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THE CANX-4&5 MISSION:
ACHIEVING PRECISE FORMATION FLIGHT AT THE NANOSATELLITE SCALE

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Future missions involving multiple nano- and microsatellites will require highly precise absolute and relative position knowledge and control; intersatellite communications; high-performance attitude determination and control systems; and advanced, compact propulsion systems for orbit maintenance. The dual spacecraft CanX-4&5 mission, slated to launch in 2013 on India's Polar Satellite Launch Vehicle (PSLV), will demonstrate all of these capabilities at the nanosatellite scale: both as standalone subsystems, and in concert, to accomplish autonomous formation fight with sub-meter relative position control and centimeter-level relative position determination. CanX-4 and CanX-5 are individual spacecraft based on the Space Flight Laboratory (SFL) Generic Nanosatellite Bus (GNB). Each spacecraft is identical, and formation flight is enabled by each satellite having a GPS receiver, on-board propulsion system, S-Band inter-satellite link, and fine guidance, navigation and control (GNC) computer. The two spacecraft will share on-board position, velocity, and attitude data wirelessly over their intersatellite link, and one of the two spacecraft will perform propulsive maneuvers to achieve and maintain a series of autonomous formations. The technologies and algorithms used on CanX-4&5 are extensible to a broad range of missions and satellites at the nano- and microsatellite scale; thus, this ambitious technology demonstration will serve as a pathfinder for several formation flight and constellation applications.

INTRODUCTION

The CanX–4 and CanX–5 formation flying demonstration mission is an experiment being developed by the Space Flight Laboratory (SFL) at the University of Toronto Institute for Aerospace Studies (UTIAS). The purpose of this dual-spacecraft mission is to both demonstrate precision on-orbit formation flying of nanosatellites, and to do so in an autonomous fashion, independent of ground control. For the purposes of this demonstration, precision formation flying is defined as sub-metre autonomous formation control requiring sub-centimetre relative position determination. This feat has to date been achieved only by larger spacecraft of many tens to hundreds of kilograms. CanX–4 and CanX–5 will be the first nanosatellite mission to demonstrate sub-metre autonomous formation flying control [1].

The high-level objectives of the CanX-4&5 mission are as follows:

1) Demonstrate autonomous acquisition and maintenance of several dual-satellite formations;
2) Demonstrate carrier phase differential GPS techniques to perform relative position determination measurements with accuracies of 10 cm or better;
3) Demonstrate sub-meter relative position control;
4) Validate fuel-efficient formation flying algorithms; and
5) Demonstrate enabling technologies, such as the Canadian Advanced Nanosatellite Propulsion System (CNAPS) and S-band Inter-Satellite Link (ISL).

The mission will demonstrate two formation types, each at two separations—an along-track orbit (ATO) at distances of 1000 m and 500 m, and a projected circular orbit (PCO) at 100 m and 50 m. In each formation, the deputy spacecraft performs active orbit maintenance and control to achieve the desired relative motion with respect to the chief spacecraft. If desired, the spacecraft may swap roles throughout the mission, though all mission objectives are achievable with a single chief/deputy assignment. The spacecraft will maintain each formation for ten orbits with one orbit of reconfiguration manoeuvres between formations. The nominal mission life is thus less than seven days once the spacecraft are fully commissioned [2].

MOTIVATION

Although CanX-4&5 are themselves very small satellites, there is no intrinsic restriction on the sizes or distributions of vehicles undertaking the kind of formation flight that will be demonstrated by this mission. Formation flight may be executed between a nanosatellite and a vehicle as large as the international space station—a possibility that has been the subject of some attention in literature, as more and more people recognize the benefits of formation flying for applications ranging from on-orbit inspection and repair to sparse aperture sensing. The prospect of replacing one large satellite with several smaller, less expensive spacecraft can be highly beneficial, both in terms of reducing cost-of-entry for large programs and providing functional and operational redundancy, as well as improving performance with increases in revisit time, effective aperture size, or both depending on the mission [1].

MISSION OVERVIEW

Two different types of formation maneuvers will be demonstrated by CanX-4&5: Along Track Orbit (ATO) and Projected Circular Orbit (PCO) formations. In the ATO formation, both satellites will be in the same orbit but with the one satellite leading the other by a chosen time constant. Following the completion of this formation, one satellite will then perform a plane change in order to maneuver into the PCO formation. In the PCO formation one satellite appears to be orbiting the second as viewed from the Earth (Figure 1).

During operations, each satellite will take on one of two roles, the chief or the deputy. The deputy satellite will perform propulsive maneuvers to maintain the formation with the chief satellite. At the same time the chief satellite will mimic the attitude of the deputy satellite to ensure the same GPS satellites are visible to both spacecraft. The mutual attitude is constrained in each control cycle to maintain the GPS antennas on both satellites generally in the zenith hemisphere.

Over the course of the mission, two ATO and two PCO configurations will be flown with varied baseline distances. These formations will be flown in the following sequence: a 1000m ATO, a 500m ATO, a 50m PCO, and a 100m PCO. Each formation configuration will be flown for approximately 10 orbits. A series of impulsive maneuvers will be performed by the deputy satellite to transition into each new formation.

There is sufficient propellant in the deputy satellite alone to satisfy the baseline mission requirements. The unused fuel in the chief satellite (which will change roles with the deputy satellite at the end of the primary mission) will be used to perform additional formation flying experiments. These may include long duration formation flying (i.e. more than 100 orbits in a single formation), inspection maneuvers, and/or J2-invarient formations for extremely long duration formation flying.

Mission Sequence

Both CanX-4 and CanX-5 will be deployed individually from the PSLV upper stage, using separate SFL XPOD ejection systems. Following commissioning of the both spacecraft, which is anticipated to take less than one month, one of the two satellites will be assigned the role of deputy, and will perform a series of drift recovery thrusts to begin maneuvering back towards the other satellite. At a range of approximately 10 km, both satellites will be within communication range and can begin exchanging GPS and attitude information over the intersatellite link. At this point, the satellites enter a coarse station-keeping mode, in which a minimum separation is maintained in preparation for precision formation flight. Once ready, the satellites will be commanded to execute the ATO formations, followed by the PCO formations, with intermediate reconfiguration orbits between them. Once station-keeping has been achieved, the anticipated time required to undertake the entire mission is only days, though the drift recovery itself may require several weeks, depending on the drift rate following deployment. Both satellites are sized to recover from a worst-case separation velocity (magnitude and orientation) of 2.5 m/s.

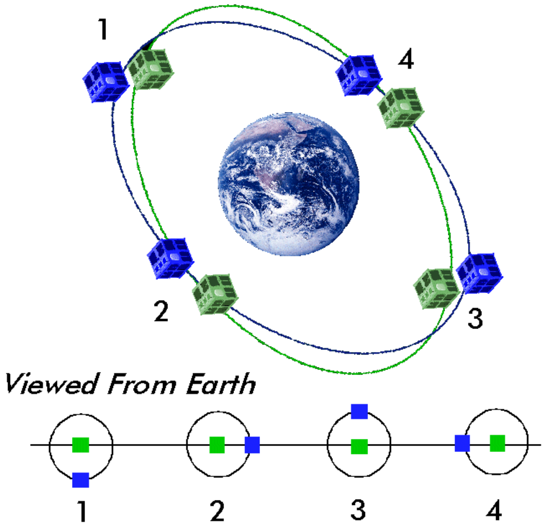

Figure 1: Projected Circular Orbit (PCO) As Viewed from Earth

Experiment Verification

Two criteria will be used to determine the performance of CanX-4&5 over the course of the mission. First, the level of accuracy to which the satellites are able to control their relative position in each formation configuration will be determined. Second, the ability of the deputy satellite to minimize its fuel consumption by correcting for secular perturbations in the orbit while ignoring any periodic changes will be evaluated. Each satellite will determine its absolute position and velocity using an onboard GPS receiver. This data will be logged by the satellite and downloaded by the ground station. This data can then be analyzed to accurately determine the relative distance of each satellite over time. In addition, Two-Line Elements (TLEs) obtained from NORAD will be used as a coarse means of verifying performance early in the mission.

PERFORMANCE REQUIREMENTS

Precisely achieving and maintaining a satellite formation requires precise relative position determination and accurate thrusting. The total ΔV and relative position determination requirements are driven by the desired degree of precision for the satellite formation control [2]. The thrusters on the CNAPS propulsion system for both satellites are located on one face only. Therefore, attitude pointing is singularly the responsibility of the attitude determination and control system for accurate thruster pointing. In addition, the two satellites must communicate with each other to relay position, velocity and attitude information. The inter-satellite link (ISL) communication system must accommodate the desired relative distance of the satellites in each formation as well as the required data rates. Table 1lists the parameters required to meet the formation flying requirements of the CanX-4&5 nanosatellites.

Table 1: Performance Requirements for CanX-4&5 Satellites

Performance	Requirement
Position Control	1 m
Relative Position Determination	10 cm
Minimum Relative Distance	50 m
Maximum Relative Distance	1000 m
Attitude Control	5° (3σ)
Intersatellite Link Range	5 km
Intersatellite Link Date Rate	10 kbps
Total ΔV	12 m/s
Specific Impulse	40 s
Thrust	10 mN /thruster
Minimum Impulse Bit	0.7 mN·s

SATELLITE PLATFORM: THE GENERIC NANOSATELLITE BUS

The CanX-4&5 satellites are based on the highly successful Generic Nanosatellite Bus (GNB) platform, which has been used successfully as the platform on the AISSat-1 satellite (> 3 years on-orbit), UniBRITE and BRITE-Austria (on-orbit since February 2013), and which is the basis of seven other satellites currently in development at SFL.

The Generic Nanosatellite Bus (GNB) consists of an aluminum structure in a ~20 cm cubical form factor. A Housekeeping Computer (HKC) enables communications with the ground, as well as telemetry collection and mass-data storage, while an Attitude Determination and Control Computer (ADCC) executes satellite attitude control algorithms. Both computers are identical in design, and only one computer is required for both housekeeping and ADCS functions. The attitude determination and control system uses a suite of six sun sensors, a 3-axis magnetometer, rate sensors, three air-core magnetorquers and three reaction wheels to accomplish better than 5-degree (3-sigma) pointing accuracy. A UHF receiver provides a 4 kbps command uplink, while an S-band transmitter provides telemetry downlink at 32 kbps minimum, 1 Mbps maximum. A GPS receiver is included as well for CanX-4&5 as one of the primary mission payloads, but can also be added in general to augment attitude and position knowledge. A distributed power system allows various payloads to be switched on and off and also provides voltage and current telemetry for all power switches. More than 10 W orbit-average power is generated by multiple body-mounted strings of triple-junction solar cells, and energy is stored in two independent 4.8 Ah lithium-ion batteries, each of which is interfaced to the bus via integral Battery Charge/Discharge Regulators (BCDRs). The spacecraft power system uses a high-efficiency direct-energy transfer (DET) topology with peak-power tracking (PPT) capability.

GNB spacecraft are designed to use the UTIAS/SFL XPOD separation system. Different XPOD designs can accommodate one or more spacecraft of sizes up to 200 x 200 x 440 mm and 15 kg. The XPOD releases its spacecraft when signaled to do so by the launch vehicle at the appropriate time in the launch sequence. The XPOD-GNB, designed to release a single GNB-sized spacecraft, has been used to successfully deploy four spacecraft in the past five years (CanX-6, AISSat-1, UniBRITE, and BRITE-Austria).**Error! Reference source not found.**Figure 2 depicts an exploded view of the Generic Nanosatellite Bus. Most hardware shown can be mutually included depending on mission requirements. Figure 3 shows the GNB external configuration for CanX-4&5.

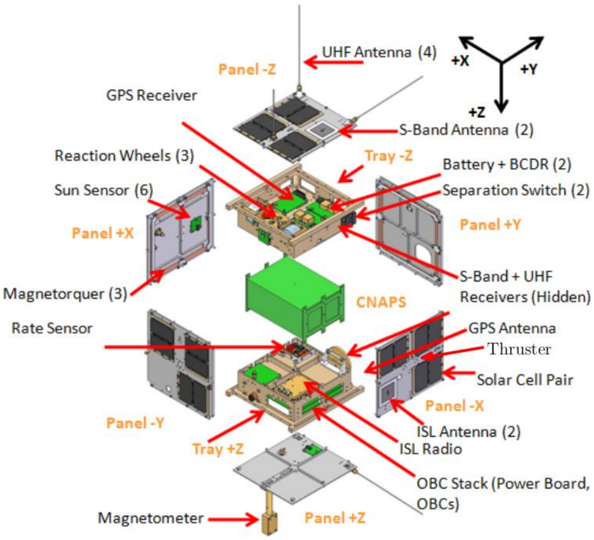

Figure 2: The Generic Nanosatellite Bus (GNB) configured for CanX-4&5

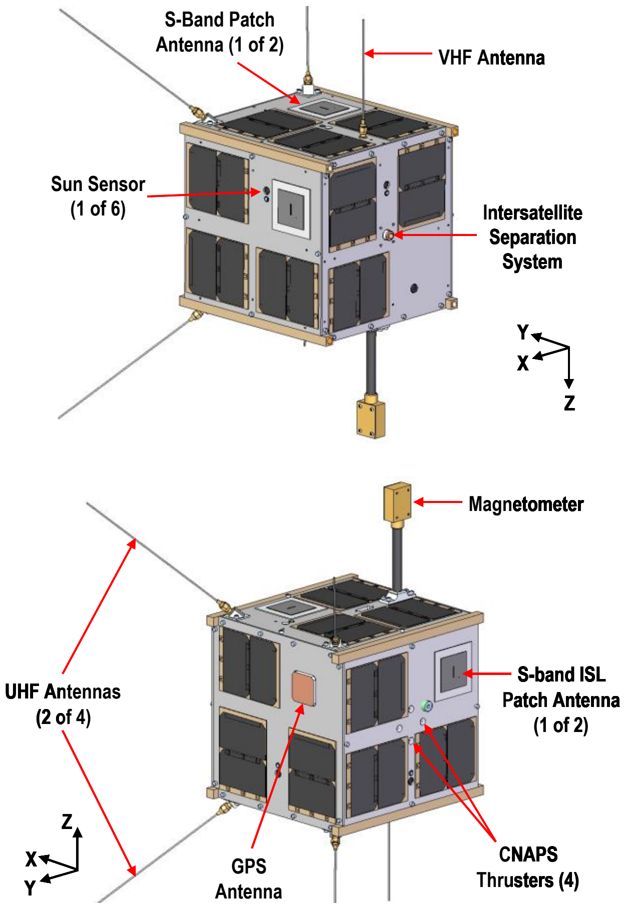

Figure 3: CanX-4&5 Satellite Configuration

MISSION-SPECIFIC TECHNOLOGIES

In addition to the GNB platform, the CanX–4 and CanX–5 mission itself is enabled by three payloads: a commercial-off-the-shelf (COTS) GPS receiver (Figure 4), a custom-built intersatellite link radio (ISL, Figure 5), and the Canadian Nanosatellite Advanced Propulsion System (CNAPS, Figure 6). The telemetry returned by the GPS receiver is used by the specialized relative navigation software (RelNav) to obtain a sub-centimetre relative position solution between the two spacecraft. RelNav requires raw GPS data from the receivers on both spacecraft in order to obtain this solution. The ISL provides a wireless link between the spacecraft that enables the autonomous transfer of this data between the spacecraft throughout the mission.

The ISL was designed to close a 10 kbps communications link at separations of up to 5 km with 6 dB margin, well above the nominal maximum spacecraft separation of 1 km. Once a relative position solution is obtained, the deputy spacecraft employs the cold-gas thrusters of CNAPS to perform orbit control. Each CNAPS is capable of delivering a total of 12 m/s of delta-V to the 7 kg spacecraft [2].

Figure 4: Novatel GPS Receiver

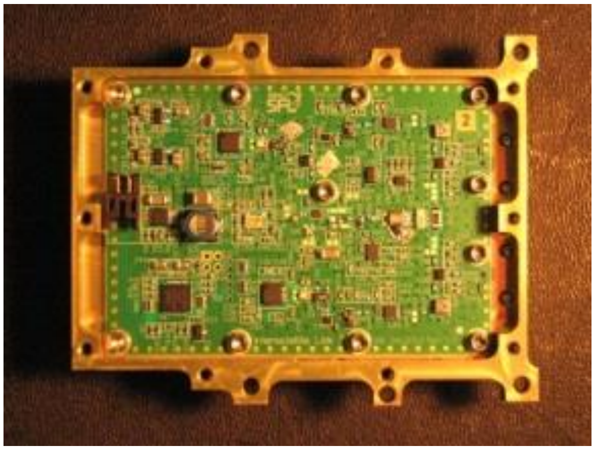

Figure 5: Inter-Satellite Link (ISL), enclosure lid removed

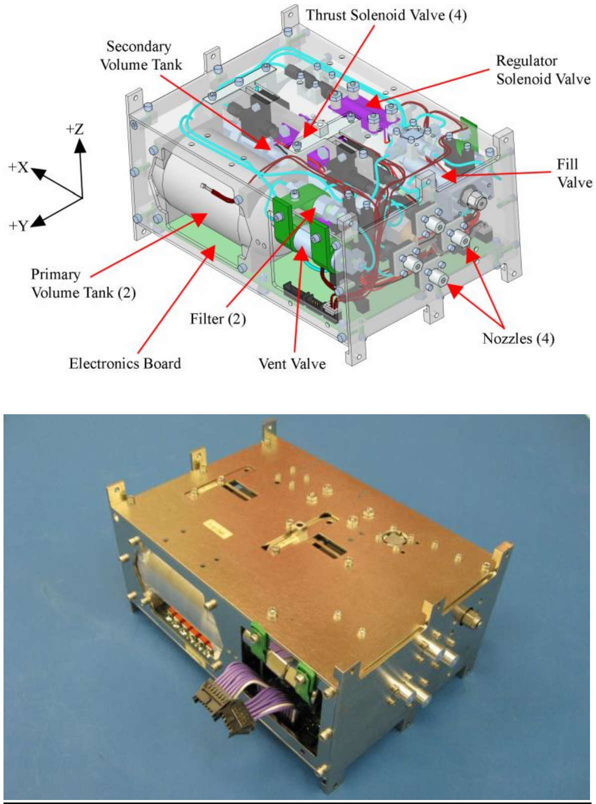

Figure 6: CNAPS Propulsion System – Solid model (top) and flight model for CanX-5 (bottom)

CURRENT STATUS

The CanX-4 and CanX-5 satellites have both been undergoing acceptance testing during 2013, for an expected December 2013 launch on the PSLV C-23 launch vehicle. For each satellite, the full system-level acceptance campaign consists of EMC and radio sensitivity testing (including GPS and ISL); vibration testing at PSLV acceptance levels and durations; and thermal vacuum (TVAC) testing, during which satellite long-form functional testing, simulated commissioning and operations are performed. Figure 7 shows the CanX-4 satellite undergoing vibration testing inside its XPOD launch vehicle ejection system, while Figure 8 and Figure 9 depict the CanX-5 satellite in its TVAC rig at SFL's Microsatellite Science and Technology Centre (MSTC). All satellite testing has been undertaken at SFL's facilities in Toronto, Ontario Canada, and both satellites will also be operated from the MSTC mission control centre.

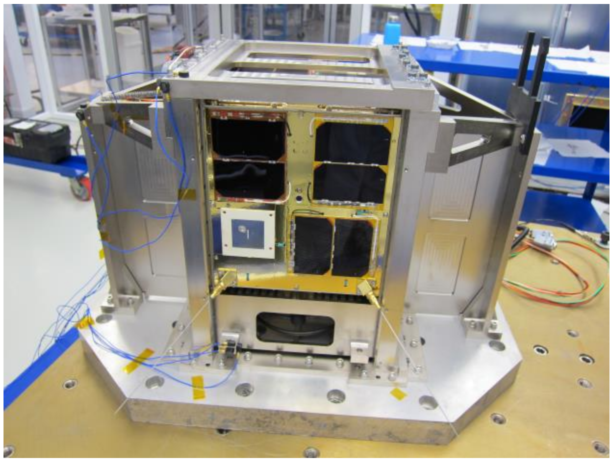

Figure 7: CanX-4 Satellite in Vibration Testing

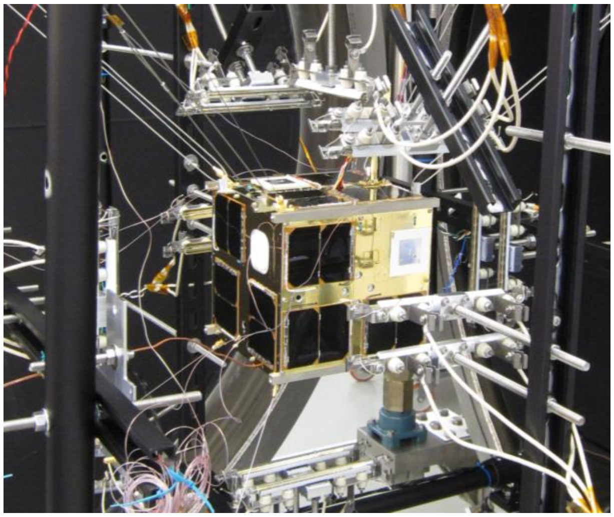

Figure 8: CanX-5 Satellite in TVAC Testing

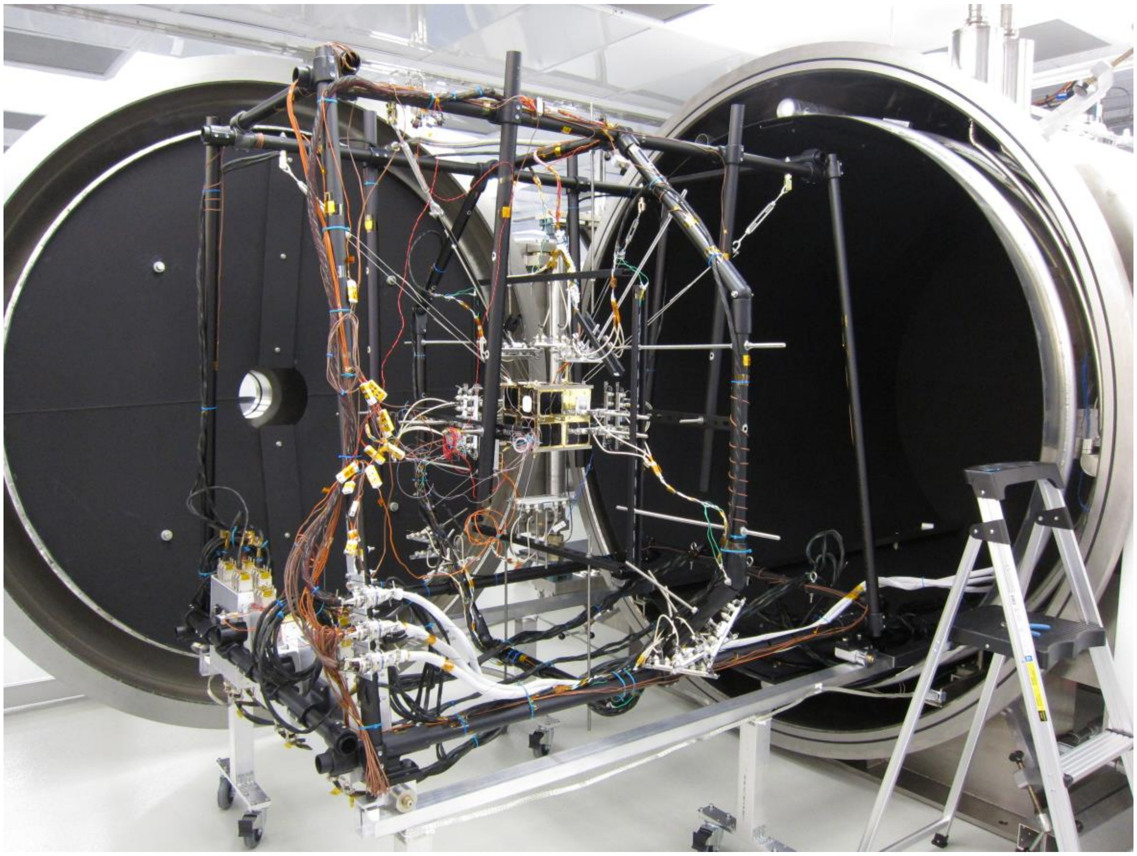

Figure 9: TVAC Rig with CanX-5 at SFL MSTC

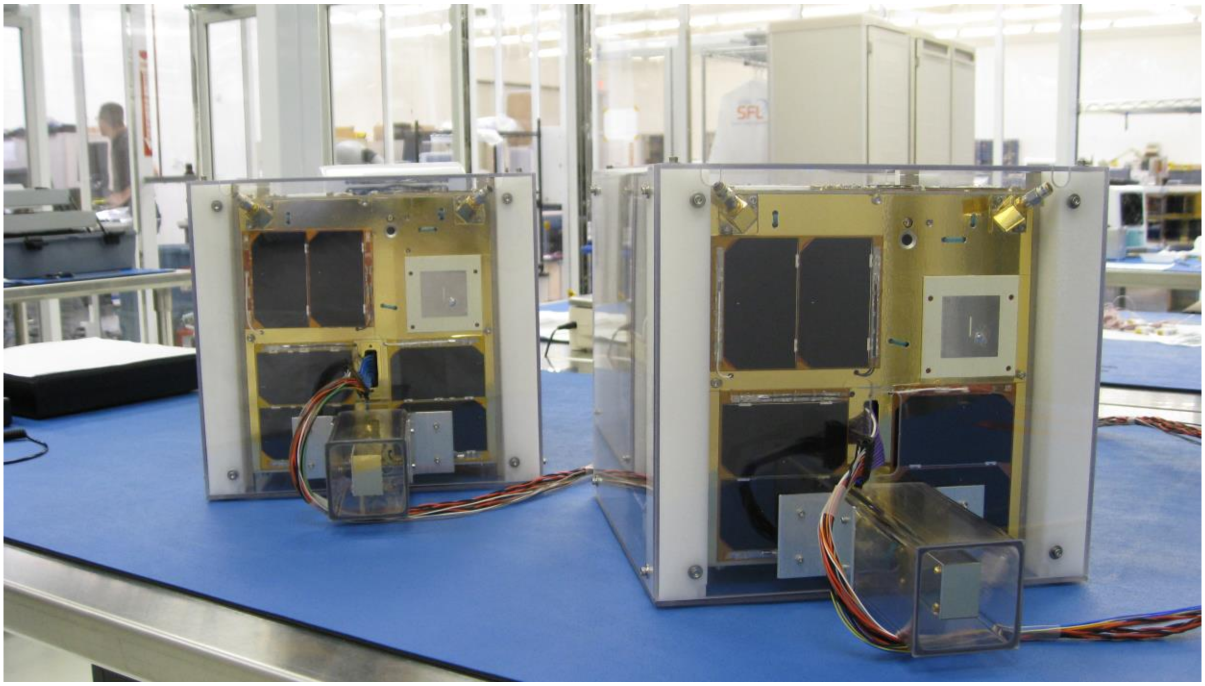

Figure 10: CanX-4 (foreground) and CanX-5 (background) in protective containers during burn-in

CONCLUSIONS

The CanX–4 and CanX–5 demonstration mission is an exciting experiment that aims to break new ground in capabilities of nanosatellite formation flying missions. The success of CanX-4 and CanX-5 will represent a major milestone in demonstrating the viability of precise formation flying with small, inexpensive satellites, which in turn may enable even larger and more ambitious applications of high-precision formation flight in low-Earth orbit.

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- Sinclair Interplanetary

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REFERENCES

[1] N. H. Roth, “Navigation and control design for the CanX-4/-5 satellite formation flying mission,” Master’s thesis, University of Toronto, Toronto ON, Canada, 2010.

[2] S. E. Armitage, L. Stras, G. R. R. Bonin, and R. E. Zee, "The CanX-4/-5 Nanosatellite Mission: Technologies Enabling Formation Flight", IWSCFF-2013-08-05, 7th International Workshop on Satellite Constellations and Formation Flying, Lisbon, Portugal, 13-15 March 2013.

[3] N. G. Orr, J. K. Eyer, B. P. Larouche, and R. E. Zee, “Precision Formation Flight: The CanX-4 and CanX-5 Dual Nanosatellite Mission”, SSC07-VI-2, 2007 AIAA/USU Conference on Small Satellites, Logan, UT., August 2007.