IAC-05-B5.6.A.15

CANADIAN ADVANCED NANOSPACE EXPERIMENT 2: SCIENTIFIC AND TECHNOLOGICAL INNOVATION ON A THREE-KILOGRAM SATELLITE

Karan Sarda
M.A.Sc. Candidate, University of Toronto
ksarda@utias-sfl.net

Stuart Eagleson, M.A.Sc. Candidate, University of Toronto
Eric Caillibot, M.A.Sc. Candidate, University of Toronto
Cordell Grant, M.A.Sc. Candidate, University of Toronto
Daniel Kekez, M.A.Sc. Candidate, University of Toronto
Freddy Pranajaya, CanX/NLS Program Manager
Dr. Robert E. Zee, Managing Director, Space Flight Laboratory

Space Flight Laboratory
University of Toronto Institute for Aerospace Studies
4925 Dufferin Street, Toronto, Ontario, Canada, M3H5T6
Tel: 416-667-7903 Fax: 416-667-7799
Email: rzee@utias-sfl.net Web: www.utias-sfl.net

ABSTRACT

The Space Flight Laboratory (SFL) at the University of Toronto Institute for Aerospace Studies (UTIAS) is developing its second nanosatellite, the Canadian Advanced Nanospace eXperiment 2 (CanX-2) as a part of the CanX program. The objective of the CanX program is to produce highly capable nanospacecraft, each within a two-year period, i.e the time it takes to complete a graduate degree. CanX missions offer extremely low cost and rapid access to space for scientists and commercial exploitation. CanX-2, which is compatible with the Stanford University and California Polytechnic State University "CubeSat" standard, is a "triple CubeSat" with dimensions measuring 10 x 10 x 34 cm and a mass of 3.5 Kg. This nanosatellite features an ambitious suite of scientific and engineering payloads, and enlarges the envelope of capability for this class of spacecraft. The primary mission of CanX-2 is to test and demonstrate several enabling technologies for precise formation flying. The secondary purpose of CanX-2 is to fly a number of university experiments. The spacecraft mission, the engineering and scientific payloads, and their implication to planned SFL nanosatellite formation flight missions form the basis for this paper. CanX-2 is currently well within the two-year design period and fast approaching flight-ready status with launch scheduled for mid 2006.

1.0 INTRODUCTION

University of Toronto's Space Flight Laboratory initiated a nanospace program, the Canadian Advanced Nanospace eXperiment (CanX) in 2001. Building off the laboratory's expertise in microsatellite design, the CanX program was created in order to develop highly capable nanospacecraft within a two-year period – i.e. the time that it takes to complete a graduate degree. The CanX program mandate is two fold. First, provide Canada with a continuous supply of highly skilled and experienced space system engineers, and second, offer a low-cost, quick-to-launch satellite platform upon which to execute scientific and technology demonstration missions. In the CanX program, graduate students receive hands-on training and mentoring from SFL's professional engineering staff. Canada's first space telescope, the MOST (Micro-variability and Oscillation of Stars) microsatellite was designed, integrated and tested within SFL [1]. With this expertise on hand, SFL graduate students can tap into a diverse wealth of knowledge during the design of a CanX nanosatellite. Within this unique educational environment, students experience all phases of spacecraft design, from mission conception to on-orbit operations. Thus, graduate students work to implement aggressive and ambitious missions that push the envelope of achievable performance with commercial technologies.

Figure 1 – CanX-2 being assembled by a Masters student in the SFL clean room.

After rapid, cost-effective in-situ space testing, technologies tested on CanX nanosatellites can perform vital functions in future SFL spacecraft, or more generally in missions of any spacecraft class. This modular design approach is in-fact the heart of the CanX spacecraft design method. With a focus on aggressive experimentation, CanX missions offer extremely low cost and rapid access to space for Canadian scientists and commercial exploitation.

2.0 SFL FACILITIES

The Space Flight Laboratory at UTIAS is a modern satellite engineering facility built within the confines of a world-recognized centre for aerospace research. The laboratory boasts a suite of facilities allowing most of the design, assembly, and testing of UTIAS/SFL satellites to be accomplished in-house.

This equipment includes a full set of tools to build and test custom surface-mount electronics such as computers and radio boards. Furthermore, to ensure the performance of these developed space systems in a space-like environment, SFL holds two thermal chambers and a small vacuum chamber. This test equipment can be used in parallel for full functional testing of individual components or an entire nanosatellite within a representative space thermal environment.

A Class-10 000 clean room is used for all SFL spacecraft during final integration, spacecraft cleaning, testing and holding prior to shipping the spacecraft to the launch site.

The SFL ground station has fully automated capabilities within the UHF/VHF/S-Band frequencies. In order to communicate within the UHF and S-Band frequencies, a dual Yagi antenna array and a 2.1-meter parabolic dish antenna are used respectively.

3.0 CANX-1

CanX-1, the first spacecraft developed in the CanX project, was launched with the MOST microsatellite on June 30th 2003. This satellite was a single 'CubeSat' and built according to the California Polytechnic State University (CalPoly) and Stanford University CubeSat standards [2]. CanX-1 consisted of a stacked PCB arrangement enclosed by an aluminum frame with dimensions measuring 10 x 10 x 10 cm and a mass of 1 kg.

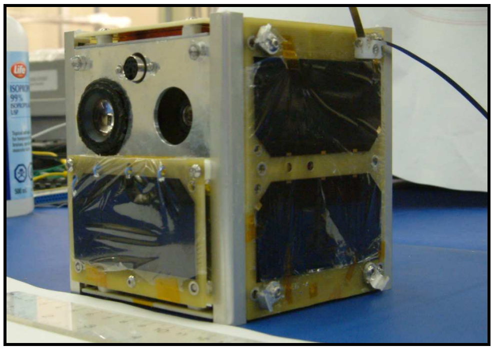

Figure 2 – The CanX-1 nanosatellite

In order to provide a foundation of technology and design philosophy for future CanX spacecraft, the primary objective for the CanX-1 was one of technology demonstration [3]. Several technologies, which were intended to be core features for future nano and micro-spacecraft, were developed at SFL, thus the main priority was to space-qualify these components. The flight tested technologies included a custom designed on-board computer using an ARM7 processor, a custom designed UHF radio operating in the 70 cm amateur satellite band, a magnetic B-dot attitude control system and colour and monochrome CMOS imagers.

Several important lessons were learned from the CanX-1 project. First, all future SFL nanospacecraft will carry a VHF beacon which will be useful during the initial period of on-orbit operations. This beacon will be designed to be as independent from the rest of the spacecraft as possible. The beacon will broadcast basic telemetry in the amateur VHF frequencies to the ground station, notifying operators of the systems state of health. Secondly, staff involvement in future SFL spacecraft will be increased, especially in the design and development of key spacecraft systems such as the computers and radios. In addition, all future SFL nanospacecraft will be launched in their own dedicated deployment systems.

A large majority of the CanX-1 mission objectives were fulfilled. First, a unique spacecraft program was created in Canada where students develop valuable skills through hands on training. Masters students were able to experience all phases of the development cycle and preliminary phases of flight operation. Second, CanX-1 served its overarching purpose as a pathfinder mission for future CanX spacecraft.

4.0 CANX-2

CanX-2 is a much more ambitious spacecraft with respect to CanX-1. CanX-2, being a triple CubeSat measuring 10 x 10 x 34 cm in dimensions and 3.5 kg in mass, packs enough engineering and scientific experiments to push the envelope of what has been previously attempted in this scale of spacecraft.

Figure 3 – CanX-2 mission patch

The mission objective for this spacecraft is two-fold. The principle objective is to demonstrate technologies that were identified to be critical for the upcoming CanX-4/5 formation-flying mission. The CanX-2/4/5 missions are designed to develop and demonstrate capabilities for formation flying and inspection in space on the smallest platform possible. Within this series of spacecraft, CanX-2 will serve principally as a risk mitigation mission for CanX-4 &-5.

Engineering payloads to be investigated include hardware essential for centimeter-accurate GPS determination of relative satellite positions, a nano-propulsion system based on commercial off the shelf components, a three-axis sub-degree accurate attitude determination system, a CMOS imaging system for inspection and navigation, a high performance computer and a high data rate radio system.

The second objective for CanX-2 is 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, a GPS atmospheric occultation experiment to determine vertical profiles of electron and water vapour content of Earth's atmosphere, a surface material experiment that will measure the effects of atomic oxygen on advanced materials and a dynamic spacecraft networking protocol experiment.

4.1 Formation Flight Technology Demonstration

Future SFL missions will benefit from the CanX technology demonstration missions 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. 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 [4].

The CanX-2/4/5 mission will lay the groundwork for subsequent diverse formation flying missions such as on-orbit servicing and remote sensing. A nanosatellite flying in formation with a client's satellite could perform a thorough inspection of it for diagnostic or maintenance purposes. A satellite could also dock, using formation flying techniques, with a failed or degraded spacecraft to provide a rapid electronics upgrade or repair. Furthermore, satellites flying in formation can create virtual instrumentation with an unlimited aperture size, as the baseline between the satellites can be as large or as small as desired and their geometrical arrangement is flexible.

A group of small satellites flying in formation, such as those shown in Figure 4, have several advantages when performing the same mission over a single, larger satellite. One advantage is higher reliability, as the loss of a single satellite does not terminate the mission. Furthermore individual, cheaper satellites in a formation can be easily replaced over time, gradually upgrading the system with a more spread out investment. 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.

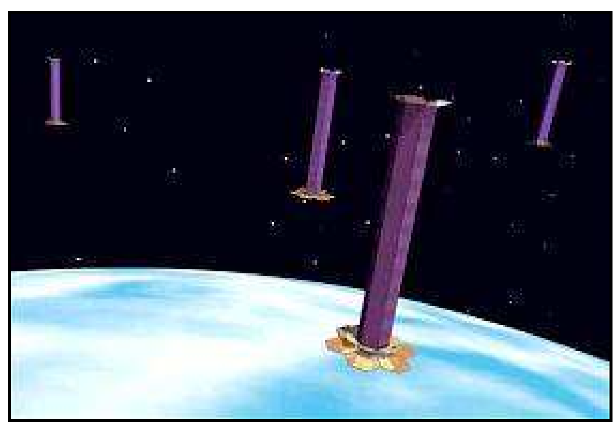

Figure 4 - Flying in formation offers advantages such as potentially unlimited apertures sizes [5].

The first step toward the CanX formation flight demonstration will be the CanX-2 mission where its primary objective is the qualification of nanosatellite formation flying enabling technologies, the cornerstones of which are described below.

4.1.1 Centimeter Level GPS Based 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-4/5 missions will achieve this by measuring the change in frequency and phase of two GPS signal carriers from four GPS satellites. This carrier shift is proportional to relative satellite velocity and distance. When using this technique, the capabilities to measure positional accuracies on the centimeter level have been shown [6].

While CanX-4/5 will fly with this technology, the formation flight demonstration mission will rely on technology evaluation conducted by CanX-2. Specifically, CanX-2 will be used to assess the GPS hardware and data quality. Secondly, once evaluated, the data will be processed using standard single-point GPS techniques to provide positional accuracies on the order of 2-10 m.

4.1.2 Nano-Propulsion System

Formation flight applications require a propulsive system for several reasons. First, there is a need to control secular disturbances caused by perturbative forces. Second, for applications such as on-orbit inspection, the surveyor satellite must be able to maneuver around the target.

To this end, a small experimental liquid fueled cold-gas propulsion system, the Nano Propulsion System (NANOPS), has been developed and will be tested on CanX-2 [7]. The CanX-2 propulsion system is shown in Figure 5. A slightly larger variant will be subsequently flown on the CanX-4/5 mission. The system uses sulfur hexafluoride (SF_6) as 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 pressure, flow, and temperature readings. The satellite angular rates achieved by NANOPS will be measured using the on-board attitude determination system. Key performance requirements of NANOPS are shown in Table 1.

Table 1- NANOPS performance attributes

Parameter	Requirement
Total ΔV	>35 m/s
Specific Impulse (I_{SP})	50-100 s
Thrust	50-100 mN
Minimum Impulse Bit	<0.1 mN·s

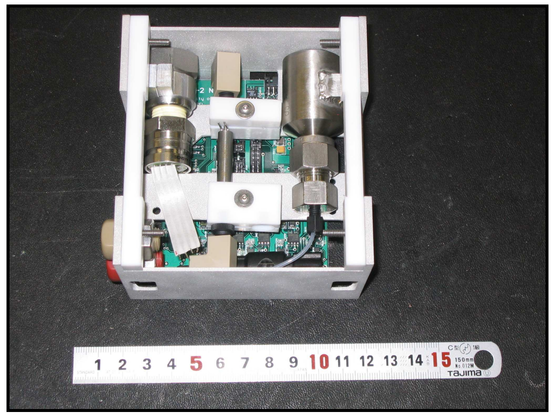

Figure 5 - NANOPS system

4.1.3 Attitude Determination and Control System

Mapping formation flight applications often demand high attitude determination and control accuracies. Furthermore, for applications such as on-orbit servicing, where satellites will be positioned extremely close to each other for docking, high accuracies will be required.

To attain sub-degree attitude determination and control performance, which is necessary for accurate formation flight, CanX-4/5 will feature an ambitious suite of actuators and sensors. Accurate three-axis stabilization and control will be achieved using a set of three orthogonal nano-reaction wheels, high precision Sun sensors, a nanospacecraft-sized star tracker, a magnetometer and a magnetic control system consisting of magnetorquer coils.

The aforementioned system in most part has not been flight proven. To this end, CanX-2 will evaluate the performance of these actuators and sensors in a momentum bias three-axis stabilized attitude configuration.

4.1.4 CMOS Imagers

Many applications of formation flight require the use of an imager for visual inspection. To this end, CanX-2 will be equipped with both monochrome and colour CMOS imagers of 1280 x 1024 resolution with a 30 degree field of view. CMOS imagers were chosen in favour of CCD technology because of its power efficiency and performance.

The CanX-2 CMOS imagers will be used to take pictures of targets of interest such as the Earth, Moon and star fields. Star field pictures will subsequently be used to assess the capability of the CMOS imagers as nano-scale star trackers.

4.2 Scientific Objectives

CanX-2 hosts several experiments, each with the promise of advancing knowledge and understanding within the scientific community. The instruments, described subsequently, are shown in Figure 6.

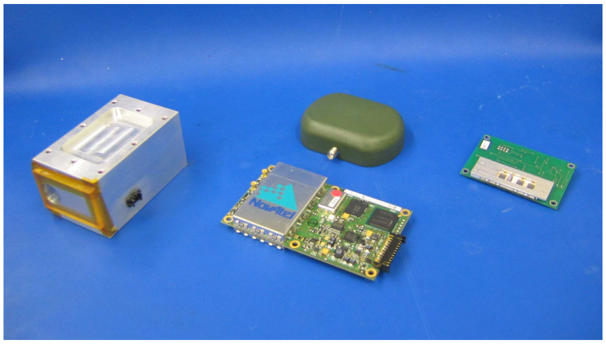

Figure 6 - CanX-2 science instruments: Atmospheric spectrometer (left), GPS antenna (center top), GPS receiver (center bottom), advanced surface material experiment (right)

4.2.1 Atmospheric Spectrometer

The Argus Spectrometer, developed by researchers at York University, aims to yield a better understanding of greenhouse gases in the atmosphere [8]. Specifically, this 230 g device will analyze in the near infrared spectrum, looking at the radiance response of carbon dioxide, methane, nitrous oxide, oxygen, and water around the 1.5 to 1.8 μm mark.

The spectrometer onboard CanX-2 is a technology demonstration unit. Its current footprint will be one square kilometre, and will track only along nadir. Once Argus has demonstrated its ability to analyze greenhouse gases, future missions will allow full three-axis control to the spectrometer to support international treaties such as the Kyoto Protocol. The idea is that the gas flux from specific regions may be determined, the effect of cross-border pollution flux may be quantified and a more precise understanding of climate warming may be acquired.

4.2.2 GPS Atmospheric Occultation

Researchers at the University of Calgary are interested in minimizing ranging errors that GPS receivers experience due to uncertainties in both the troposphere and ionosphere [9]. To study this phenomenon, CanX-2 will carry a dual band GPS receiver, complemented with a directional antenna. In the experiment, signals from occulting GPS satellites, which experience a signal delay, will be compared with those from ground-based GPS stations. Using differential methods, the total electron content (ionosphere) and water vapour content (troposphere) will be mapped as a time-varying function of altitude. A successful map of atmospheric properties will allow mitigation of GPS position errors. It will also allow the monitoring of auroral activity, magnetic sub-storms, and other enhanced ionospheric activities that impact navigation and communications systems.

4.2.3 Surface Material Experiment

Atomic oxygen in Earth's atmosphere causes severe erosion to satellite materials in low Earth orbit. A new process has been developed by the University of Toronto to treat such materials, improving their resistance to the harsh environment of space. CanX-2 includes a materials degradation experiment to test this treatment.

Two identical material samples, whose behavior in space is well known, will be flown onboard the satellite. Both will be exposed to space, but only one will have been treated to resist atomic oxygen erosion. The electrical resistance of both samples will be measured over time, which will give an indication of how the samples' volumes change, and so quantifying the effectiveness of the treatment process.

4.2.4 Nanosatellite Communication Protocol

An innovative method of networking low Earth orbit satellites has been devised by researchers at Carleton University [10]. The aim is to allow satellites to dynamically transfer data. That is, the network protocol on a given satellite activates in response to incoming data; it in turn relays information to other satellites or ground stations as they come into the operational field of view. In this manner, data may be routed globally in a dynamic, self-organizing sense.

CanX-2 will carry this software protocol onboard, and for demonstration purposes will interact with available ground stations. The layered protocol will also test new methods of dealing with data transport errors that occur within low Earth orbit satellite links.

4.3 CanX-2 Bus

The structural design of CanX-2 is based in part around a nanosatellite deployer, known as P-POD[1], which conforms to Stanford/CalPoly standards for cubic satellites (CubeSats). This deployer drove CanX-2's form factor, in that it is quintessentially a triple CubeSat, measuring 10 x 10 x 34 cm. Since the satellite boasts so many instruments and experiments, an Al. 6061-T6 tray based design was chosen to simplify assembly and integration. A large majority of CanX-2's internal components are directly mounted to the tray, as are most of the body panels that enclose them. Externally, four aluminum rails act as contact surfaces with the deployer.

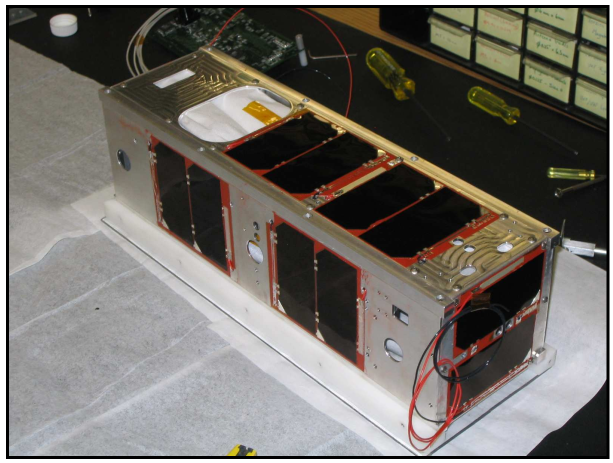

Figure 7 - Partly integrated CanX-2 spacecraft

Protection of CanX-2 from the on-orbit thermal environment follows a passive thermal control strategy. Computer modeling and simulation led to prudent material selection and placement of components as well as selection of external surface treatment. The thermal control strategy is effective over a wide range of orbits.

CanX-2 relies on twenty-two solar cells spread over its surfaces to generate power. In eclipse, power is drawn from a rechargeable 3.6 Ah lithium ion battery. Direct energy transfer is used to enable the anticipated 2 to 7 W of electrical energy for use by the various subsystems. Power is directed via an

[1] Poly – Pico Satellite Orbital Deployer.

unregulated power bus, which nominally operates at 4.0 V.

Attitude determination and control of the satellite centres around a simple but novel system. Determination with an accuracy of ±1º is achieved using a suite of SFL-developed sun sensors, supplemented by a three-axis magnetometer deployed approximately 20 cm from the satellite at the end of a boom. Three-axis control, to an accuracy of at least ±10º, is achieved on CanX-2 using a momentum bias system with three orthogonal electromagnetic coils and a momentum wheel. The NanoWheel®, developed by Dynanon Inc., generates a maximum torque of 0.4 mNm and has a maximum momentum storage of 10 mNms. It will be flight tested for the first time on CanX-2. Additional verification of the system will be made through images taken of the Earth, the Moon, and the stars by the on-board CMOS imagers. The attitude determination and control suite of components is shown in Figure 9.

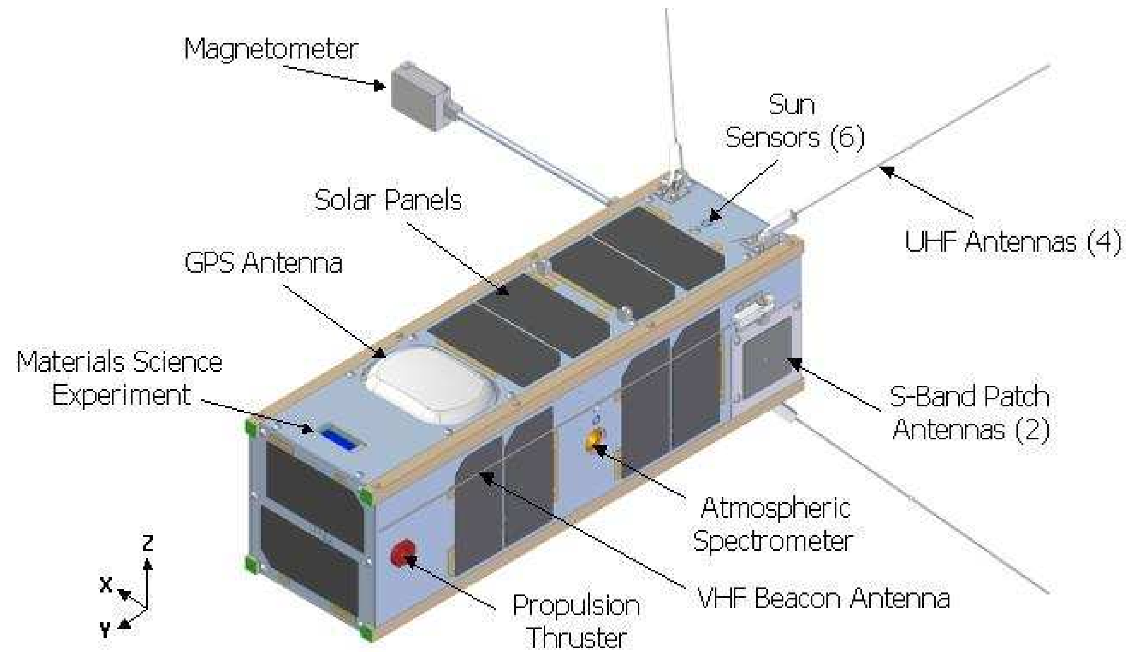

Figure 8 - CanX-2 bus overview

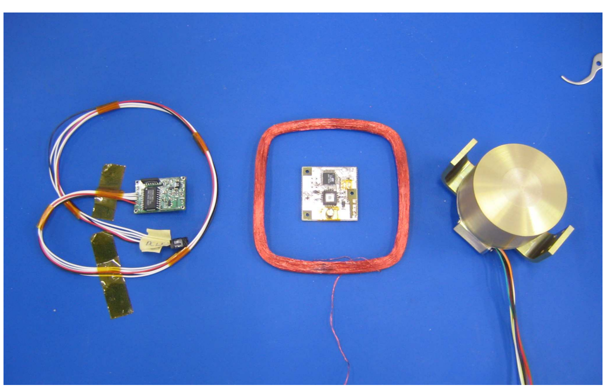

Figure 9 – CanX-2 ADCS components: Magnetometer (left), Sun sensor (center), Magnetorquer coil (center), NanoWheel (right)

The central brain for CanX-2 is composed of two computer boards, each hosting a 15 MHz ARM7 processor with 2MB of SRAM equipped with triple-voting error detection and correction (EDAC) and 4 MB without EDAC protection. Each computer also holds 16 MB of flash memory for storage of telemetry, science data, images and pre-positioned code. An SFL operating system, CANOE,[2] runs all of the application software and handles all internal communication with the hardware components. Moreover, 58 telemetry points

[2] Canadian Advanced Nanospace Operating Environment.

will be gathered, keeping track of CanX-2's status with fine detail. These computers are shown in Figure 10.

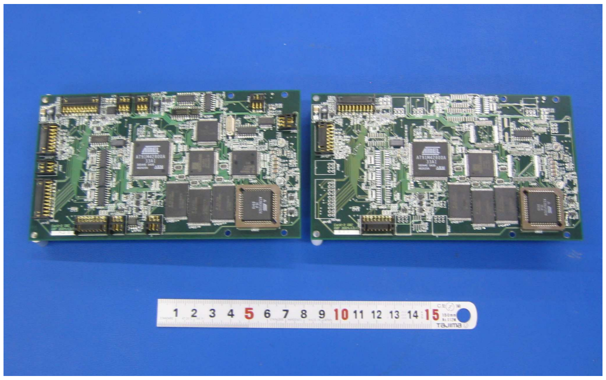

Figure 10 - CanX-2 on-board computers

Communication with CanX-2 takes a three-pronged approach. The first method uses a VHF beacon that broadcasts basic telemetry back to Earth via Morse code at a rate of 15 words per minute. The second method uses a set of four cantilevered antennae to broadcast in the UHF band at a maximum rate of 4000 bps. The third method will employ an SFL developed S-band transmitter which may operate between 32 and 256 kbps. Due to the large amount of information CanX-2 is expected to process, the ideal communication configuration is full-duplex, with the UHF being used for uplink, and the S-band transmitter being used for downlink.

5.0 CANX-4 AND CANX-5 MISSION

Taking advantage of the key enabling technologies demonstrated by CanX-2, the CanX-4/5 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. Launch for CanX-4/5 is anticipated for 2008.

Table 2 lists the performance requirements for the CanX-4/5 mission.

Table 2. 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

5.1 Design Overview

CanX-4/5 will be identical nanosatellites in order to keep the cost of the mission low and to make the formation flying experiments symmetrical. Much of the CanX-4/5 bus technology will be flight-proven as a result of the CanX-2 mission.

Notable differences between the CanX-2 and the CanX-4/5 bus include the structure. With respect to a thermal control and power generation standpoint, the form factor for CanX-4/5 will be cubic, measuring approximately 17 x 17 x 25 cm [4].

Another notable difference between CanX-2 and CanX-4/5 is the attitude determination and control system. While CanX-4/5 will fly the much of same ADCS components which will be flight proven on CanX-2, the system will be geared towards higher accuracies. This will result in orthogonally mounting three nano-reaction wheels to achieve a three-axis control and stabilized zero momentum system as opposed to a pitch-axes momentum-bias configuration of CanX-2.

Lessons learned from the CanX-2 flight or requirements for higher performance will result in other minor modifications throughout the spacecraft. NANOPS is an example of a system which will be modified for performance motives. For CanX-4/5 heaters may be applied to the nozzle in order to increase specific impulse and a greater amount of fuel will be flown to increase the delta-V.

5.2 Formation Flight Inspection and Control Algorithms

Orbital propagation and control algorithms are required prior to flying CanX-4/5 in formation. The starting point for formation flight algorithms are the Hill equations whose solutions describe suitable trajectories for the lead (chief) and following (deputy) satellites.

The Hill equations provide solutions for circular orbits where there are no perturbative forces. For the high accuracies required, predicting the effect of disturbance forces are necessary. The main perturbation not accounted for is the J2 effect attributed 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 breakup in formation. This differential J2 perturbation is the difference of two small effects, thus the Hill equations must be modified to include second order terms resulting in a non-linear replacement of the Hill equations.

Aside from analytically solving for perturbative dynamics, the modified Hill equations must also incorporate active feedback control to correct for 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.

Dr. Chris Damaren, from UTIAS, is currently developing these modified Hill equations which take into account for differential effects of J2. The CanX-4/5 formation flight algorithms will stem from these orbital dynamic equations and developed feedback control laws.

5.3 Experiment Plan

In order to verify accuracy in position determination, CanX-4/5 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 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-4/5 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 11, 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-4/5 will also use their imaging systems to create stereo images of the Earth, demonstrating an effective use of formation flying.

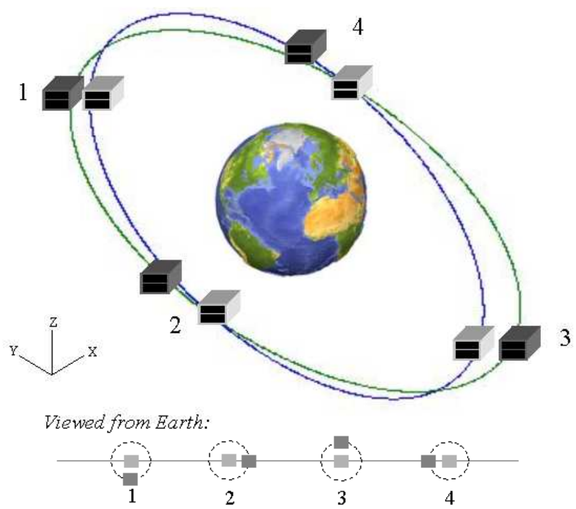

Figure 11 - Halo orbit

6.0 CONCLUSION

The enormous promise of spacecraft formation flight applications has 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 possible. Working on the nanosatellite scale offers many advantages such as low launch and development costs and greater launch flexibility. Many of the technologies developed on this scale, fortunately, are directly applicable to any class of spacecraft.

The first of the series of spacecraft developed by SFL for formation flight objectives is CanX-2. This mission will evaluate core technologies that were identified to be critical for demonstrating formation flight capable of a very ambitious centimeter level relative position determination. Key technologies being investigated include a cold-gas propulsion system, GPS position determination hardware and algorithms, three-axis stabilized attitude determination and control system, a high performance computer and a data rate S-band radio.

CanX-2's secondary objective is to provide low-cost access to space for the scientific and industrial communities. As such, the spacecraft will be carrying a suite of payloads for experiments ranging to probing pollution distribution to evaluating special surface coatings to prevent atomic oxygen degradation.

The design and operations of CanX-4/5 will rely on the lessons and experience of the CanX-2 flight. All together, the CanX-2/4/5 mission will demonstrate highly accurate formation flight and lay the ground work for future formation flight missions of any spacecraft class.

7.0 ACKNOWLEDGMENTS

The authors are indebted to each member of the Space Flight Laboratory student team for their contributions and dedication to the development of CanX-2, and to the staff for their invaluable mentorship. The student engineering team includes Cecilia Mok, Stephen Mauthe, Liam O'Brien, Nathan Orr, Luke Stras and Tarun Tuli. The SFL engineering staff includes Alex Beattie, Daniel G. Foisy, and Sangtak Park.

The authors would also like to acknowledge the principle investigators for the CanX-2 scientific experiments. The science team includes Dr. Brendan Quine (Spectrometer), Dr. Susan Skone (GPS occulation), Dr. Jacob Klieman (Materials) and Dr. Barbeau (Networking protocol). The efforts of Dr. Chris Damaren and Dr. Elizabeth Canon are gratefully acknowledged with respect to the formation flight and GPS position determination algorithms respectively.

The UTIAS Space Flight Laboratory gratefully acknowledges the following sponsors of the CanX program:

Defense Research and Development Canada (Ottawa) - Natural Sciences and Engineering Research Council of Canada (NSERC) -

MacDonald Dettwiler and Associates Space Missions - Dynacon Incorporated - Ontario Centers of Excellence, ETech Division - Canadian Space Agency - Radio Amateur Satellite Corporation (AMSAT)

In addition, the following organizations have made valuable donations to the program: AeroAntenna Technology Inc. – Agilent Technologies – Altera – Alstom – Altium – Analytical Graphics Inc. – Ansoft – ARC International – ATI – Autodesk – @lliance Technologies – Cadence – CMC Electronics – EDS – E. Jordan Brookes – Emcore – Encad – Honeywell – Micrografx – National Instruments – Natural Resources Canada – NovAtel Inc. – Raymond EMC – Rogers Corporation – Stanford University – Texas Instruments – The MathWorks – Wind River.

8.0 REFERENCES

1. Grocott, S. C. O., R. E. Zee, and J. M. Matthews, "The MOST Microsatellite Mission: One Year in Orbit," Proc. 18th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, August 2004
2. Puig-Sauri, J. and R.J. Twiggs. "Cubesat Design Specifications Document: Revision IV." California Polytechnical State University, 2001
3. L. N. Stras, D. D. Kekez, G. J. Wells, T. Jeans, R. E. Zee, F. M. Pranajaya, and D. G. Foisy, "The Design and Operation of The Canadian Advanced Nanospace eXperiment (CanX-1)," Proc. AMSAT-NA 21st Space Symposium, Toronto, Canada, Oct. 2003, pp.150-160.
4. Caillibot E.P.,Grant C.C., Kekez D.D., "Formation Flying Demonstration Missions Enabled by CanX Nanosatellite Technology" Proc. 19th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, August 2005.
5. Martin, M., S. Kilberg, and J. Winter, "TechSat 21 and Revolutionizing Space Missions Using Microsatellites," Proc. 15th AIAA/USU Conference on Small Satellites, Logan, Utah, August 2001
6. Busse, F.D., How, J.P., Sampson, J. "Demonstration of Adaptive Extended Kalman Filter for Low Earth Orbit Formation Flying Using CDGPS" Proceedings of the Institute of Navigation GPS-02 Conference, Portland, OR, September 24-27 2002, pp. 2047-2058.
7. Mauthe, S., F. Pranajaya, and R. E. Zee, "The Design and Test of a Compact Propulsion System for CanX Nanosatellite Formation Flying," Proc. 19th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, August 2005.
8. Quine, B. http://www.yorku.ca/bquine/
9. Skone, S. http://www.eng.ucalgary.ca/resrch_geomatics/Geo_Skone.htm
10. M. E., Z. Li, M. Barbeau, and E. Kranakis, "The eXtended Satellite Transport Protocol: Its Design and Evaluation." Proc. 17th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, August 2003.