

# CanX-4 & CanX-5: Precision Formation Flight Demonstrated by Low Cost Nanosatellites

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*The Space Flight Laboratory (SFL) at the University of Toronto Institute for Aerospace Studies (UTIAS) is currently developing a precision formation flying demonstration mission using nanosatellites. As part of the Canadian Advanced Nanospace eXperiment (CanX) program, two nanosatellites will employ innovative technology that will expand the capabilities of this class of spacecraft and prove technologies directly applicable to precise formation flying missions using larger spacecraft. Revolutionary capabilities will be demonstrated particularly in the fields of nanosatellite attitude and spacecraft orbital control, ultimately enabling missions of widespread commercial and military interest such as on-orbit inspection and sparse aperture remote sensing. The formation flying mission will involve two low cost nanosatellites, CanX-4 and CanX-5, each operating on less than ten watts of power and each having a mass under five kilograms. The dual spacecraft mission will rely on state-of-the-art technologies, including a custom propulsion system, commercial GPS receiver, high-performance attitude determination & control hardware, and miniature S-band radios. With these technologies, plus centimetre-accurate position determination algorithms developed at the University of Calgary and formation control algorithms developed at UTIAS, CanX-4 and CanX-5 will demonstrate relative position control to an unprecedented sub-meter accuracy. To mitigate risk, several components critical to the formation flying mission will be test flown aboard the CanX-2 nanosatellite mission with launch expected in 2007. Development for CanX-4 and CanX-5 has commenced with launch anticipated in 2008. This paper will discuss the CanX-4 and CanX-5 mission design and describe the impact and benefits of the project.*

## **1.0 Introduction: SFL CanX Program**

University of Toronto's Space Flight Laboratory initiated the Canadian Advanced Nanospace eXperiment (CanX) program in 2001 to design and build low-cost nanosatellites for education and research. By exploiting the laboratory's expertise in microsatellite design, the CanX program was created in order to develop highly capable nanospacecraft within a two-year period, roughly the time that it takes to complete a master's degree. The CanX program mandate is three-fold. The first and foremost goal is to train students at the master's level, channelling their varied undergraduate backgrounds into highly qualified areas of expertise through hands-on training in all aspects of spacecraft development. Students are mentored by SFL's engineering staff who were responsible for developing critical systems of Canada's first space telescope, the MOST (Micro-variability and Oscillation of Stars) microsatellite [1]. In this way, the University of Toronto supplies Canada with a continual supply of experienced space engineers. The second goal of the CanX program is to push the limits of scientific understanding and technical capability. Incorporating leading edge scientific experiments and prototype engineering instruments serves to meet the university's mandate of academic excellence and to position Canada as a global leader in the nanospace field. As a corollary, the third goal is to provide a low-cost, accessible platform by which government agencies, universities and companies may conduct science or prove technologies in an orbital environment.

At present, UTIAS/SFL is completing the CanX-2 nanosatellite. At 3.5 kg and 34x10x10cm, CanX-2 is host to almost a dozen scientific and engineering payloads. The two main objectives for CanX-2 are to prove, at the component level, critical technologies required for precision formation flight and to provide cost-effective access to space for the research and development community in Canada. Scientific experiments flown on CanX-2 include a miniature atmospheric spectrometer used to detect greenhouse gases in support of the Kyoto protocol, a GPS atmospheric occultation experiment to determine vertical profiles of electron and water vapour content in Earth's atmosphere, a surface material experiment that will test the effectiveness of a new atomic-oxygen-resistant coating and a dynamic spacecraft networking protocol experiment. CanX-2, one of the most ambitious nanospacecraft built to date, is currently undergoing final integration and environmental testing with launch expected in early 2007.

As CanX-2 nears completion, SFL is currently developing two missions in tandem: CanX-3 (otherwise known as BRiGht Target Explorer, or "BRITE" Constellation), a space astronomy mission; and CanX-4 & CanX-5, a dual satellite mission to demonstrate autonomous formation flying. SFL aims to expand the capabilities of nanosatellites by developing a generic nanosatellite bus (GNB) that will be easily adaptable to a range of missions. The GNB will allow CanX-3 and CanX-4 & CanX-5, two vastly different missions, to use the same basic low-cost platform, thus reducing non-recurring engineering and minimizing overall cost. A description of the CanX-4 & CanX-5 mission and an overview of the GNB design are the basis of this paper.

## **2.0 Spacecraft Formation Flight**

Due to the nature of space flight, most spacecraft are not designed to be upgraded or serviced in orbit. This implies that spacecraft must be built to be highly autonomous, highly fault-tolerant and thus prohibitively expensive. Space missions are often regarded as high cost endeavours, and thus conservative design rules usually form the basis of the design approach. Instead of accepting calculated risks, traditional design approaches often lead to an overwhelming risk aversion mentality. A high program cost results from this philosophy since, in order to mitigate risk, a program requires scores of skilled labour, detailed documentation and space-proven components.

Formation flight using a cluster of small low cost satellites is a progressive step toward reducing the cost of space missions when contrasted to a single satellite of equivalent capability. In this context, formation flight involves two or more satellites controlling their position with respect to one another. Spacecraft in a formation can act cooperatively by, for instance, sharing processing, communication and payload functions to perform the function of a single larger satellite. Recently, because of its numerous advantages, formation flight has received considerable international attention.

A principle advantage that formation flight offers over a single satellite is higher reliability and redundancy. A constellation of satellites allows for natural degradation of individual satellites with time. A constellation could be designed such that if a satellite in the cluster fails, the formation could reconfigure to compensate for the loss. Thus, the loss of one satellite may not result in mission termination. Second, formation flight allows for greater flexibility in system upgrades since individual low-cost satellites can be added to increase or replenish the overall functionality of the cluster. This is in contrast to the traditional approach where all functions are performed by a single, large satellite and any changes necessitate complete replacement of that satellite. Furthermore, as a result of the low replacement cost of a small satellite, it may be feasible to periodically upgrade members of a constellation in order to exploit advances in technology throughout the operational lifetime. Third, satellites in formation can be arranged in various configurations in order to vary the virtual aperture size or to adjust ground coverage and revisit time in order to accommodate evolving needs. Finally, developing a cluster of small low cost satellites to fly in a formation offers significant cost savings because the non-recurring engineering costs are spread over the entire fleet and the future replacements. Thus, formation flight offers greater flexibility, performance and cost savings over a single large satellite.

These cost and performance advantages have paved the way to a diverse new array of potential space system applications. Within the realm of remote sensing, spacecraft flying in formation can create virtual instrumentation with virtually unlimited aperture configurations. This freedom to vary the cluster configuration can enable very large virtual apertures and special arrangements which will enable very high resolution remote sensing and digital elevation mapping missions. Formation flight, once demonstrated and matured, can also lead to the creation of an industry of on-orbit servicing. A small satellite flying in formation with a client's satellite could perform a thorough inspection of it for diagnostic or maintenance purposes. A satellite flying in formation could also dock with a failed or degraded spacecraft to provide a rapid upgrade or repair. Many military applications of formation flying also exist. These include RF sparse aperture imaging, precision geolocation, ground moving target indication, single-pass digital terrain surveying, electronic protection, and single-pass interferometric synthetic aperture radar.

A great deal of theoretical analysis has been conducted in the field of spacecraft formation flying within academia and industry, however precision formation flight yet has to be implemented due to several key challenges. First, the cost to demonstrate formation flight using a traditional space system design approach is prohibitively expensive. Second, precision formation flight demonstrating sub-meter relative position control requires the development of space-based algorithms for centimeter level inter-satellite position determination and fuel-efficient formation control. These algorithms are available for ground vehicles, but have yet to be able to be adapted for spacecraft use [2]. Lastly, since it is not possible for orbit maintenance maneuvers to solely occur over a particular ground location, the system is required to be highly autonomous.

### **3.0 CanX-4 & CanX-5: SFL Formation Flight Mission**

Canada is a world leader with respect to spacecraft remote sensing through the success of large Canadian space missions such as RadarSat. Through research and development within the spacecraft formation flying field, Canada can build on its international superiority in remote sensing capabilities. While considerable benefits can be obtained through formation flying space missions, this technology has yet to mature to an operational level.

#### **3.1 Formation Flight Mission Objectives**

Through the upcoming CanX-4 & CanX-5 mission, SFL plans to make Canada the first to demonstrate autonomous spacecraft precision formation flight. By exploiting SFL's experience in designing and operating low-cost satellites, this mission will demonstrate formation flying hardware and software using the smallest platform currently available, the nanosatellite. The intent is to prove and develop the enabling technologies at low cost with the aim of transferring or scaling this technology onto an operational cluster of micro or small satellites for a future application.

SFL plans to achieve the following programmatic objectives through its formation-flying mission:

- Demonstrate precision formation flying capabilities using low cost satellites in space
- Demonstrate centimeter-accurate relative position determination and sub-meter relative position control
- Demonstrate autonomous formation maintenance of two satellites in multiple orbital configurations and at various separation distances
- Develop fuel efficient autonomous formation flight algorithms

### 3.2 Formation Flight Mission Design

Currently in development, CanX-4 and CanX-5, will be launched together in mid-2008 to demonstrate actual autonomous formation control. Aboard the CanX-4 & CanX-5 satellites are enabling technologies such as a compact liquid fuel warm-gas propulsion system for orbital maneuvers, dual-band GPS receivers, algorithms based on carrier phase differential GPS techniques for centimeter-level position determination, algorithms for fuel-efficient formation control, a three-axis attitude control system including sensors and actuators for sub-degree accurate pointing, low-power on-board computers and low-power high-data rate S-band radios for ground and inter-satellite communications.

Many of the enabling technologies, which will be flown on CanX-4 & CanX-5, are custom developed at SFL or commercial-off-the-shelf (COTS) technologies. The use of COTS technologies is an integral part of the nanosatellite low-cost design philosophy. In order to mitigate risk, many of these enabling technologies will be flown initially on CanX-2 in early-2007 in order to validate their performance on a component level prior to full system level operation on CanX-4 & CanX-5. Enabling technologies to be evaluated on CanX-2 include a commercial dual-band GPS receiver, a prototype nano-propulsion system based on COTS components, a momentum biased attitude control system with a prototype nanosatellite reaction wheel, a high performance computer and a high data rate S-band transmitter and UHF radio transceiver [3].

### 3.3 CanX-4 and CanX-5

In general, the development approach for CanX-4 & CanX-5 is to use two satellites with identical buses to keep non-recurring engineering costs to a minimum and provide full redundancy between the satellites. These nanosatellites will have a cubic form factor with a 20 cm side length and a mass of approximately 5 kg. Within a formation, the reference or lead satellite is termed the chief and the remaining satellites, which control their positions relative to the chief, are referred to as deputies. Each satellite will be able to fulfill the role of chief or deputy while formation flying due to their identical design, and as such, the possibility of doubling the formation flying experiment duration is possible. This symmetry implies that not only are the computational and communication abilities of both satellites identical, but that both satellites will have a propulsion and attitude determination and control system for formation flying maneuvers. Table 1 below highlights some of the system specifications for the CanX-4 & CanX-5 mission.

*Table 1 - Performance Requirements for CanX-4 and CanX-5*

<b>Performance Indicator</b>	<b>Target</b>
Position Determination	< 10 cm (< 5 cm stretch goal)
Position Control	< 1 m (< 10 cm stretch goal)
Closest Relative Distance	< 100 m (< 50 m stretch goal)
Attitude Determination	< 0.5° (< 0.1° stretch goal)
Attitude Control	< 1°
Intersatellite Link Data Rate	Between 32 kbps and 256 kbps
Satellite Mass (each)	<5 kg

The ability of CanX-4 and CanX-5 to fly in formation will be tested in stages. The first test will involve a simple coarse formation where one satellite will simply try to negate secular drift in the separation distance between the two satellites. Next, an along-track formation will be attempted where both satellites are arranged in the same orbit with one leading the other by a specified distance. Once arranged in the along-track configuration, the spacecraft will demonstrate autonomous formation flight at separation distances ranging from 500m to 5000m. Once the nanosatellites have successfully completed this simple formation, one satellite will be maneuvered into a halo orbit around the other, as illustrated in Figure 1, by performing an orbital

plane change. Within this halo, or projected circular orbit configuration, the spacecraft will demonstrate formation flight at separation distances ranging from 50m to 500m. Each formation will be maintained for a duration of approximately 100 orbits. While 10 orbits would be sufficient to prove that formation flying has been achieved, flying for a much longer duration than the minimum required time would strengthen the success of the mission. Also, it will allow SFL to demonstrate that precision formation flight can be maintained for an extended period of time that might be useful for applications where a long-term formation is necessary. Furthermore, the satellites' ability to autonomously cancel out secular variations in their orbits, while ignoring periodic variations in order to save fuel, will be evaluated. Finally, if fuel remains, CanX-4 and CanX-5 will attempt to use their imaging systems to create stereo images of the Earth and image each other, demonstrating an effective use of formation flying.

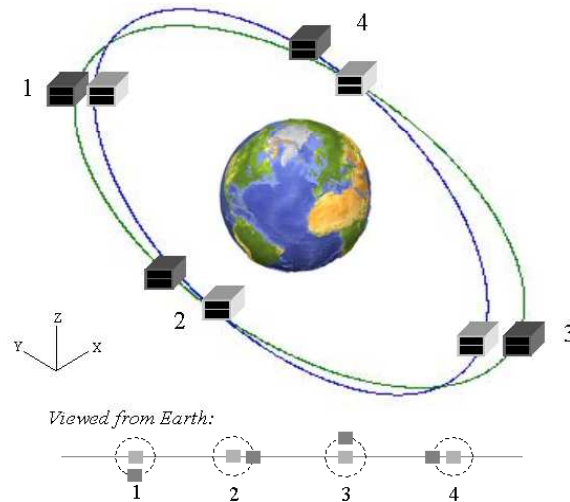


Figure 1 - A Halo Orbit or projected circular orbit [3]

In order to verify accuracy in position determination, CanX-4 and CanX-5 will individually compute their geocentric positions using information obtained from their on-board GPS receivers and relay these positions to the ground. The computed positions will be compared with each other and with orbital element data obtained from NORAD. While NORAD data will be less accurate than the nanosatellite-based GPS information, it will provide a coarse method of determining whether the GPS receivers are functioning correctly. More accurate tracking information, used for comparison, will also be obtained by computing range rate information using the nanosatellites' inter-satellite transmitters.

#### 4.0 General Nanosatellite Bus Overview

The capacity to produce multiple missions in tandem is the result of taking the design of CanX-2 one iteration further. Instead of designing an entire satellite to be adaptable to a wide variety of payloads and mission objectives, the CanX series now focuses on designing specific spacecraft systems to be adaptable to a variety of missions. This approach is particularly evident with SFL's generic nanosatellite bus. This design concept, allows the BRITE (CanX-3) and CanX-4 & CanX-5 missions to use the same basic design for two vastly different missions. While BRITE satellites will fly a cutting edge CMOS-based telescope, CanX-4 & CanX-5 will use the generic bus' payload space for a warm-gas propulsion system. While several other differences such as a star tracker (BRITE) and an inter-satellite communication system (CanX-4 and CanX-5) highlight the adaptability of the generic design philosophy, systems such as attitude control and power show how modular concepts lead to a robust multi-purpose product. Through

the GNB, SFL will position itself as a leader in the low-cost spacecraft industry by providing a platform that can support a range of potential payloads.

#### 4.1 CanX Generic Nanosatellite Bus

A variety of performance drivers influence the design of the GNB. First, the GNB holds to the nanospace design philosophy. Nanosatellites have earned a reputation of being economical and capable platforms through aggressive and resourceful development. In this respect, the GNB adheres to a low cost design process such that development is limited to two years and the system, including a payload, will have a nominal 5 kg flight mass which balances top down mission requirements and bottom up cost constraints.

A generic nanosatellite platform was envisioned with the objective to minimize cost and development time by designing a system that is easily adaptable to both the SFL astronomy (BRITE) and formation flying missions (CanX-4 & CanX-5). This driver necessitates a modular and generic design such that the bus is virtually independent of the payload. The GNB will consist of a stacked tray design whereby similar components will be grouped together. A large and conveniently situated central payload bay is designed to interface with little or no modification to the supporting bus.

The GNB will be one of the most proficient and capable nanosatellite platforms on which to conduct scientific or engineering missions and experiments. To meet this ambitious target, the GNB will offer a highly accurate three-axis attitude determination and control system (ADCS) employing three orthogonal nano-reaction wheels, magnetorquers and sun sensors. The ADCS is designed to be capable of sub-degree determination and control stability. A nanosatellite star tracker, developed by Dynacon Inc., can be flown in order to provide attitude determination to several arcseconds in order to meet the requirements of precision pointing missions such as BRITE which requires arcminute pointing stability. Furthermore, the ADCS system is sized to provide quick and efficient large angle slews in order to support missions requiring rapid manoeuvrability. The CanX-4 & CanX-5 mission, for instance, require highly manoeuvrable spacecraft that are capable of thrusting in any direction. In addition, in order to support the needs of sophisticated nanosatellite missions, the GNB will be designed to carry multiple on-board system computers and a set of low power radios for communications in multiple bands.

Spacecraft produced within the CanX program are built upon the heritage of their predecessors. This modular, step-wise design approach results in progressively more reliable and sophisticated nanospacecraft. For instance, the GNB will feature a cubic form factor as a result of the difficulties posed by the rectangular prism shape of CanX-2. CanX-2, a triple CubeSat, is 3.4 times longer than it is wide. A direct consequence of this form factor is that the ratio between the maximum and minimum effective area illuminated by the sun is five to one. The spacecraft thermal and power states are therefore strongly dependent on the orientation of the spacecraft with respect to the solar vector. In fact, the worst case hot and worst case cold conditions are so widely separated that a single passive thermal design could not meet the thermal requirements for any orbit. A cubic shape would remove the strong relationship between temperature and orientation and thus simplify the thermal and power subsystem design and analysis. A further example of building from heritage is that the GNB will feature only fixed-in-place antennas as opposed to deployables as a result of design and testing challenges experienced on the CanX-1 and CanX-2 spacecraft. Using fixed appendages will also minimize risks associated with moving parts such as non-actuation or jamming.

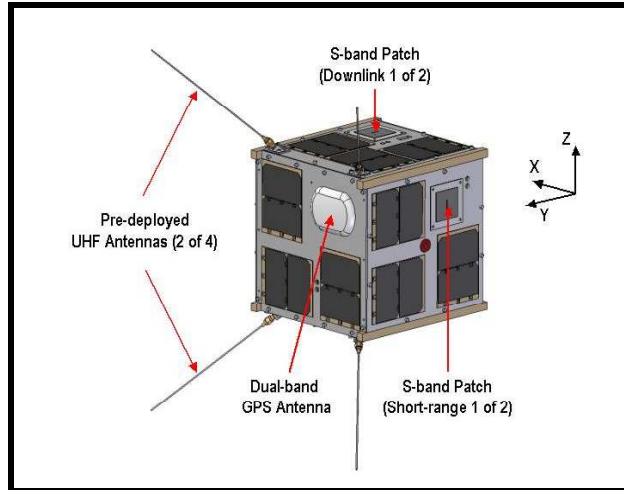


Figure 2 - External layout of CanX-4 or CanX-5. The figure displays the fixed-in-place UHF quad canted monopole antennas and body mounted solar cells and patch antennas.

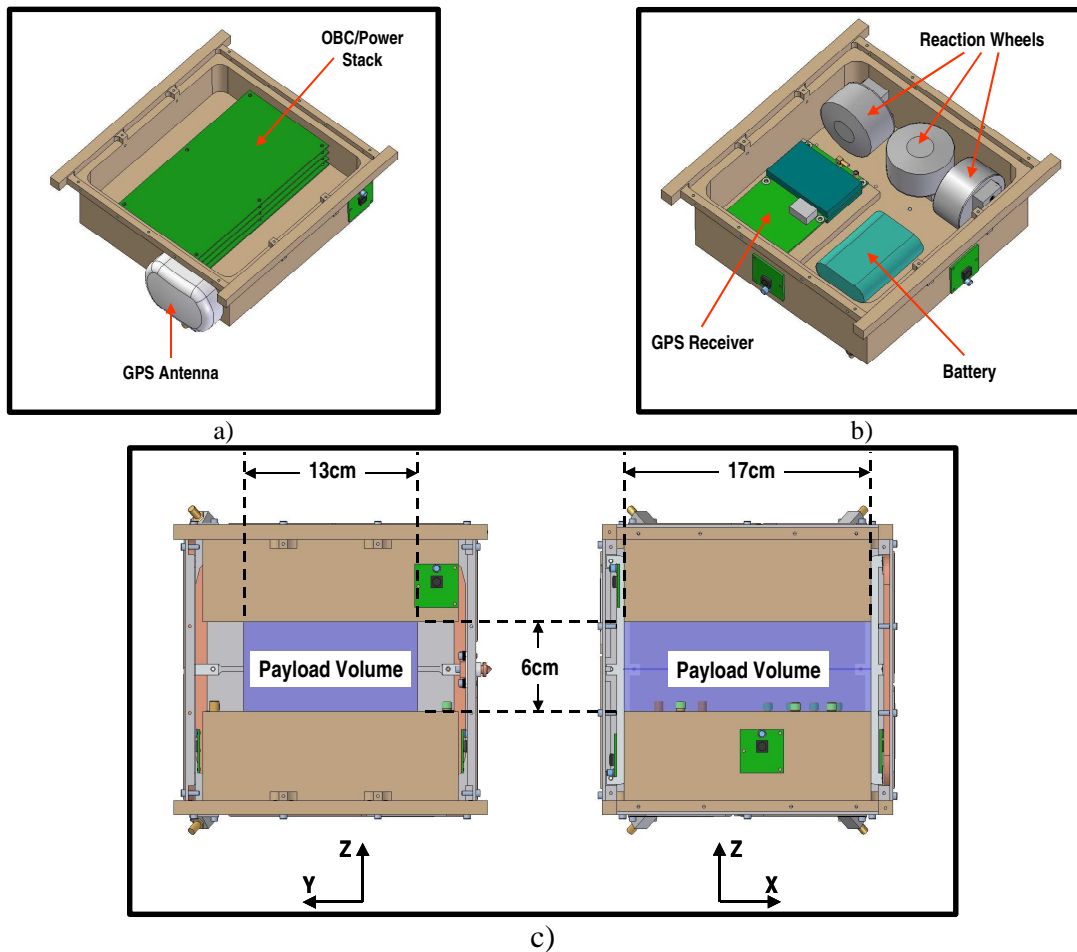


Figure 3 - The two structural trays of CanX-4 or CanX-5. 3a illustrates the tray holding the computer stack. 3b illustrates the tray housing the ACS suite. The radios are mounted on the underside. 3c illustrates the assembled tray configuration as well as the proximity and dimensions of the payload bay.

## 4.2 Structure and Thermal

The structure of the GNB will be constructed from 6061-T6 aluminum, however magnesium alloy has also been considered if further mass reduction is necessary. The GNB employs a modular tray-based design with satellite dimensions of a 20-centimeter cube and a mass of approximately 5 kilograms including a payload. In this respect, the spacecraft bus is separated in segments, grouping similar systems within a tray. For example a single tray holds a stack of on-board computers and power regulation boards. A second tray will act as a mount for the attitude control suite. This leaves a sizable, readily adaptable and conveniently situated central payload bay, thus a modular tray-based design offers payload engineers critical design flexibility. Illustrations of these two trays, as well as the payload bay are shown above in Figure 3. A further motivation for a modular tray based design was to ensure that enough internal structural mounting area exists to prevent component mounting on the spacecraft exterior shell. Protection of the GNB from the on-orbit thermal environment follows a passive thermal control strategy. Computer modeling and simulation facilitates prudent material selection, component placement and selection of external surface treatments. The thermal control strategy is effective over a wide range of orbits.

## 4.3 Attitude Determination and Control

The GNB attitude determination and control system is fundamentally a second iteration design of CanX-2's system, with mission specific modifications. It is a clear example of a modular system design that may be applied to a range of nanosatellite missions.

The stability demands of BRITE and the nature of the formation flying planned for the CanX-4 & CanX-5 mission is what defines the scope of the attitude system requirements. In relation to CanX-4 & CanX-5, the control system must be able to slew each satellite such that their propulsion thrusters can deliver the correct impulse at a rate of about once per minute, and with an accuracy of about one degree. Also, the formation flying algorithms depend on GPS phase differentials for relative positioning, hence, the satellites should be able to slew the spacecraft to see at least four GPS satellites at any given moment.

In general, the pointing requirements of formation flight mission are fairly coarse. As such, the GNB will employ digital sun sensors and a three-axis magnetometer to measure the solar vector and the local magnetic field. Both of these sensors were originally designed, tested, and built in-house at the Space Flight Laboratory, and represent a design iteration that incorporates lessons learned during development for CanX-2.

Due to the adaptable nature of the GNB, a nanosatellite star tracker can also be flown in order to provide high accuracy attitude determination knowledge, as is the case for BRITE satellites. Employing a star tracker in addition to the nominal GNB ADCS suite, BRITE satellites will deliver three-axis attitude control with arc-minute stability – a new precedent for nanosatellites.

Oasys, the laboratory's custom attitude software, will fly on the satellites. The software uses an extended Kalman filter that propagates attitude information over time and corrects the results based on sensory measurements. This is especially useful for CanX satellites, where explicit rate information is not used, but which becomes available as a result of iterative updates.

On the control side of the system, three vacuum-core magnetorquers are used to control general tumble, damp body rates, and shed momentum from the reaction wheels. Three reaction wheels are used to actually implement three-axis control. This orthogonal strategy represents an enhancement to the general, multi-mission design of the CanX-2 attitude system, as it was found that one-degree control or better is quite difficult with only one wheel configuration.

#### 4.4 Power

The GNB will make use of up to 36 high-efficiency (6 mounted on each face) triple junction GaAs solar cells in order to generate 5 to 10W of power. Through a direct energy transfer system, these cells will be used to charge a 5.3Ah Li-ion battery pack, which provides a nominal unregulated bus voltage of 4V to the spacecraft.

Since final launch parameters of the GNB will not be known until well into its development and construction cycle, analyses must be performed to ensure that the GNB will remain power positive at its end-of-life in any low-Earth orbit.

#### 4.5 On-board Computers (OBC)

The GNB will employ a centralized computing architecture similar to CanX-2. Each spacecraft will have three separate 48MHz ARM7 computers, all using an identical design, each responsible for particular tasks. The first computer, the main OBC, will be responsible for most housekeeping tasks aboard the spacecraft such as collecting basic telemetry, coordinating the communications system and relaying data between various subsystems. A second computer will be employed for the ADACS system. Its main responsibility will be the execution of the attitude control algorithms as well as the control and sampling of all actuators and sensors related to the spacecraft attitude system. Finally, a payload computer will be employed and configured specifically for a particular mission. In the case of CanX-4 & CanX-5 for example, it will be responsible for the execution of the formation control and relative position determination algorithms. Each computer will have EDAC-protected SRAM and NAND flash memory for both short and long term storage of spacecraft and experimental data.

CANOE (Canadian Advanced Nanospace Operating Environment), SFL's own in-house multithreaded operating system, will be employed on these computers. CANOE will control all software aboard the spacecraft and provide ground station operators the ability to do tasks such as dynamically load and execute new experiment software as required during the mission.

#### 4.6 Communications

The GNB is designed to carry four separate communication systems. A VHF beacon will be a downlink only channel responsible for continually transmitting basic spacecraft telemetry (such as temperature, bus voltage, etc.). The continuous wave beacon will serve as an aid in basic troubleshooting and tracking of the spacecraft. Data uplink to the spacecraft will be accomplished through the use of an SFL-developed 4 kbps UHF transceiver. This receiver is almost identical in design to the one flown aboard the CanX-2 mission. To obtain omni-directional coverage on this communication link, the system will make use of four canted pre-deployed monopole antennas mounted at one end of the satellite. High-speed data downlinks will be accomplished using another SFL custom-developed radio, a S-Band transmitter, which is identical to the design used on CanX-2, and is capable of data rates of 32Kbps to 1Mbps. This transmitter will be fed into two patch antennas mounted to opposing faces of the spacecraft. Additionally, for CanX-4 & CanX-5, an inter-satellite communication system is being developed as the two spacecraft must be able to communicate with each other to perform their formation flying maneuvers. This system will make use of an existing commercial variable speed system-on-a-chip communication device. Through this system and a set of patch antennas, the spacecraft will be able to exchange information with one another regardless of their relative orientation.

#### 4.7 CanX-4 & CanX-5 Formation Flight Payloads

In order to achieve precision formation flight, CanX-4 & CanX-5 require innovative hardware and software. First, a custom-developed liquid-fuelled warm gas propulsion system is necessary to produce

the changes in velocity required for orbital maneuvers. Second, fuel-efficient formation control algorithms with appropriate position determination filters must be flown. Lastly, in order to achieve centimeter level position determination, accurate inter-satellite positioning algorithms and dual-phase GPS hardware must be flown.

#### 4.7.1 Warm Gas Propulsion System

CanX-4 & CanX-5 will both be flying the Canadian Nanosatellite Advanced Propulsion System (CNAPS – pronounced ‘synapse’) in order to achieve the formation flying relative position control goals (see Table 1). CNAPS is a product of testing and experience gained in the development of the NANOsatellite Propulsion System (NANOPS) that was designed for the CanX-2 mission. NANOPS is a cold-gas propulsion system and was intended to evaluate the flight performance of COTS components while verifying propulsion capabilities using sulphur hexafluoride ( $\text{SF}_6$ ) as a propellant. CNAPS will take the lessons learned from NANOPS and use similar hardware to create a warm-gas propulsion system in order to achieve the higher  $I_{sp}$  values required to minimize on-board fuel and keep satellite mass below 5kg.

NANOPS stores its propellant as a liquid in order to increase the storage density of the fuel. Two solenoid valves are connected in series to control the flow of propellant out of the system. The pressure drop created by opening the valves allows for the propellant to evaporate and flow out to the nozzle. Two solenoid valves are used not only for redundancy, but also because the first solenoid valve (the regulator valve) will be tested to see how it can regulate the downstream pressure through pulse-width modulation. The second valve (the thrust valve) simply controls flow of propellant out of the system. CNAPS will control the flow in a manner similar to NANOPS except that it will be flying two parallel regulator valves and two thrust valves for added redundancy and variable thrust output. Also, in order to be a warm-gas propulsion system, heaters will be added so that the propellant is warmed just before reaching the nozzles. This is done so the heat losses from the propellant to the system and power consumption of the heaters are minimized. A diagram of provisional system can be seen in Figure 4.

Several propellants were originally considered for use with NANOPS and they include traditional cold gas propellants such as Iso-Butane ( $\text{C}_4\text{H}_{10}$ ) as well as unconventional options such as the refrigerant 1,1,1,2-Tetrafluoroethane/R134a [4]. The main drivers for the propellant selection were:

- Ease of use.
- Propellant safety.
- High storage density.
- Relevant to future NANOPS derivatives.
- Allows for sufficient testing of the NANOPS components

In the end, sulphur hexafluoride ( $\text{SF}_6$ ) was chosen to be the propellant for NANOPS, and thus CNAPS, since it is non-toxic, inert, and a known electrical insulator. This propellant is also widely used in plasma sources in semiconductor processing; therefore, it is relevant to a future CNAPS concept that uses a plasma source to inject energy into the propellant.

In order to store the liquid  $\text{SF}_6$ , a tank made of bent titanium tubing will be used to reduce the dry mass of the system as well as increase the tank efficiency, which is defined as the tank storage volume versus the allocated tank volume. Titanium tubing offers both a lower density and increased strength, thus enabling weight savings. The tubing will be bent in a manner that will allow the propellant tank to be separated from the other components in CNAPS, allowing for easier integration and servicing. CNAPS will be designed to store roughly 300cc of propellant within a tank having a mass of approximately 250g to 350g depending on the thickness of material used.

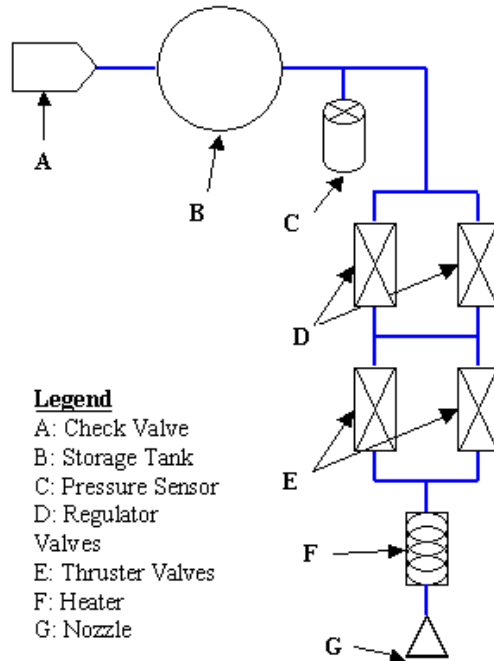


Figure 4 - Provisional CNAPS System Diagram

During formation flight, both relatively high and low  $\Delta V$  maneuvers are required. The high  $\Delta V$  maneuvers will be on the order of 0.5m/s, and will be used to raise or lower the relative orbit of the deputy satellite with respect to the chief or provide plane changes. In order to maintain formation flying, station keeping burns will also be required. These low  $\Delta V$  maneuvers will be on the order of  $3.5 \times 10^{-4}$  m/s and are performed once every 1-2 minutes. High-thrust impulsive burns are favourable for orbit changes to avoid low-thrust orbit propagation, while low-thrust burns allow for finer position control of the deputy satellite. In order for CNAPS to provide these two different levels of thrust, several options are being explored such as using two different exhaust nozzles or using internal plumbing to control exhaust flow. One nozzle will produce higher thrust levels while the other will have a restricted mass flow and different nozzle geometry in order to achieve the low thrust levels needed for station keeping. With the system configuration described above, it is expected that CNAPS will be able to provide approximately 5-10mN of thrust for station keeping and 400mN of thrust for larger  $\Delta V$  maneuvers, with a theoretical maximum specific impulse of 70s. General performance parameters of CNAPS and NANOPS are shown in the Table 2 below.

Table 2 – Performance Parameters of CNAPS and NANOPS

Parameter	CNAPS on CanX-4 and CanX-5	NANOPS on CanX-2
$\Delta V$	~35 m/s	~1.5 m/s
Specific Impulse ( $I_{SP}$ ) (theoretical maximum)	~45 sec (cold gas) ~70 sec (warm gas)	~45 sec (cold gas)
Thrust	5-400 mN	100 mN
Minimum Impulse Bit ( $I_{BIT}$ )	0.1 mN-sec	<0.1 mN-sec
DC Power Consumption	3 W (TBC)	4 W
Overall Wet Mass	1500 grams (TBC)	700 grams
Overall Volume	8x12x17 cm (TBC)	5x10x10 cm

#### 4.7.2 Fuel-Efficient Formation Flight Algorithms

Orbital propagation and orbital control algorithms are required to fly CanX-4 & CanX-5 in formation. The starting point for formation flying algorithms are the Hill equations whose solutions describe stable trajectories for the chief and deputy satellites. These equations are linearized and are valid for motions in a circular orbit. One solution of the Hill equations is a constant relative position in the along-track and a zero relative position in the radial and cross-track positions. Another solution to the Hill equations, termed 'halo orbit' (see Figure 1), is one where the relative orbit of the deputy is a circle with the chief at its centre when viewed from Earth.

The Hill equations provide solutions for circular orbits where there are no perturbative forces. For the sub-meter position control accuracy required, predicting the effect of disturbance forces is necessary. The main perturbation not accounted for by Hill's equations is the J2 effect due to the oblateness of Earth. Although both the chief and deputy are affected by the J2 effect, each are affected differently leading to a slow break-up in formation.

Aside from analytically solving for perturbative dynamics, the modified Hill equations must also incorporate active feedback control to deal with the secular and cyclic disturbances and small errors in the initial conditions. In the interest of conserving fuel, while acknowledging a sacrifice in positional accuracy, only secular terms will be compensated for by the feedback control system. Thus, the replacement Hill equations must differentiate between secular and cyclic disturbances.

#### 4.7.3 Centimeter Position Determination

Formation flight holds promise for many spacecraft applications, however it can only be realized if the relative states of the vehicles can be measured accurately in real-time. The CanX-4 & CanX-5 mission will achieve this by measuring the change in frequency and phase of two GPS signal carriers from four or more GPS satellites. This carrier shift is proportional to relative satellite velocity and distance. When using this technique, the capability to measure relative position with centimeter-level accuracy has been shown [5].

#### 4.8 Current Status

The CanX-4 & CanX-5 mission is currently nearing the end of its preliminary design phase. Many of the lessons learned from the design and test of CanX-2 have already been incorporated into this mission; more will be included in the detailed design phase once CanX-2 is launched as scheduled in the fourth quarter of 2007. The next major milestone is a preliminary design review at the end of May, after which the detailed design segment will get under way. Formal research and development with industrial partners is proceeding, and will continue to expand as the potential applications of formation flying are realized.

### 5.0 Conclusion

The SFL-developed CanX-4 & CanX-5 satellites will make Canada the first to demonstrate precision autonomous formation flight in space. These satellites will demonstrate centimeter-level relative position determination, sub-metre relative position control and autonomous formation maintenance in various orbits and configurations.

CanX-4 & CanX-5 will utilize the SFL-designed Generic Nanosatellite Bus (GNB). The GNB will host an advanced suite of computers, sensors and actuators that will considerably expand the capability of nanosatellites. The GNB was designed with the motivation of developing spacecraft subsystems that are easily compatible with a range of missions. In light of recent advances in nanosatellite technology, these satellites have earned a reputation of being economical and capable space platforms. This has led to a

variety of new missions being realized for nanospacecraft, such as CanX-4 and CanX-5's autonomous formation flight demonstration and CanX-3's stellar astronomy mission.

The promises of spacecraft formation flight applications have generated a recent surge of interest and development within the international community. The Space Flight Laboratory is at the forefront of this development by not only developing a series of spacecraft missions to demonstrate formation flight, but doing so on the smallest platform currently possible. Working on the nanosatellite scale to prove technologies and concepts offers cost and schedule advantages by exploiting the rapid development cycle of the nanosatellite. Although developed for nanosatellites many of the technologies used on this scale will be directly applicable to any class of spacecraft.

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