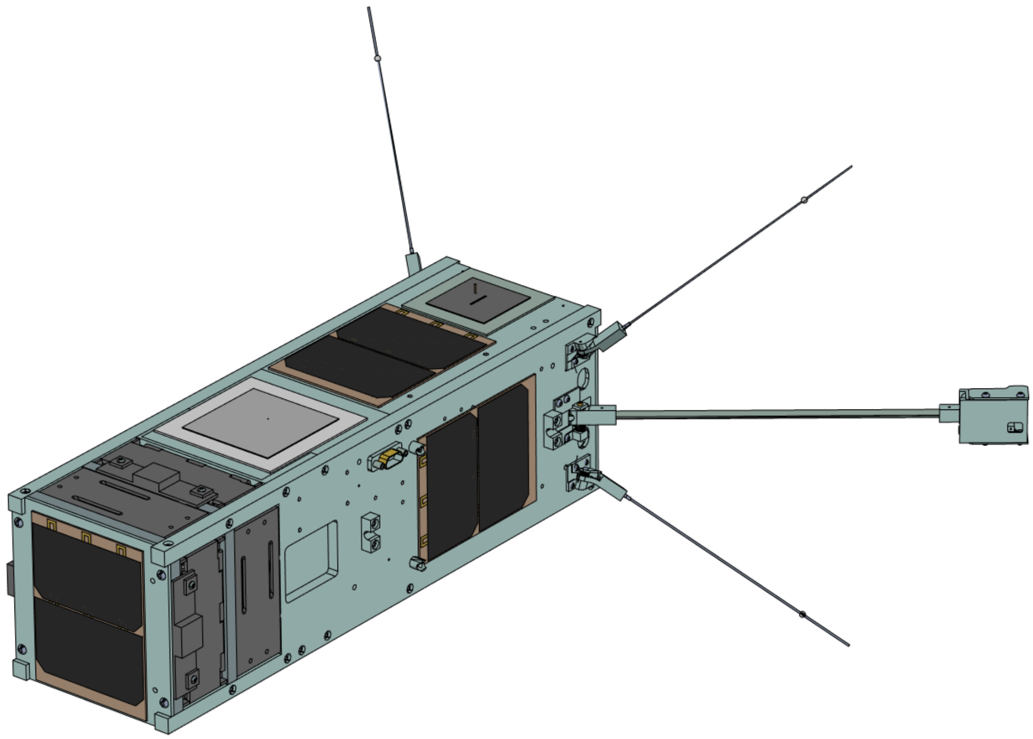

Figure 7: The CanX-7 Nanosatellite (Prior to Sail Deployment)

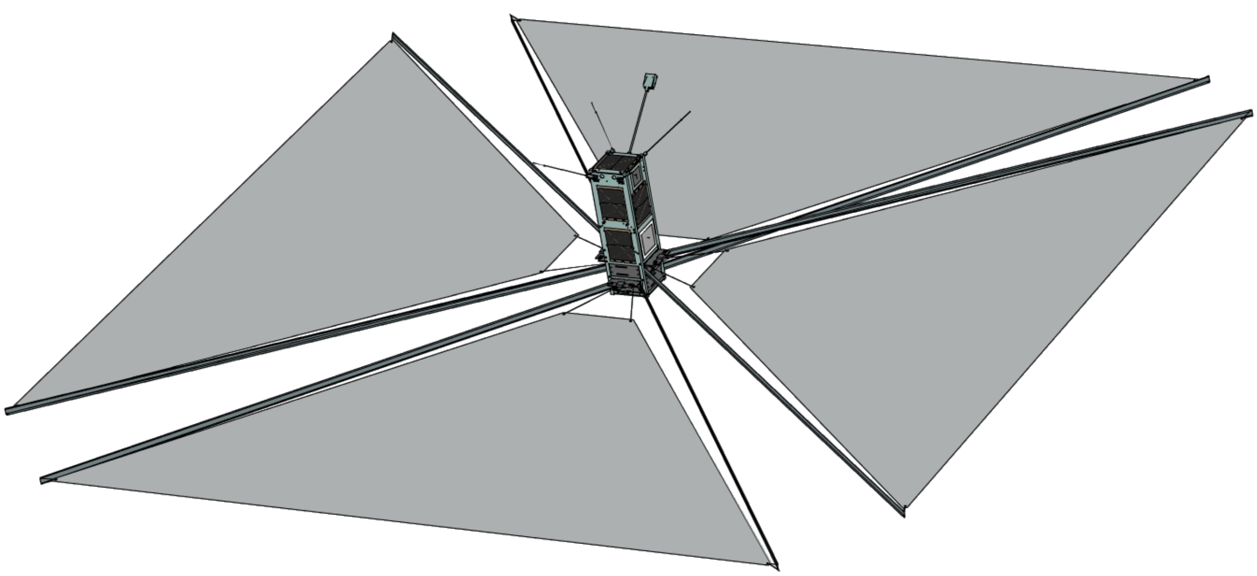

Figure 8: CanX-7 with Drag Sails Deployed

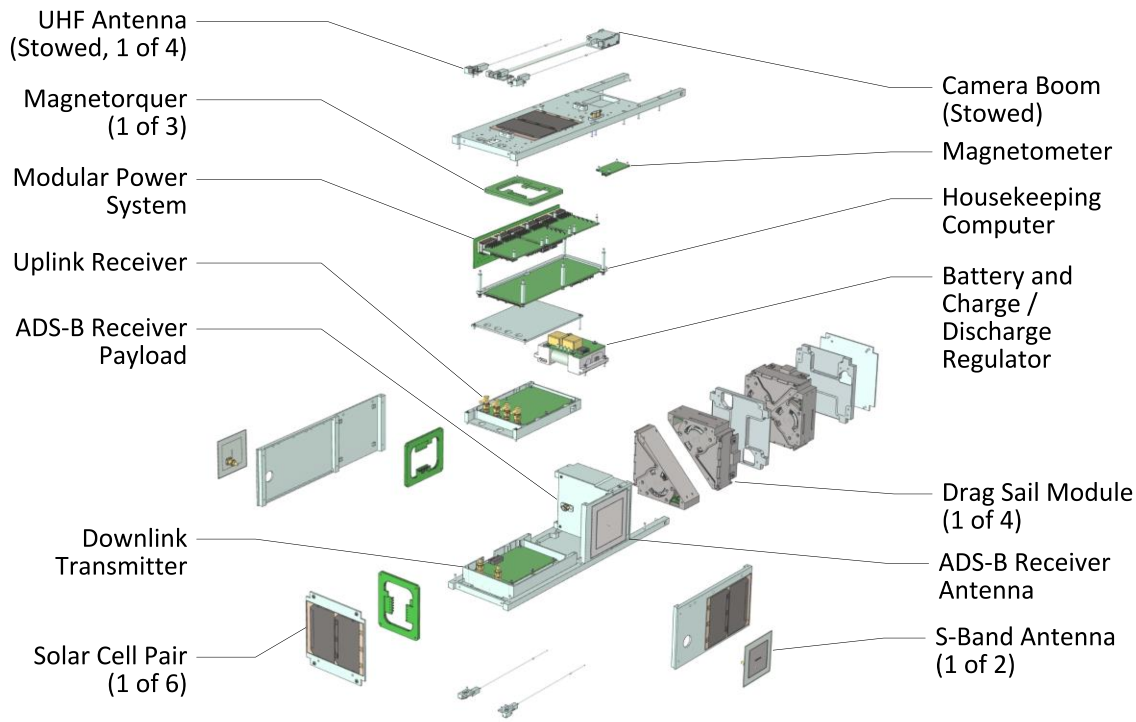

Figure 9: CanX-7 Satellite General Layout Expanded View

Table 4: CanX-7 Specifications

Specification	**Value**
Spacecraft Form Factor	10 x 10 x 34 cm
Mass (including margin)	4 kg
Attitude Control	±10^{o} (2σ)
Attitude Pointing Mode	LMF Tracking
Power Generation	1.8 – 6.0 W
Battery Capacity	4.8 Ah
Nominal Bus Voltage	4.2 – 5.5 VDC
Peak Payload Power	4.2 W
Command Uplink (UHF)	4 kbps
Telemetry Downlink (S-Band)	32 kbps – 1 Mbps
Data Storage	Up to 1 GB
Bus Operational Temperature	-20 to +60^{o}C
Launch Interface	XPOD Triple

4.2 Drag Sail Mechanical Design

The CanX-7 drag sail payload design is modular, consisting of four separate sail modules as described earlier, which combine to form a subassembly that fits within the constraints of the 3U CanX-7 bus. Each individual sail in the subassembly can be released individually and commanded directly over the spacecraft uplink. The drag sail modules are wedge-shaped, and each deploys a trapezoidal sail supported at its corners. Figure 10 shows a single drag sail module in its pre-deployed state, while Figure 11 shows an exploded view. For CanX-7, the four modules are assembled in two decks, and mated to each other and the spacecraft with two interface brackets. This complete assembly is shown in Figure 12.

Each drag sail module is deployed using the stored energy of coiled steel tape spring booms, which are restrained pre-deployment by a closed door that is tied to the module structure by a Vectran cord. Upon command, a heater is used to cut this cord, and the booms push the door open and draw out an aluminized Upilex sail. Each sail module individually telemeters the operation of its cord-cutting heater, the position of its door, and the motion of its boom reel, allowing both confirmation of deployment initiation as well as assessment of the extent and quality of deployment. A high level of integration (sail area per unit volume) has been achieved in the module design using additive manufacturing techniques, with the structure of each module predominantly consisting of Windform XT 2.0. Figure 13 shows the sail module engineering model deployed after vibration testing, while Figure 14 shows the deployment of the engineering qualification model.

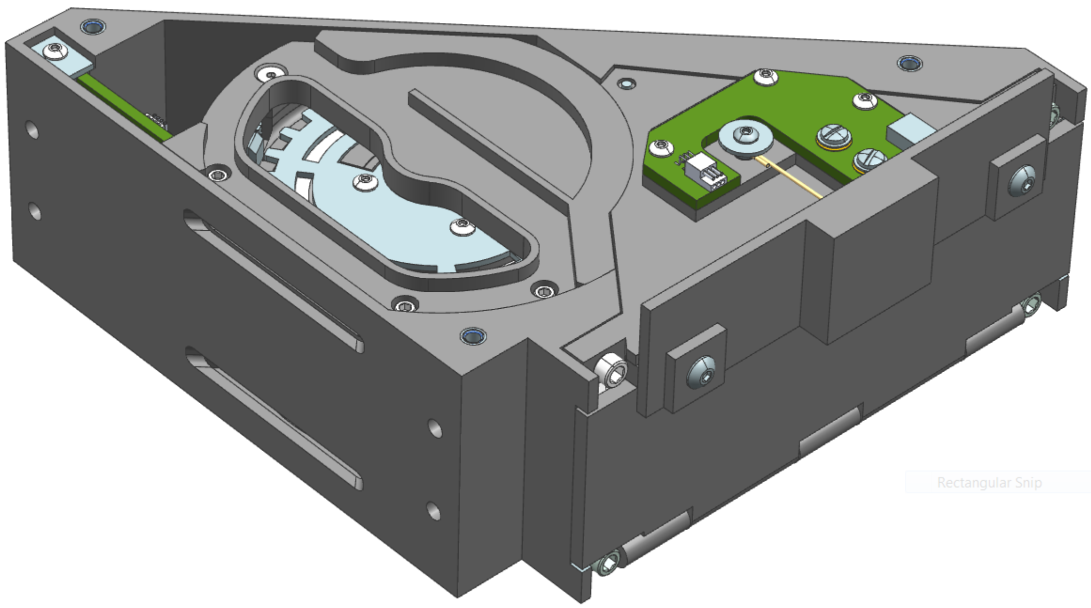

Figure 10: Single Drag Sail Module

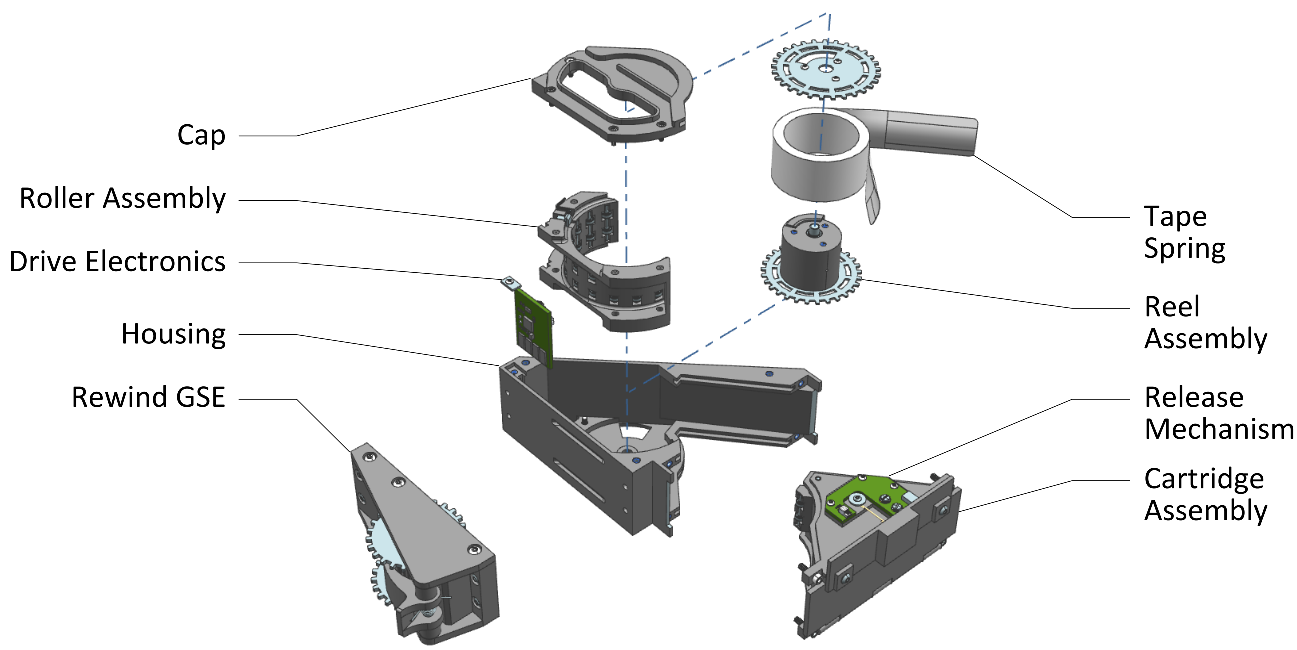

Figure 11: Drag Sail Expanded View

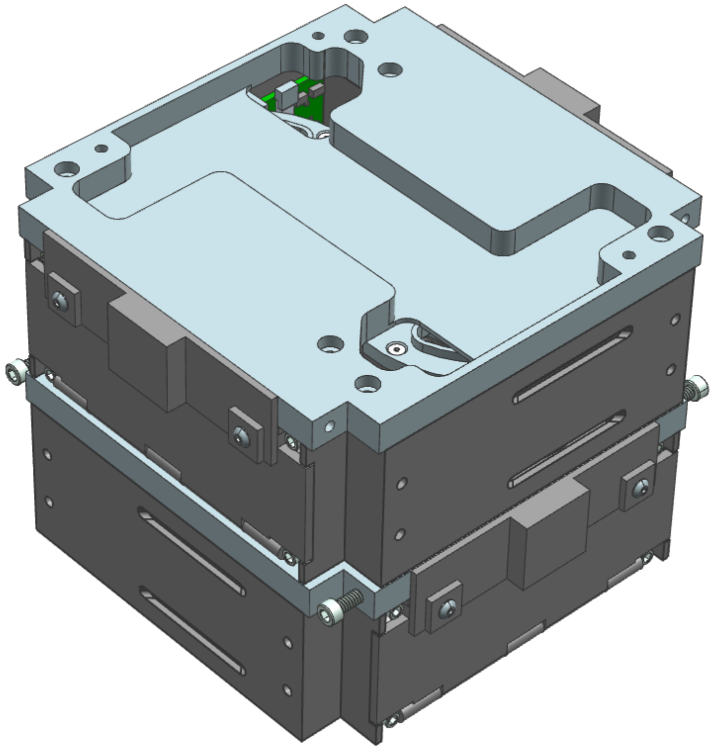

Figure 12: Drag Sail Subassembly (Four Modules, 3U Configuration)

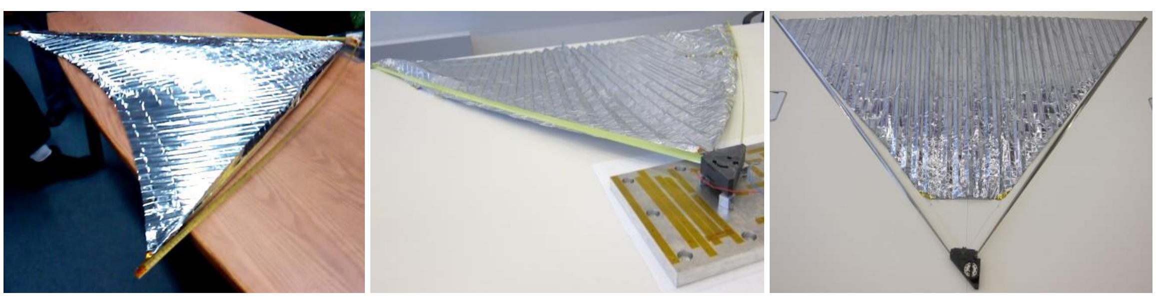

Figure 13: Drag Sail Deployment Tests
Prototype (left), Engineering Model (centre) and Qualification Model (right)

Figure 14: Drag Sail Qualification Model - Deployed

4.3 Sail Module Electronics

The sail module electronics are responsible for processing deployment commands sent from the ground; driving the release mechanism heater; and collecting telemetry on deployment confirmation and the extent of deployment. The sail is deployable only via ground command on CanX-7, requiring two separate ARM and FIRE commands sent in sequence to be initiated.

At the payload subassembly level, each drag sail module is connected to three multi-drop busses: a power bus; a telemetry bus (asynchronous serial) from the housekeeping computer; and a command bus (synchronous serial) from the UHF receiver. Figure 15 shows a high-level sail module interconnection diagram, in which each sail module is shown on the power and data busses that run through the sail subassembly.

At the individual drag sail module level, each unit contains its own compartmentalized telemetry and drive electronics, and the operation of each module is independent from adjacent modules. Each drag sail module contains:

- A microcontroller connected to the spacecraft's housekeeping computer and UHF receiver, which accepts commands to deploy the sail and transmits telemetry when instructed;
- A driver circuit to monitor and activate the release mechanism heater;
- A microswitch to detect whether the sail door is closed or open; and
- A Hall effect sensor to monitor motion of the boom reel.

The sail modules receive ARM and FIRE deployment commands directly from the spacecraft command uplink. The sail modules also receive commands and transmit telemetry to the spacecraft housekeeping computer through a dedicated serial interface.

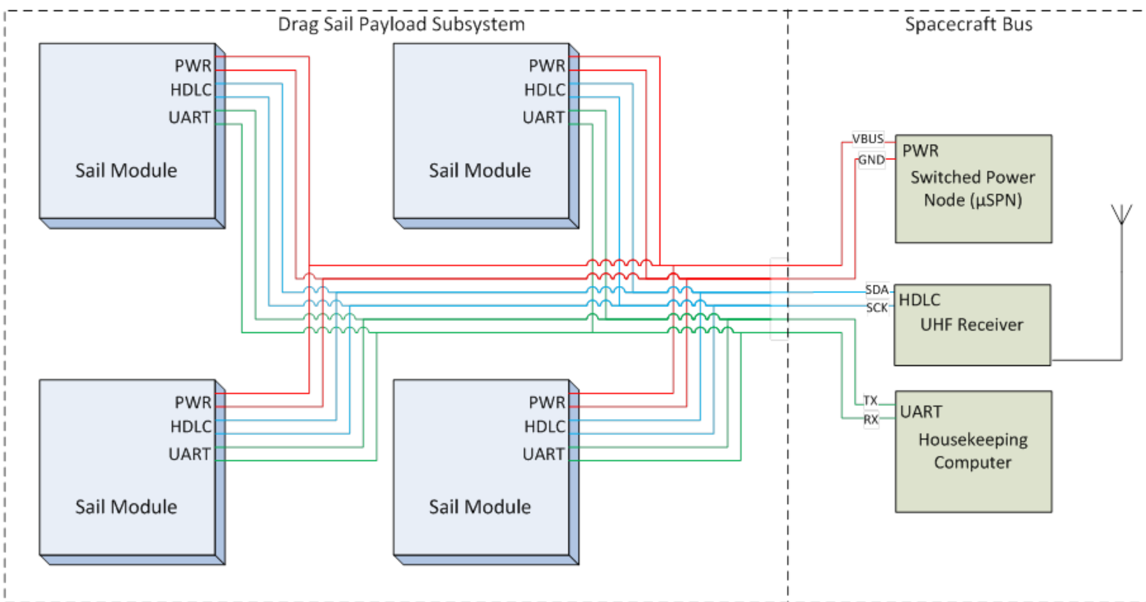

Figure 15: Block Diagram of Drag Sail Payload Electrical Interconnection

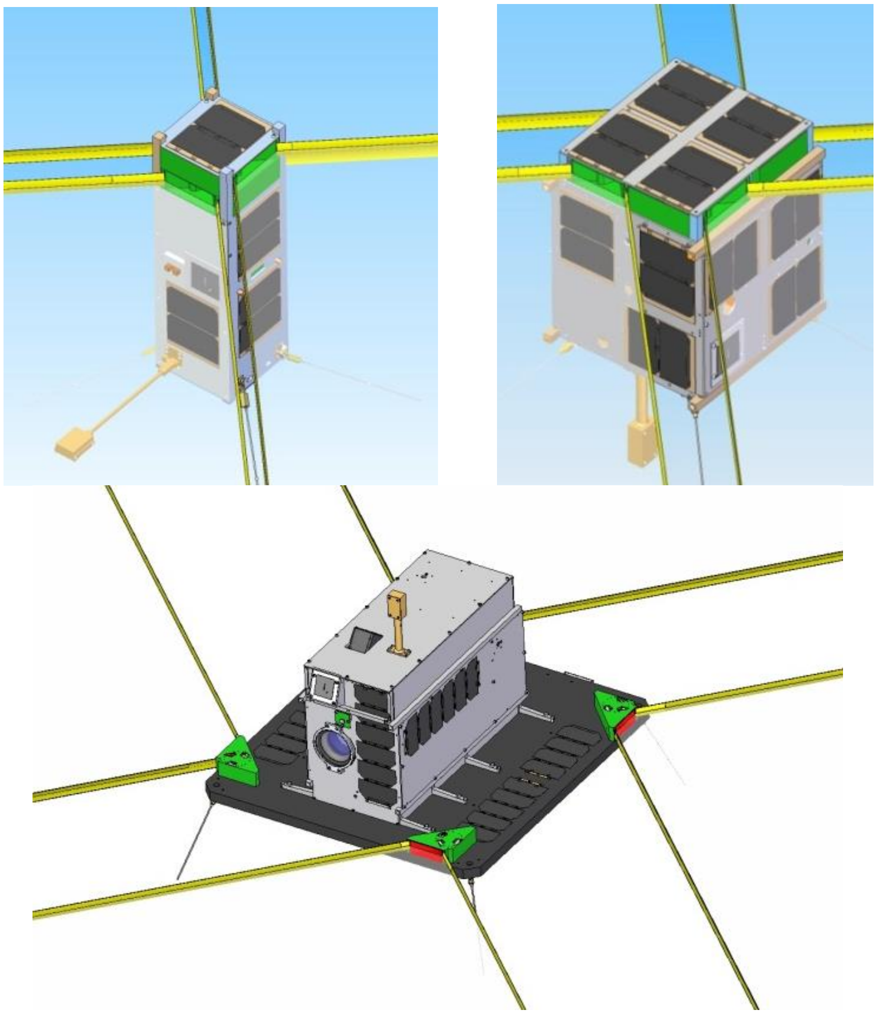

Figure 16: Drag Sail Integration with Triple Cube (Top-Left), GNB (Top-Right), and NEMO (Bottom) Satellites

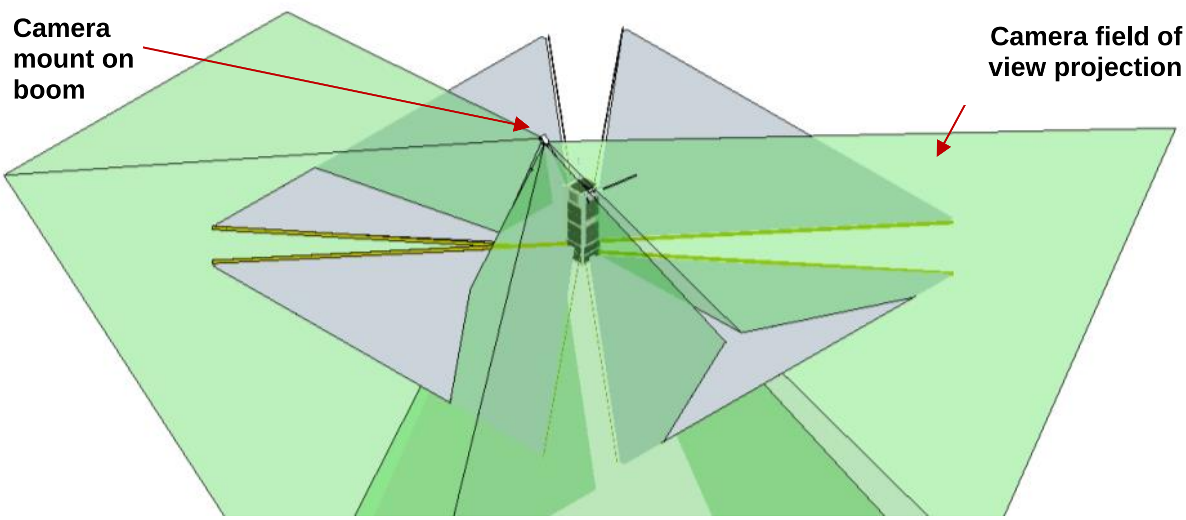

Figure 17: Imager Projections on Deployed Sails

4.4 Integration with Larger Satellites

While CanX-7 uses a stacked drag sail subassembly configuration, the basic module is designed to be adapted to different SFL satellites with further development. Figure 16 illustrates three different integration concepts for the triple cube, GNB, and NEMO busses described in earlier sections, using tiled configurations instead of the stacked triple-cube configuration.

4.5 Sail Imaging

The CanX-7 Camera Boom (CamBoom) is a deployable boom containing three COTS imagers used for imaging the drag sails following deployment. The use of imagers was down-selected as the most direct and compelling means of verifying not just whether the sails have deployed, but also to assess the *quality* of deployment. The CamBoom will use three VGA resolution imagers. The current design, with field of view projections for the three imagers, is shown in Figure 17.

The CamBoom design makes use of a modified magnetometer boom from CanX-2 to allow for a maximum separation between the cameras and the sail, such that larger areas of the sail are visible. Redesign of the internal case and the boom extension angle has allowed maximization of the sail viewing area for the camera array, as illustrated in Figure 17. Camera orientations were chosen to maximize both the number of sails observed, as well as the number of sail features observed across the planform (such as booms, sail edges, sail middles, and sail-to-sail spacing). The current configuration is able to image approximately half of the total deployed sail area.

4.6 CanX-7 Deorbiting Analysis

The mechanism for deorbiting using the CanX-7 sail payload is aerodynamic drag. However, because drag is highly dependent on spacecraft projected area in the velocity direction, the rate of orbital decay accomplished over time is extremely sensitive to spacecraft attitude, which in turn will vary with the magnitude of drag relative to other environmental disturbances. Whereas in Section 1 the assumption of negligible spacecraft dipole was made, for CanX-7 there is the possibility of a non-negligible residual magnetic moment that must be accounted for in deorbiting analyses.

To predict the effectiveness of an aerodynamic deorbiting device, variations in spacecraft attitude throughout its deorbiting period are assessed and incorporated into an estimate of average ballistic coefficient (and therefore, assuming constant mass and drag coefficient, an overall effective drag area). A modified version of the SFL MIRAGE attitude simulator is used to determine attitude variations and overall effective area over time, while AGI's Satellite Tool Kit (STK) is used to determine deorbiting rate as a function of the predicted overall effective area. Since this effective area changes with altitude, the analysis is iterative, and the deorbiting trajectory is evaluated piecewise over time.

For CanX-7, a parametric study was used to assess the deorbiting performance of the sail payload across a wide range of orbits, environmental disturbances, and spacecraft parameters. Figure 18 shows the estimated best- and worst-case deorbit trajectories for CanX-7, assuming a 2014 launch to an altitude of 800 km. Figure 18 indicates that the CanX-7 spacecraft will deorbit within 5 to 10 years of initial deployment at its maximum design altitude, depending on LTAN and final spacecraft magnetic moment, which is uncontrolled on CanX-7.

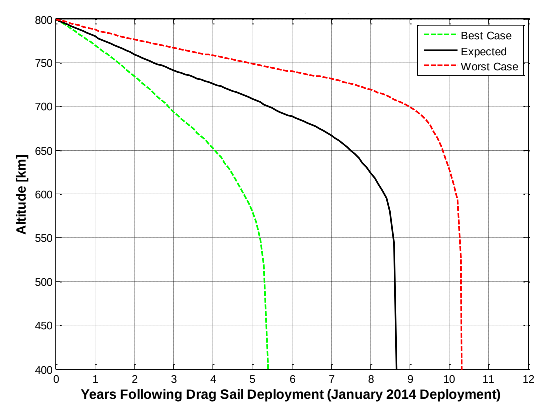

Figure 18: Range of Deorbit Trajectories for CanX-7

4.7 Deorbit Monitoring and Detection

Two-Line Elements (TLEs) will be used to monitor the CanX-7 deorbiting progress following drag sail deployment. Deorbiting success will be determined by evaluating the rate of decay over time and correlating observed changes to the attitude and orbit models described above. The figure of merit will be changes in the CanX-7 semi-major axis over time. However, there will be uncertainties associated with the estimate of semi-major axis due to the accuracy of the TLEs. Furthermore, the natural CanX-7 deorbiting rate without sails deployed must also be considered, since the satellite will deorbit (albeit at a much lower rate) without the drag sail as well.

Figure 19 shows the predicted deorbit rate for CanX-7 from an initial altitude of 800 km. The solid blue line represents the satellites' natural decay rate without the dray sails deployed, while the green line represents the worst-case decay rate with all four sails deployed. The dashed red lines indicate the worst-case uncertainty in spacecraft altitude estimates using TLEs, which was determined by comparing TLE- and GPS-based semi-major axis estimates on the AISSat-1 spacecraft over the course of approximately nine months.

Based on this analysis, the efficacy of the CanX-7 drag sail will be confirmed within the first month following drag sail deployment, assuming global worst-case altitude, LTAN, and spacecraft characteristics. While initially the estimate in deorbiting *rate* will be uncertain, this uncertainty will quickly diminish as the two curves in Figure 19 begin to diverge.

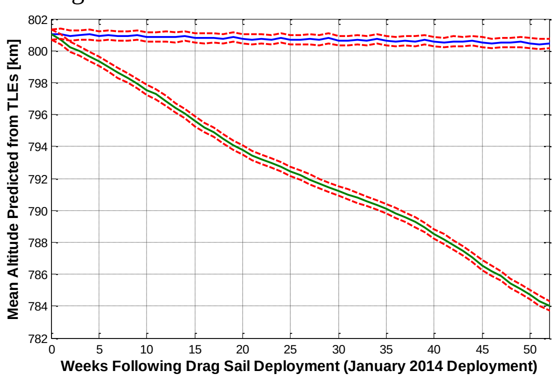

Figure 19: Estimated Altitude Decay for CanX-7

4.8 Secondary Payload: ADS-B Receiver

CanX-7 will also accommodate a secondary ADS-B receiver payload being developed by COM DEV and RMC. This secondary payload will be operated for six months following spacecraft commissioning, both in order to emulate an operational implementation of a deorbiting device (in which the drag sails are deployed once operations of a given payload cease), as well as to undertake potentially the first on-orbit demonstration of aircraft tracking from a nanosatellite [6]. ADS-B signals are transmitted by aircraft in L-band (1090 MHz), and encode aircraft identity and position information derived from on-board navigation systems. Transmission power from aircraft ranges from 75 W to 500 W (49 dBm to 57 dBm), occurring at randomized intervals using PPM modulation.

The continuing increase in commercial aviation traffic, combined with the inability of current radar surveillance to track aircraft beyond sight of land, have led to increasing interest in monitoring air traffic from space. When combined with other situational awareness techniques, space-based ADS-B monitoring can assist in flight planning over oceans and remote areas, which in turn would allow for decreased flight times, improved aircraft fuel economy, and reduced engine emissions [6].

The concept of operations for the CanX-7 ADS-B payload is illustrated in Figure 20. Aircraft encode position, velocity, time and identity from on-board instruments and GPS satellites, and transmit ADS-B signals which are received by CanX-7 and transmitted to the CanX-7 ground station during next access. The ADS-B receiver for CanX-7 is illustrated in Figure 21.

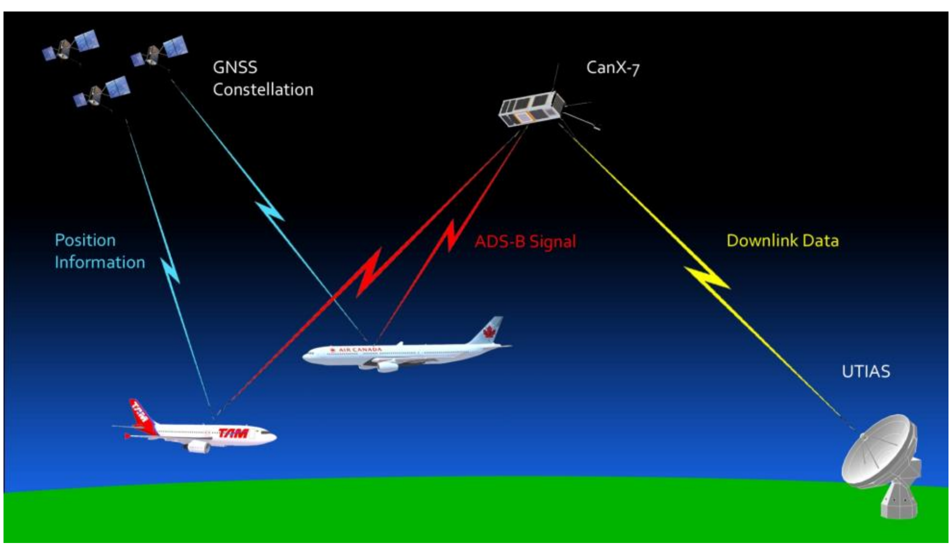

Figure 20: CanX-7 ADS-B Concept of Operations

Figure 21: ADS-B Payload and Payload Computer

4.9 Current Status

At present, the CanX-7 drag sail payload is undergoing qualification testing, after a series of risk-reduction vibration and thermal tests were performed on a mechanical engineering model to identify design issues and build confidence in the flight design. Initial integration and testing of the ADS-B payload with the CanX-7 bus have proceeded without issue, and the majority of bus subsystems have completed acceptance testing. CanX-7 is expected to be flight-ready in mid-2014.

5 CONCLUSIONS

This paper has provided an overview of the CanX-7 drag sail demonstration mission, prefaced by a discussion of different deorbiting methods, their so-called "killer trades", and an evaluation of drag-based deorbiting across a range of reference satellites and LEOs. For spacecraft in the nanosatellite-to-microsatellite range, and at LEOs below 1000 km, passive drag sails offer a superior solution for deorbiting spacecraft with relatively small characteristic dimension and no post-deployment attitude control required.

The CanX-7 mission is expected to be ready for launch in 2014. Following the completion of the CanX-7 mission, its drag sail technology can then be adapted and scaled for future, larger missions, enabling future Canadian spacecraft and their operators to be stewards of the increasingly crowded low-Earth orbit environment, to the benefit of all nations.

6 ACKNOWLEDGEMENTS

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