Formation Flying Demonstration Missions Enabled by CanX Nanosatellite Technology

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ABSTRACT: Two nanosatellite missions that lay the groundwork for satellite formation flying are being realized at the University of Toronto Institute for Aerospace Studies, Space Flight Laboratory (UTIAS/SFL). Such an undertaking has never before been attempted with satellites of this size (< 10 kg). These missions will establish the core technologies necessary for formation flying endeavours at any scale, while capitalizing on the low-cost nature and rapid design cycle of nanosatellites. The key technologies being developed for the nanosatellite missions are nanosatellite propulsion, centimeter-level position determination, and active, three-axis attitude control. The first mission, CanX-2, currently nearing completion, will evaluate the core subsystems listed above. Its planned launch is scheduled for mid-2006. CanX-2 will be followed by a dual satellite mission, CanX-4 and -5, to be launched in 2008, that will build upon the experience gained from CanX-2 and demonstrate actual formation flying. This paper describes the design of CanX-2 and the practical lessons learned to date that can be applied to CanX-4 and -5. The objectives and preliminary mission profile for CanX-4 and -5 are also outlined.

INTRODUCTION

Small satellite technology has advanced to the point that nanosatellites and microsatellites can now complete missions that were previously only possible using larger satellites, resulting in impressive cost savings. Thanks to their inexpensive nature, small satellites are now making a new generation of sophisticated multiple-satellite mission concepts feasible. The Space Flight Laboratory (SFL) is currently preparing a formation flying mission in which two nanosatellites will perform a formation flight, opening the door to subsequent nanosatellite and larger satellite formation flying missions.

The Space Flight Laboratory at the University of Toronto Institute for Aerospace Studies (UTIAS) is a research laboratory with the objective of advancing the state-of-the-art in nanosatellite and microsatellite technology, working in close collaboration with industry, while providing hands-on education by directly involving graduate students. Past achievements by SFL include the design, construction, launch and operation of the Microvariability and Oscillation of STars (MOST)[1] and Canadian Advanced Nanospace eXperiment 1 (CanX-1)[2] satellites. The next mission in the CanX program is CanX-2: a nanosatellite designed to flight test and prove technology needed to enable nanosatellite formation flying, including a three-axis stabilized attitude control system and a cold gas propulsion system. CanX-4 and CanX-5 will use the technology proven aboard CanX-2 to actually perform a formation flight, demonstrating centimeter-level accurate position determination and autonomous formation maintenance.

CanX Program Overview

The Canadian Advanced Nanospace eXperiment program provides a framework for the rapid development and application of new technology in space. Missions involve nanosatellites (< 10 kg) — an emerging class of next generation satellites that exploit commercial off-the-shelf, mass-produced technologies. Currently, nanosatellites demonstrate the level of capability seen in microsatellites a decade ago: rudimentary pointing technologies, and low data rate transmitters. In the CanX program, the boundaries for nanosatellites are rapidly expanding and capabilities are growing. These spacecraft are developed over the course of a two-year design cycle by a multidisciplinary team of Masters students. The team brings together their backgrounds in mechanical, electrical, computer, communications, and systems engineering as the students follow the microspace approach to satellite development[3] under the supervision of experienced satellite engineers. The microspace approach allows for reduced cost of satellite development, and the low mass of nanosatellites results in cheaper launches (assuming a suitable cost sharing arrangement with other nanosatellite developers[4]). However, balanced against the microspace approach, the CanX program adds an element of aggressive experimentation, similar to that used by the U.S. Air Force in the development of X planes in the 1950's, to achieve high performance

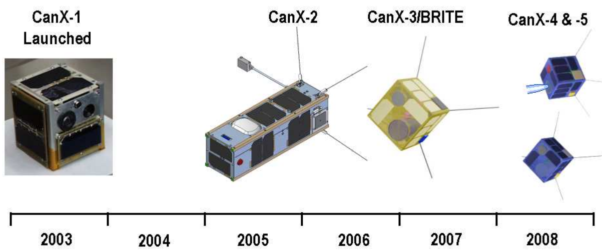

Figure 1. CanX Program Timeline.

missions with an emphasis on innovation and quick turnaround in exchange for moderate risks.

To mitigate the risks associated with rapid development, the CanX program employs a staged approach: as new innovative designs are proven on each mission, they become the baseline for the next satellite, increasing the capabilities of each mission. Two CanX missions are currently underway to develop formation flying capabilities. In this context, formation flying is defined as two or more satellites controlling their position and orientation with respect to one another to achieve a predefined configuration necessary for coordinated operations. In the formation, several satellites act as a single mission spacecraft for coordinated observations, in situ measurements, or virtual instrumentation (e.g. interferometry, distributed sensing). This emerging area of research is receiving much attention internationally as such formations offer the capabilities of large spacecraft at the lower cost common to small satellites.

TECHNOLOGY BENEFITS & APPLICATIONS

Future nanosatellite missions benefit from the CanX program by having new technologies and ideas to draw from that have been proven on a nanosatellite scale. This in turn makes it possible to complete missions never before thought possible using nanosatellites, resulting in huge cost savings. Examples of such enabling technologies include a nanosatellite propulsion system and momentum nanowheels. While some technology would need to be scaled up for larger satellites, other systems can be used at the CanX scale, providing large mass and power reductions, which naturally translates into significant cost savings and greater flexibility. Examples of technology not requiring scaling include an attitude determination sensor suite of coarse and fine sun sensors and magnetometer, a star tracker depending on CMOS imagers, and a GPS-based position determination system. Furthermore, algorithms for attitude control and relative position control, taking into account collision avoidance, fuel minimization, autonomous formation maintenance, and autonomous formation change, are useful at any scale.

The CanX-4 and -5 mission will lay the groundwork for subsequent diverse formation flying missions; one category of such missions is on-orbit servicing. A nanosatellite flying in formation with a client's satellite could perform a thorough inspection of it on-orbit for diagnostic or maintenance purposes. A satellite could also dock, using formation flying techniques, with a failed or degraded spacecraft to provide rapid electronics upgrade or repair. For example, a satellite could rescue a spacecraft whose attitude determination and control system has failed, by permanently docking with the satellite and taking over those functions. Another mission category enabled by formation flying is remote sensing. Satellites flying in formation can create virtual instrumentation with unlimited aperture size, as the baseline between the satellites can be as large or as small as desired, and their geometrical arrangement is flexible.

Many military applications of formation flying nanosatellites (or larger satellites) 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 group of small satellites flying in formation have several advantages when performing the same mission as a single, larger satellite. One advantage is higher reliability, as the loss of a single satellite does not terminate the mission. Furthermore, the ability of the satellites to reconfigure their formation provides an inherent redundancy. Formation flying satellite systems can be easily upgraded: individual, cheaper satellites, can be replaced in the formation over time, gradually upgrading the system with more spread out investment, versus replacing a single, large satellite. Perhaps the most important advantage is the cost savings made possible by "mass producing" the satellites used in the formation, thus spreading out the non-recurring engineering costs. Moreover, purchasing mass-produced off-the-shelf components for nanosatellites reduces the per-unit cost of the components compared with the cost of building a single unit.

FORMATION FLYING OBJECTIVES

The initial step to prepare for operational formation flying missions is to develop and demonstrate the critical technologies required for two satellites to operate in formation. The programmatic objectives for the CanX precursor missions are, therefore, the demonstration of formation flying and inspection capabilities in space, the demonstration of relative centimeter-accurate position determination and control, and use of nanosatellites for formation flying. Once a formation flight has been accomplished, the enabling technologies can be applied to develop an operational cluster of nano- or microsatellites for any application.

CanX-2

The first step toward formation flying will be the CanX-2 mission, currently nearing completion and planned for launch in 2006. It is a 3.5 kg nanosatellite, shown in Figures 3 and 4, and its primary objective is the qualification, at the subsystem level, of nanosatellite formation flying enabling technologies. CanX-2 will validate the SFL nanosatellite bus, the performance of the propulsion system, and the accuracy of the attitude determination and control system.

Figure 2. CanX-2 Mission Patch.

CanX-3

The CanX-3 mission (BRIght-star Target Explorer or BRITE) was conceived separately from the CanX-4 and -5 mission and focuses on astronomical science[5]. Although not directly involved with formation flying CanX-3/BRITE will feature an augmented bus design similar to the bus for CanX-4 and -5. Additionally, the CanX-3/BRITE mission has pointing requirements far greater than previously required from a nanosatellite, which will influence the development of the attitude control system also used in CanX-4 and -5.

CanX-4 and CanX-5

CanX-4 and -5 are currently in the preliminary design process and are scheduled to fly in 2008. Launched together, this pair of nanosatellites will demonstrate actual formation control and inspection maneuvers. The focus is not on specific applications of formation flying or servicing, but on demonstrating accurate relative position and attitude determination and control, as well as inter-satellite communications on a nanosatellite platform.

CanX-4 and -5 will be largely based on CanX-2, building upon the experience gained and incorporating improvements and upgrades suggested by the results of the CanX-2 mission. The mission will verify the performance of various hardware elements to a greater accuracy and evaluate the complete formation flight system. Specifically, the following will be demonstrated:

- Achievement and maintenance of several controlled formations in orbit and evaluation of propellant usage required
- Demonstration of innovative carrier-phase differential GPS techniques to obtain relative position measurements accurate to less than 10 cm
- Verification of an inter-satellite communications link using radio and/or optical communication systems

Many of the objectives of these formation flying missions are similar to those in the TechSat 21 program, underway at the U.S. Air Force Research Labs[6]. Yet, where they are exploring such capabilities with 150 kg satellites, the CanX program will use nanosatellites weighing no more than 5 kg.

Figure 3. Masters Student Assembling CanX-2.

CANX-2 MISSION

Over the course of the one-year CanX-2 mission, the nanosatellite bus will be validated, and the performance and accuracy of its innovative systems will be evaluated. The technologies being tested on CanX-2 include the following:

- Liquid-fuelled cold-gas propulsion system for orbital maneuvers and station keeping
- Commercial high performance dual-band GPS receiver for centimeter-level position determination
- Nanosatellite-sized reaction/momentum wheel for momentum bias three-axis stabilized attitude control
- Custom-designed attitude determination system using a suite of coarse and fine sun sensors and a three-axis magnetometer
- S-band transmitter for high-volume data transmission and range rate determination

The form-factor for CanX-2 is a triple CubeSat (34×10×10 cm) designed to fit the Stanford/CalPoly poly-picosatellite orbital deployer (P-POD)[7]. The aluminum 6061-T6 structure consists of six structural solar panels and a tray, to which most large internal components and payloads are mounted. Satellite power (2 to 6 W depending on orientation and orbit) is provided by 22 triple junction gallium-arsenide (GaAs) solar cells using a direct energy transfer (DET) method. During peak usage periods and eclipse conditions, CanX-2 uses a 3.6 Ahr Lithium-Ion battery connected to an unregulated satellite power bus operating nominally between 3.6 and 4.2V. The relatively tight operating temperature range for this battery (0 to 45ºC) requires that a battery heater be added to the otherwise passive thermal control subsystem of CanX-2, which makes use of external coatings, prudent selection of materials, and cold straps to control satellite temperatures. However, the battery heater may be removed from the design once a launch and orbit for CanX-2 have been secured and worst-case thermal scenarios are narrowed.

The CanX-2 on-board computers (main and payload) were developed at SFL and each uses an ARM7 processor running at 15 MHz with 2 MB of SRAM equipped with triple-voting error detection and correction (EDAC), 6 MB without EDAC protection, for running spacecraft software. Each computer also contains 16 MB of Flash for storage of telemetry, science data, images and pre-positioned code. When in orbit, CanX-2 will collect data from 58 on-board telemetry points including temperatures, currents, bus

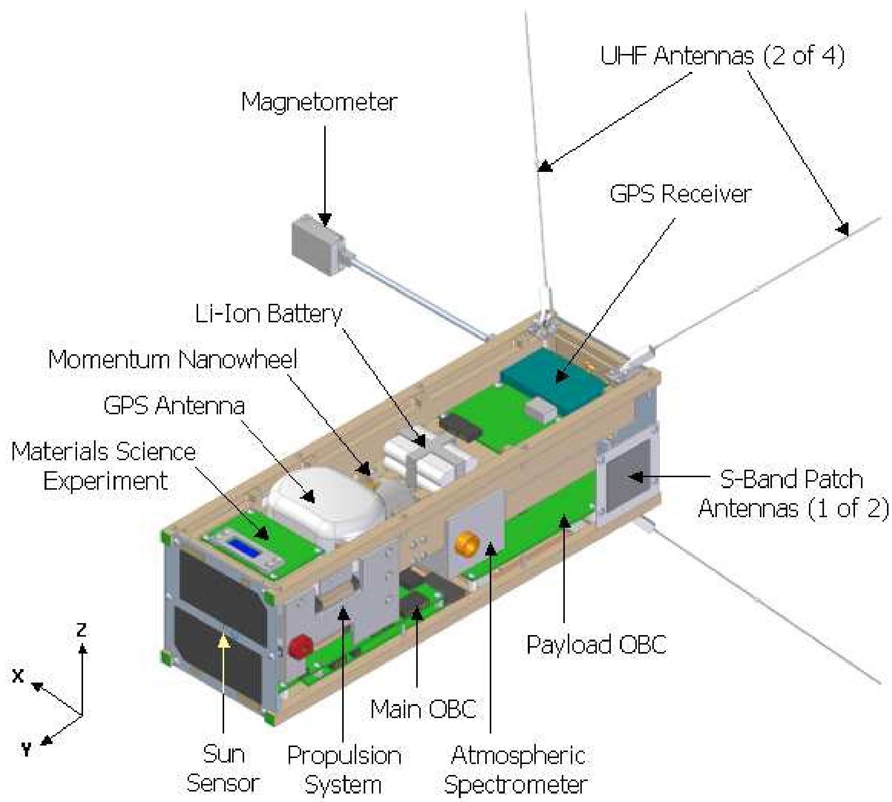

Figure 4. CanX-2 Layout.

voltage, and software outputs, which will be used to monitor satellite health from the ground. Primary communication to and from the satellite is achieved using a SFL-designed half-duplex UHF transceiver operating in the amateur satellite band with a maximum data rate of 4000 bps. The UHF antenna arrangement is a quad-canted monopole configuration that is deployed (passively) upon ejection from the P-POD and provides near omni-directional coverage. The downlink of larger data volumes will be achieved using a SFL-developed variable data rate S-band transmitter operating between 32 and 256 kbps which is being flight proven on CanX-2. The nominal configuration for command and control is full-duplex communication with the UHF uplink and S-band downlink. Also present on the satellite is a continuous-wave beacon, operating in the VHF amateur satellite band, which broadcasts basic satellite telemetry on a continual basis to aid in satellite identification, tracking and debugging, particularly in the days following launch. Command and control of CanX-2 is accomplished through the ground station at SFL.

The nanosatellite propulsion system (NANOPS) is a liquid-fuelled cold gas system (see Figure 5) using sulfur hexafluoride (SF_6) as a propellant. The nozzle is oriented such that thrusting induces a major-axis spin on CanX-2. Through a series of experiments, several performance characteristics of NANOPS will be inferred from this motion combined with pressure, flow, and temperature readings[8]. The satellite angular rates achieved by NANOPS will be measured using the on-board attitude determination subsystem. Attitude determination with an accuracy of ±1º is achieved using a suite of six SFL-developed sun sensors (one on each satellite face), each of which contains fine and coarse sun sensing elements. This system of sun sensors is supplemented by a SFL-developed three-axis magnetometer that uses Honeywell solid-state analog sensing integrated circuits and is deployed approximately 20 cm from the satellite on the end of a boom. Three-axis attitude control is achieved on CanX-2 using a momentum bias system with three orthogonal vacuum-core magnetic torquer coils and a momentum wheel. The nanowheel, shown in Figure 6, which is being developed by Dynacon Inc., generates a maximum torque of 0.3 mN·m and has a maximum momentum storage of 10 mN·m·s and will be flight tested for the first time on CanX-2. The attitude control system will achieve a pointing accuracy of ±10º and maintain a pointing stability of ±1º. Additional verification of the ADCS will be made through images taken of the Earth, the Moon, and the stars by the on-board CMOS imagers.

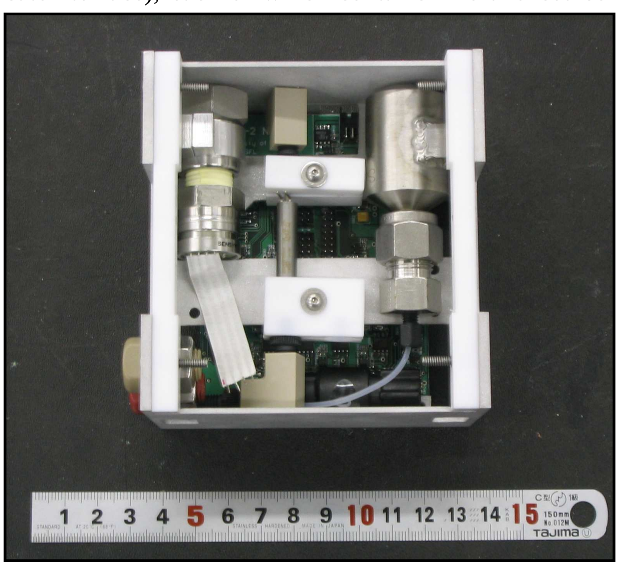

Figure 5. Nanosatellite Propulsion System.

Science Payloads

CanX-2 also has a secondary mission, which is comprised of four science and technology experiments developed by researchers from across Canada, including:

- Atmospheric Spectrometry, Brendan Quine, York University
- GPS Occultation, Susan Skone, University of Calgary
- Materials Testing, Jacob Kleiman, University of Toronto
- Ad-Hoc Network Communications Protocol, Michel Barbeau, Carlton University

The atmospheric spectrometer being developed by Quine is designed to detect airborne greenhouse gases in support of the Kyoto Protocol. The spectrometer operates in the near infrared and has a surface resolution of approximately 1 km.[9]

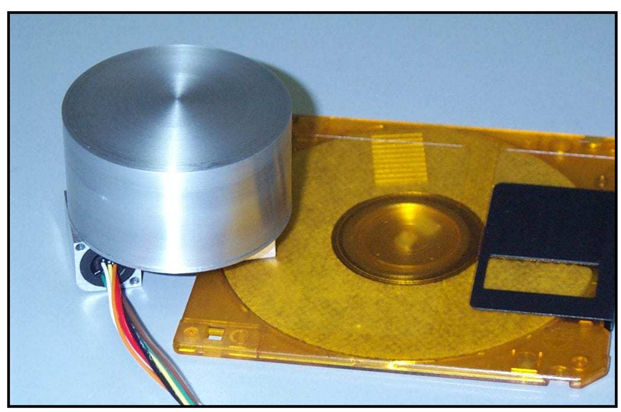

Figure 6. Dynacon Momentum NanoWheel. (3.5" Disk Shown For Scale.)

The GPS occultation experiment developed by Skone uses signals from GPS satellites occulted by the Earth's atmosphere to generate tropospheric water vapor and atmospheric electron density profiles[10]. The dual-band OEM4-G2L GPS receiver provided by NovAtel that will be used for position determination will also be used for this experiment. In large part because of its advanced ADCS subsystem, CanX-2 will be the first nanosatellite capable of performing the type of experiments being developed by Quine and Skone.

The material testing experiment designed by Kleiman will use a photon detector to test a new atomic oxygen-resistant surface treatment. The surface treatment is evaluated by comparing light transmission through treated and untreated translucent samples throughout the CanX-2 mission.

The communication protocol experiment being developed by Barbeau will test a satellite networking protocol that includes a network layer and a transport layer. In a self-organizing network approach, the protocol allows low Earth orbit (LEO) satellites to make use dynamically of ground stations or other satellites to reach a given target. This protocol also addresses data transport errors that occur specifically in LEO satellite links.[11]

CanX-2 Experience

At the time of writing, the construction phase of CanX-2 is nearing completion and system level testing is about to begin. Even though CanX-2 has not yet been launched, many lessons have been learned that can be applied to the designs of CanX-4 and -5 and to future nanosatellite missions.

As mentioned earlier, the form factor of CanX-2 is a triple CubeSat, hence it is 3.4 times longer than it is wide. More importantly, the minimum effective area that the satellite can present to the sun (small face only) is approximately five times less than the maximum effective area. This means that for any given orbit the thermal state of the satellite is highly dependent on the satellite attitude. As a result, worst-case hot and cold conditions are so widely separated that a single passive thermal design cannot meet the thermal requirements for all orbits (often a CubeSat requirement in and of itself). Because of the difficulty experienced with the CanX-2 form factor, CanX-4 and -5 will have more cubic form factors and will depart from the CalPoly CubeSat standard.

For the CanX-2 power system it was decided that a direct energy transfer (DET) rather than a peak power tracking (PPT) method would be used to transmit energy from the solar cells to the battery and bus. The DET method was chosen mainly to simplify the design of the power system. However, it was discovered that choosing the DET method made analyses involving power (i.e. power budgeting, thermal analysis, operations design, etc.) more complicated and assumption-laden, due to the difficulty of modeling battery charge level. The result is that there is less confidence in the predictions resulting from these analyses, which can lead to an overly conservative design.

Early in the design of the software architecture, eCos[12] was selected as the operating system for the custom ARM-based on-board computers (OBC). However, it was estimated that the effort and time required to port eCos to the OBC would be greater than that required to create a custom multi-threaded operating system (dubbed the Canadian Advanced Nanospace Operating Environment – CANOE) with a scheduler for thread handling and an inter-thread communications mechanism. Because CANOE only contains functionality required for CanX-2, the code size was significantly reduced. This is an important consideration since such code is stored in EDAC-protected memory which is limited to 2 MB.

CANX-4 AND CANX-5 MISSION

Taking advantage of the key enabling technologies demonstrated by CanX-2, the CanX-4 and -5 mission will focus on actually flying in formation. The purpose of the mission will not only be to refine the technology and techniques involved, but also to prove that it can be done with nanosatellites at comparatively low cost and over a short development time.

Requirements Summary

Maintaining satellites in a formation requires that their positions and attitudes be accurately known and controlled in order to allow precise thrusting maneuvers. The desired precision of the formation drives the required accuracy of the satellites' position knowledge, position control and propulsion system performance. Furthermore, as the satellites' relative positions and attitudes are autonomously adjusted, they must be able to continuously communicate their changing locations and orientations to each other. The needed accuracy and efficiency of the adjustment maneuvers influence the speed at which they must communicate with each other.

Table 1 lists the performance requirements for the aforementioned mission parameters, as well as other relevant mission requirements.

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

Performance Indicator	Target
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	< 0.5º (< 0.1º stretch goal)
Attitude Control	< 1º
Intersatellite Link Data Rate	Between 32 kbps and 256 kbps
Imaging Resolution at [50 m, 100 m, 500 m, 900 km]	[2.5, 5, 25, 45000] cm/pixel
Satellite Mass (each)	<5 kg
Total ΔV	>35 m/s
Specific Impulse (I_{SP})	50-100 s
Thrust	50-100 mN
Minimum Impulse Bit	<0.1 mN·s

Design Overview

CanX-4 and -5 will be identical nanosatellites in order to keep the cost of the mission low and to make the formation flying experiments symmetrical. The satellites will be maintained in proximity to each other during the commissioning period of the mission, possibly using a rigid coupling or tether, in order to prevent them from drifting too great a distance apart.

Much of the CanX-4 and -5 bus technology will be flight-proven, taken from the CanX-2 mission. The imagers, on-board computers and GPS receiver and antenna that will be flown on CanX-4 and -5 will be similar or identical to those flown on CanX-2. The high data rate S-band transmitter to be flown aboard CanX-2 will be a precursor to the S-band transceiver, which will provide the full-duplex link and possibly the intersatellite link for CanX-4 and -5. Like the CanX-2 mission, CanX-4 and -5 will communicate through the existing ground station at UTIAS, suitably modified for a simultaneous link with both spacecraft. This allows full use of every pass to communicate with both satellites.

The attitude determination and control hardware verified on CanX-2, namely coarse and fine sun sensors, three-axis magnetometer, magnetic torquer coils and momentum nanowheels, will be used on CanX-4 and -5. They will also fly a propulsion system of the same design as NANOPS (flown aboard CanX-2) but with a greater amount of propellant and electrical heaters added to warm the exhaust gas, increasing the I_{SP}.

The structural design of CanX-4 and -5 will be a rectangular prism measuring 17 x 17 x 25 cm. The solar cells will be body-mounted, avoiding extra deployable mechanisms and their associated risks. Although CanX-4 and -5 will fly the same nanowheel design flight proven aboard CanX-2, they will include a full complement of three wheels, orthogonally mounted along with three magnetic torquers, providing three-axis control.

Experiment Plan

In order to verify their position determination accuracy, CanX-4 and -5 will individually compute their absolute 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 information available on the ground. Orbital elements will be obtained from NORAD, and although this will be far less accurate than the nanosatellite-based GPS information, it will provide a coarse method of determining whether the receivers are functioning correctly. More accurate tracking information, used for comparison, will also be obtained on the ground by computing range rate information using the nanosatellites' S-band transmitters.

The ability of CanX-4 and -5 to fly in formation will be tested in stages. The first test will involve a simple formation of having both satellites in the same orbit, with one leading the other by a chosen time constant. Once the nanosatellites have successfully completed this simple formation, one satellite will be maneuvered into a halo orbit around the other, as shown in Figure 7, by performing an orbital plane change. 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, CanX-4 and -5 may also use their imaging systems to create stereo images of the Earth, demonstrating an effective use of formation flying.

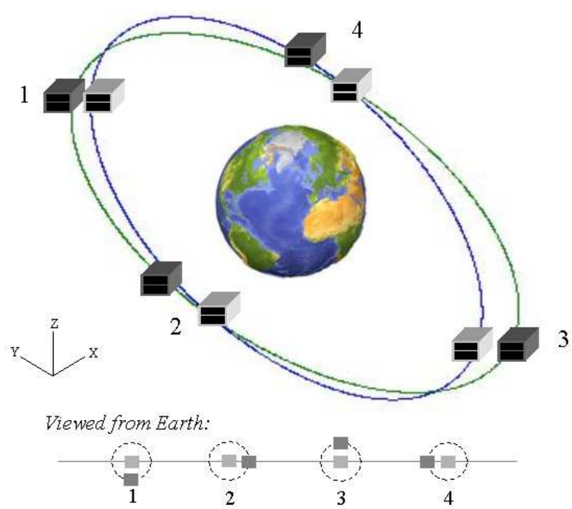

Figure 7. CanX-5 in a Halo Orbit Around CanX-4

CONCLUSION

Formation flying missions represent incredible potential for the future of space science and technology. By using nanosatellites to develop and verify the technologies required to successfully perform formation flying missions, the cost and risk of such missions can be significantly reduced.

The CanX-2 nanosatellite, developed at the University of Toronto Institute for Aerospace Studies, Space Flight Laboratory, will be used to demonstrate and flight prove the key technologies required to perform an actual formation flying mission embodied by CanX-4 and -5. The technologies to be proven on CanX-2 include a cold-gas propulsion system, centimeter-level GPS position determination, three-axis stabilized attitude determination and control system, and a high data rate S-band radio. By flight testing these technologies on CanX-2 the risk associated with the CanX-4 and -5 mission will be significantly reduced. Once the concept of formation flying has been demonstrated with nanosatellites, larger missions involving more capable microsatellites (or larger) can make use of the relevant enabling technologies, thereby reducing cost, risk and development time. Using these technologies, the promised benefits of formation flight can be made a reality.

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