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CANADIAN ADVANCED NANOSPACE EXPERIMENT 2 ORBIT OPERATIONS: ONE YEAR OF PUSHING THE NANOSATELLITE PERFORMANCE ENVELOPE

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ABSTRACT

The objective of the Canadian Advanced Nanospace eXperiment (CanX) program is to develop highly capable nanospacecraft, i.e. spacecraft under 10 kilograms, in short timeframes of 2-3 years. CanX missions offer low-cost and rapid access to space for scientists, technology developers and operationally-responsive missions. The Space Flight Laboratory (SFL), at the University of Toronto Institute for Aerospace Studies (UTIAS) has developed the CanX-2 nanosatellite that launched in April 2008. CanX-2, a 3.5-kg, 10 x 10 x 34 cm satellite, features a collection of scientific and engineering payloads that push 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 flight. These technologies include a custom cold-gas propulsion system, a 30 mN·m·s nanosatellite reaction wheel as part of a three-axis stabilized Y thomson-configuration attitude control subsystem, and a commercially available GPS receiver. The secondary objective of CanX-2 is to perform a number of university experiments including an atmospheric spectrometer. After one successful year in orbit, the nanosatellite has met or exceeded all mission objectives and continues to demonstrate the cost-effective capabilities of this class of spacecraft. Key achievements to date include a characterization of the propulsion system, a full demonstration of the attitude determination and control subsystem including capabilities in accurate payload pointing (including nadir-tracking) and orbit-normal alignment, long-duration reaction wheel operation, unprecedented radio performance for an operational nanosatellite, and successful science operations. The mission, the engineering and scientific payloads, and a discussion of notable orbit achievements and experiences of CanX-2 are presented in this paper.

INTRODUCTION

University of Toronto's Space Flight Laboratory initiated a nanospace program, the Canadian Advanced Nanospace eXperiment (CanX) in 2001. Building off of the laboratory's expertise in microsatellite design, the CanX program was created in order to develop highly capable nanospacecraft within a two to three-year period. This short development schedule is driven in order to meet the operationally-responsive needs of our clients and aggressively limit cost.

The CanX program mandate is two-fold. First, it offers low-cost, quick-to-launch satellite platforms upon which to execute a wide-spectrum of missions, ranging from scientific experimentation to technology demonstration for commercial exploitation. The successful CanX-2 nanosatellite, and SFL's flight-ready next-generation Generic Nanosatellite Bus (GNB) are industry-leading examples of what spacecraft of this size and budget are capable of accomplishing.

SFL's second mandate is to provide Canada with a continuous supply of highly-skilled and experienced space-system engineers. In the CanX program, graduate students receive hands-on training and mentoring from SFL's experienced staff. Canada's first space telescope, the MOST (Micro-variability and Oscillation of Stars) microsatellite was designed, integrated and tested at SFL [1]. With this expertise in hand, SFL graduate students can tap into a diverse wealth of knowledge during the design, test and operation of SFL spacecraft. Graduate students work to implement aggressive and ambitious missions that push the envelope of achievable performance with commercial technologies. With a focus on aggressive experimentation, CanX missions offer low cost and rapid access to space for scientists and commercial exploitation.

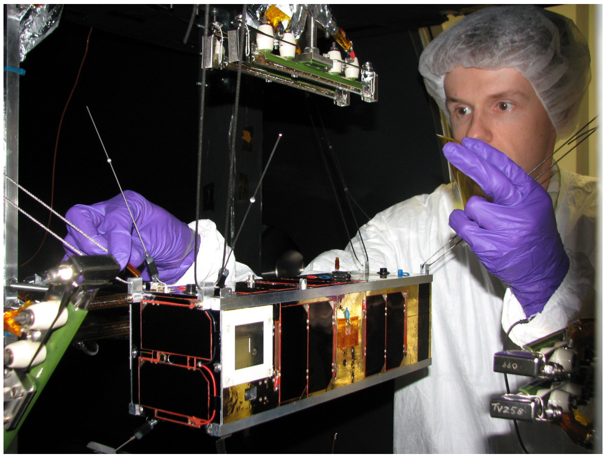

Figure 1: CanX-2 being setup for a thermal vacuum test.

CANX-2 MISSION

CanX-2, the second satellite built under the CanX spacecraft program is 10 x 10 x 34 cm in dimension and 3.5 kg in mass. This nanosatellite packs enough engineering and scientific experiments to push the envelope of what has been previously attempted on this scale of spacecraft.

Figure 2: CanX-2 mission patch

The mission objective for this spacecraft is two-fold. The principle objective is to demonstrate technologies identified to be critical for the upcoming CanX-4/-5 formation-flying mission [2]. The CanX-2 and CanX-4/-5 missions are designed to develop and demonstrate capabilities for formation fight and inspection in space on a small platform, laying the ground work for subsequent formation flying missions such as sparse aperture remote sensing and on-orbit servicing. 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 centimetre-accurate GPS determination of relative satellite positions, a nano-propulsion system based on commercial off-the-shelf components, a three-axis degree-accurate attitude determination subsystem, a miniature reaction wheel, 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. Scientific experiments flying on CanX-2 include a miniature atmospheric spectrometer used to detect greenhouse gases, a GPS atmospheric occultation experiment used to determine vertical profiles of electron and water vapour content of Earth's atmosphere, and a surface material experiment that will measure the effects of atomic oxygen on advanced materials.

FORMATION FLIGHT TECHNOLOGY DEMONSTRATION

Several formation flying enabling technologies, critical for SFL's upcoming CanX-4/-5 mission, will be demonstrated on CanX-2 and are described below.

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 mission 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 capability to measure positional accuracies on the centimeter-level has been shown [3].

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 is being used to assess the GPS hardware and data quality. Secondly, once evaluated, the data will be processed using standard single-point GPS techniques.

Nano-Propulsion System (NANOPS)

Formation-flight applications require a propulsion system for several reasons, such as maintaining relative separation distances by controlling secular disturbances caused by perturbing forces, or to have the capacity to reconfigure the controlled orbit configuration as different formations offer particular advantages. To this end, a small experimental liquid-fueled cold-gas propulsion system, the Nano Propulsion System (NANOPS), has been developed and is flying on CanX-

2 [4]. The CanX-2 propulsion system is shown in Figure 3. A slightly larger variant will be subsequently flown on the CanX-4/-5 mission. The CanX-2 system uses sulfur hexafluoride (SF_6) as propellant, with a total delta-V of 2m/s. The nozzle is oriented such that thrusting induces a major-axis spin. Through a series of experiments, performance characteristics of NANOPS are being calculated from spacecraft angular rate measurements, as well as pressure and temperature telemetry readings.

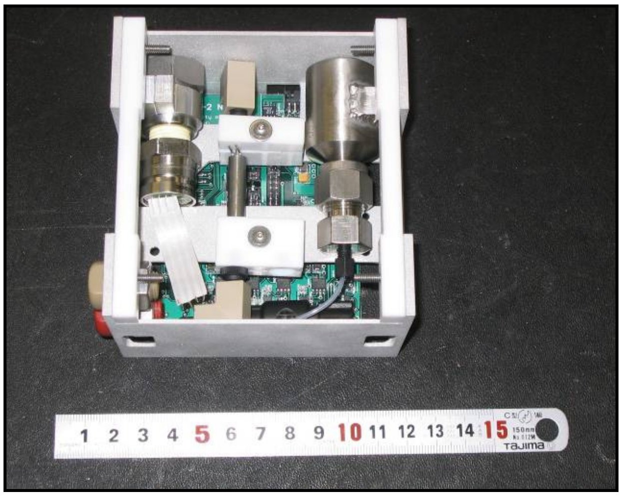

Figure 3: NANOPS system

Attitude Subsystem

To attain degree-level attitude determination and control performance, which is necessary for accurate formation flight, CanX-4/-5 requires a full suite of actuators and sensors. As a demonstrator, the ADCS system flown on CanX-2 (see the CANX-2 BUS section for more information) is comprised of many of the components and software necessary for the CanX-4/-5 mission. Evaluated technology includes a miniature reaction wheel, a magnetometer, high precision sun sensors, magnetorquer coils, and an Extended Kalman Filter for ADCS state estimation. CanX-2 is evaluating the performance of these actuators and sensors in nominal Y-Thomson configuration.

CMOS Imagers

Many applications of formation flight require the use of an imager for visual inspection. To this end, CanX-2 is equipped with both monochrome and colour CMOS imagers that have 1280 x 1024 resolution and a 30 degree field of view. CMOS imagers were chosen over CCD technology because of their power efficiency and performance. The CanX-2 CMOS imagers are used to take pictures of targets of interest such as the Earth, the Moon and star fields.

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 4.

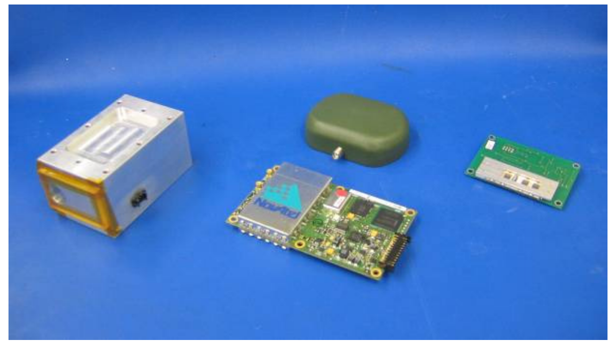

Figure 4: CanX-2 science instruments: Atmospheric spectrometer (left), GPS antenna (center top), GPS receiver (center bottom), Advanced surface material experiment (right)

Atmospheric Spectrometer

The Argus Spectrometer, developed by researchers at York University, aims to acquire a better understanding of greenhouse gases in the atmosphere [5]. Specifically, this 230 g device is analyzing wavelengths in the near infrared spectrum, looking at the radiance response of carbon dioxide, methane, nitrous oxide, oxygen, and water around the 0.9 to 1.7 µm mark.

The spectrometer onboard CanX-2 is a technology demonstration unit. When tracking along nadir, its footprint is one square kilometre, and in each observation it can scan areas up to 2050km^2. Once Argus has fully demonstrated its ability to analyze greenhouse gases, future missions equipped with full three-axis control can be used to support international treaties such as the Kyoto Protocol. The operational concept 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.

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 [6]. To study this phenomenon, CanX-2 carries a dual-band GPS receiver (the same receiver which is used for position-determination testing), complemented with a directional antenna. In the experiment, signals from occulting GPS satellites, which experience a signal delay, will be received by CanX-2's GPS antenna. 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, which impact navigation and communications systems.

Surface Material Experiment

Atomic oxygen in Earth's atmosphere causes severe erosion to satellite materials in low-altitude Earth orbits. A new process has been developed, by the Integrity Testing Laboratory, of Toronto, the University of Toronto, and University of Southampton, to treat such materials, improving their resistance to the harsh environment of space [7]. CanX-2 includes a materials degradation experiment to test this treatment.

Four identical carbon-film coated aluminum samples, whose behavior in space is well known, are onboard the satellite (with one covered as a control). The electrical resistance of each sample is being measured over time, which will give an indication of how the samples' volumes change, and so quantifying the effectiveness of the treatment process.

CANX-2 BUS

CanX-2 is a rectangular prism measuring 10 x 10 x 34 cm with a mass of 3.5-kg. Since the satellite carries many instruments and experiments, an aluminum 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.

The thermal design of CanX-2 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 was designed to be effective over a wide range of orbits.

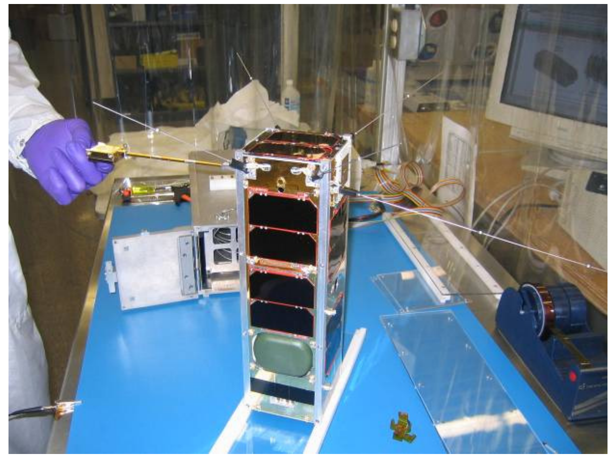

Figure 5: Integrated CanX-2 spacecraft

CanX-2 relies on twenty solar cells spread over its surfaces to generate power. In eclipse, power is drawn from a rechargeable 4.8 Ah lithium-ion battery. Direct energy transfer is used to enable the 2 to 7 W of generated electrical energy for use by the various subsystems. Power is disseminated via an unregulated power bus, which nominally operates at 4.0 V.

Attitude determination and control of the satellite centres on a conceptually simple system. Determination, with an accuracy of about ±1.5º, is achieved using a set of six SFL-developed sun sensors, supplemented by an SFL-developed, three-axis, magnetometer, which is deployed approximately 20 cm from the satellite. Orbit-normal alignment, of the satellite's minor axis, is achieved through simultaneous application of wheel bias and rate-damping control. Pitching, around the minor axis, is accurate to about 2º. The reaction wheel, used by CanX-2, was developed in partnership between SFL and Sinclair Interplanetary. It generates a maximum torque of 3 mNm and has maximum momentum storage of 30 mNms. Three hand-wound magnetorquers provide rate-damping control and wheel-momentum management, as necessary. The attitude determination and control suite of components is shown in Figure 6 and Figure 7.

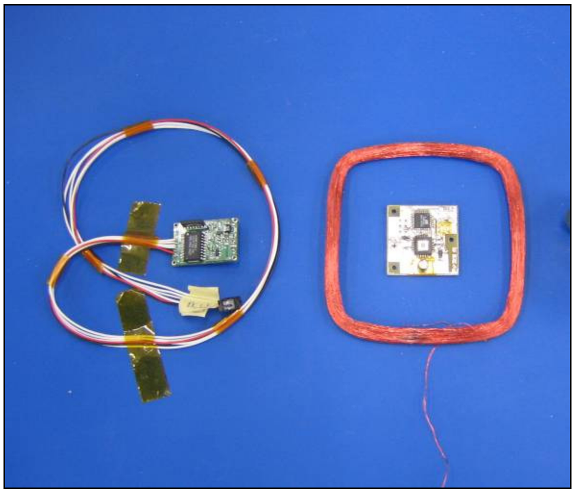

Figure 6: Attitude Components: Magnetometer, Digital Sun Sensor and Torque Coil

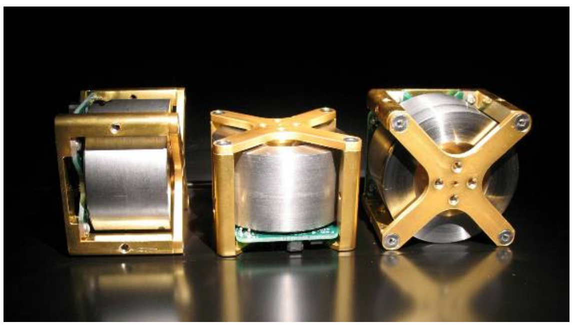

Figure 7: SFL/Sinclair Interplanetary Wheels

CanX-2 is equipped with two 32-bit ARM7-based computers. The Main On-board Computer (OBC) has 6 MB of low-power SRAM, normally configured as a 2 MB region with triple-mode error detection and control (EDAC) for single-event upsets that occur in LEO. 16 MB of serial flash memory is used to store application software and experiment data. Using the on-board peripherals and an off-chip quad-UART, the Main OBC interfaces with all the subsystems on CanX-2. It is responsible for all normal satellite operations, including a) periodic telemetry collection for the whole orbit data log, b) execution of the attitude determination and control algorithms, c) commanding of experiment payloads and d) communication with the ground Although the processor can run at up to 40 MHz, it can accomplish all its tasks at a nominal clock speed of 11.6 MHz and minimize its power consumption. The Payload OBC employs a different design to the Main OBC and is being flown to obtain heritage with a different set of components. It can also be used to record and store data from GPS experiments.

The OBCs run the Canadian Advanced Nanospace Operating Environment (CANOE), an in-house designed, multi-threaded operating system with a pre-emptive scheduler. The software is prepositioned in Flash and loaded on command from the ground. It allows all tasks to be handled while ensuring that the attitude control algorithm is executed once per second. Moreover, 58 telemetry points are gathered, keeping track of CanX-2's status with fine detail. One of these computers is shown in Figure 8.

CanX-2 employs a full-duplex dual-band communication system using SFL-designed radio systems. Uplink takes place in the UHF band with a 4 kbps GMSK receiver connected to a circularly polarized quad-canted monopole antenna system. The primary downlink is in the space-research science S-Band using a variable data rate transmitter capable of rates between 8 and 1024 kbps, with BPSK or QPSK modulation, as set by the Main OBC. A 4 kbps UHF transmitter is also present for back-up purposes.

An isometric view of the CanX-2 solid model is shown in Figure 10, illustrating the location of externally mounted and exposed components.

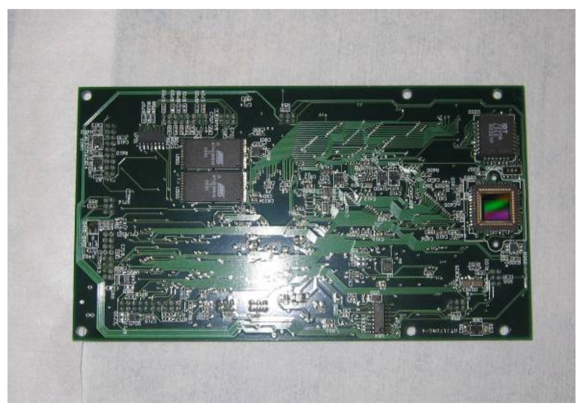

Figure 8: CanX-2 on-board computer

Figure 9: CanX-2 UHF Transceiver

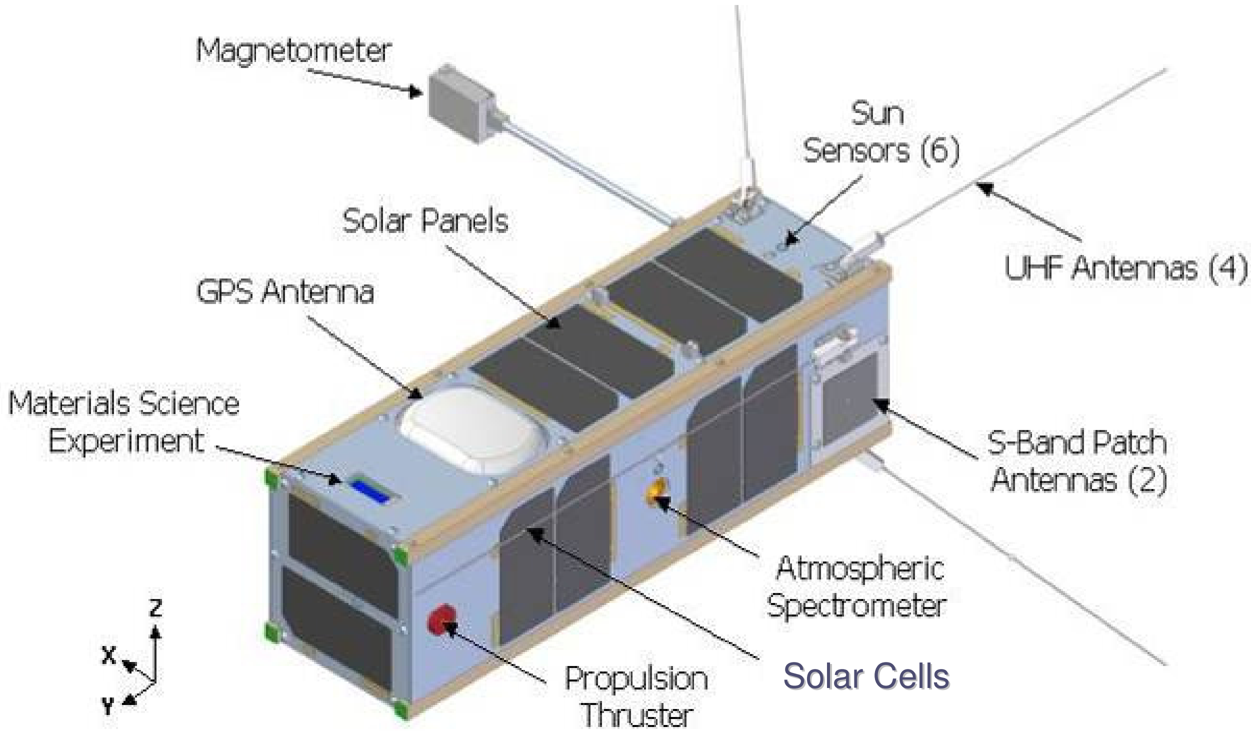

Figure 10: CanX-2 bus overview

CANX-2 LAUNCH

The CanX-2 nanosatellite was launched into a 635km sun synchronous orbit with a 9:30 am descending node on April 28, 2008 at 03:53 UTC aboard the Antrix/ISRO PSLV-C9 from the Satish Dhawan Space Center in Sriharikota, India. This launch made headlines around the world as it set a new record as ten satellites were successfully launched using a single rocket.

CanX-2 was part of the SFL-arranged 'Nanosatellite Launch Service-4' (NLS-4), which included six of the ten satellites. The other spacecraft flown on NLS-4 include Cute-1.7+APD II, from the Tokyo Institute of Technology, Japan, SEEDS, from Nihon University, Japan, Delfi-C3, from Delft University, Netherlands, AAUSAT-II, from Aalborg University, Denmark and COMPASS-1, from Aachen University of Applied Science, Germany.

SFL provides launch services for nanosatellite developers around the world under the NLS banner. The NLS services include the arrangement of launches and providing deployment systems which eject nanosatellites from the launch vehicle. These 'XPOD' deployment systems have significant space heritage and have been successfully used to deploying several spacecraft [8].

Figure 11: CanX-2 & NTS integrated along with the rest of NLS-4 & NLS-5 to the upper stage.

NLS-5 was also launched on the same PSLV flight. NLS-5 consisted of SFL's NTS satellite (also known as CanX-6), which flew a payload provided by COM DEV International Ltd. The payload onboard the 6.5-kg nanosatellite was designed to demonstrate key elements of COM DEV's space-based AIS-detection technology. NTS was conceived in October 2007 and was designed, integrated, tested and launched within seven months.

Figure 12: Antrix/ISRO PSLV-C9 launched at 03:53 UTC April 28th 2008 carrying CanX-2

CANX-2 EARLY OPERATIONS

In the first orbit, the cluster of spacecraft passed over the west coast of North America. During this first transit over California, NLS-4 and NLS-5 teams first became aware that beacon-equipped spacecraft had successfully deployed from their XPODs as local amateur radio operators heard Morse-Code broadcasts from the cluster. These independent amateur radio operators were also able to provide preliminary health verifications of some spacecraft.

Not having beacons, confirmation that the CanX-2 and NTS XPOD deployment systems had ejected the stowed spacecraft was provided by the launch vehicle during the time-span between launch and the first pass over Toronto. First acquisition of a signal from CanX-2 occurred at 13:30:37 UTC on April 28, 2008, from the SFL ground station on its first pass over Toronto, nearly ten hours following launch. The first acquisition of telemetry from CanX-2 and NTS occurred on the second pass over Toronto at 15:06:13 UTC and 15:13:18 UTC, respectively, on the same day. Telemetry indicated that both spacecraft were perfectly healthy following launch and ejection from the XPOD.

With successful acquisition of healthy telemetry from CanX-2 and confirmation that core subsystems (power, communications, deployables, thermal and computer) were functioning correctly, commissioning of the spacecraft began. The CanX-2 commissioning procedure involves incrementally building on the spacecraft functionality by activating hardware one unit at a time, while enabling progressively more capable software modes to interface with that hardware.

Within the first week of operations, the computer subsystem had been fully commissioned and was running its full suite of software. In addition, within four days of launch, CanX-2 began collecting science data as the first science payload was activated (the AO-resistant materials experiment). By the end of the second week all ADCS hardware had been commissioned allowing the initiation of CanX-2's primary experiment, the nano-propulsion system (NANOPS). By the end of June 2008 (as opportunities arose while NANOPS testing was still underway) all remaining units on the spacecraft were commissioned, including the GPS receiver/antenna and the spectrometer payload.

Once the first round of NANOPS testing was complete, the operations focus shifted to demonstrating the performance and functionality of the attitude determination and control system. Attitude demonstration operations in the third quarter of 2008 involved achievement of orbit-normal attitude alignment using a Y-Thomson configuration and accurately pointing mission payloads about the spacecraft wheel-(minor)-axis. After some initial difficulties (including having to compensate for spacecraft dipole, adjusting onboard algorithms and updating operations procedures), proper orbit-normal alignment was achieved by the end of October 2008. Further detail on the performance of all subsystems and payloads can be found in later sections of this paper.

During the course of commissioning, several interesting observations were made and numerous lessons were learned about operating a high-performance nanosatellite in low Earth orbit. One of the more interesting observations is described below.

RSSI and Spacecraft Identification

One very interesting observation associated with the cluster launch of CanX-2 (and likely to be present in other cluster launches) was the effect that spacecraft in close proximity can have on each other, particularly when broadcasting beacons.

One of the telemetry points collected onboard both CanX-2 and NTS is a parameter called the UHF Received Signal Strength Indicator (RSSI). The RSSI provides a direct measure of the amount of RF energy received by the UHF radio while in orbit. In the first few days of commissioning, it was observed that the radio onboard CanX-2 was picking up much more ambient noise than the almost identical radio on NTS.

Further observations over the next several days showed that, although the CanX-2 RSSI was noisier than the NTS RSSI, the noise was decreasing steadily over time (see Figure 11). The data also showed that during a period of approximately 20 hours, starting on April 29th, the CanX-2 RSSI had become much quieter. This period of relative calm ended on April 30, 2008, at approximately 1200 UTC, when the cluster of spacecraft was over Japan.

It was therefore suspected that the UHF beacon from one of the other satellites (and most likely one of the Japanese satellites – SEEDS or Cute 1.7 + APD II) was causing the noise. The noise in the UHF receiver was likely going down because the spacecraft in the cluster were slowly separating from each other. Confirmation of this theory came on May 7 (Launch + 9 Days), when NORAD announced that it had detected an 11th object associated with the PSLV-C9 launch. When first identified, the 11th object (catalog number 32797) was only two seconds (14km) behind object 32785. At the time, object 32785 was being tracked successfully by both the CanX-2 and Cute-1.7+APD II teams. Further, the Cute 1.7 UHF CW beacon is less than 100 KHz away from the CanX-2 uplink frequency.

Therefore, it is very likely that the noise observed on the CanX-2 radio was caused by the extreme proximity of the two satellites. Fortunately, the uplink margins in the CanX-2 UHF design were sufficient to overcome the added noise input.

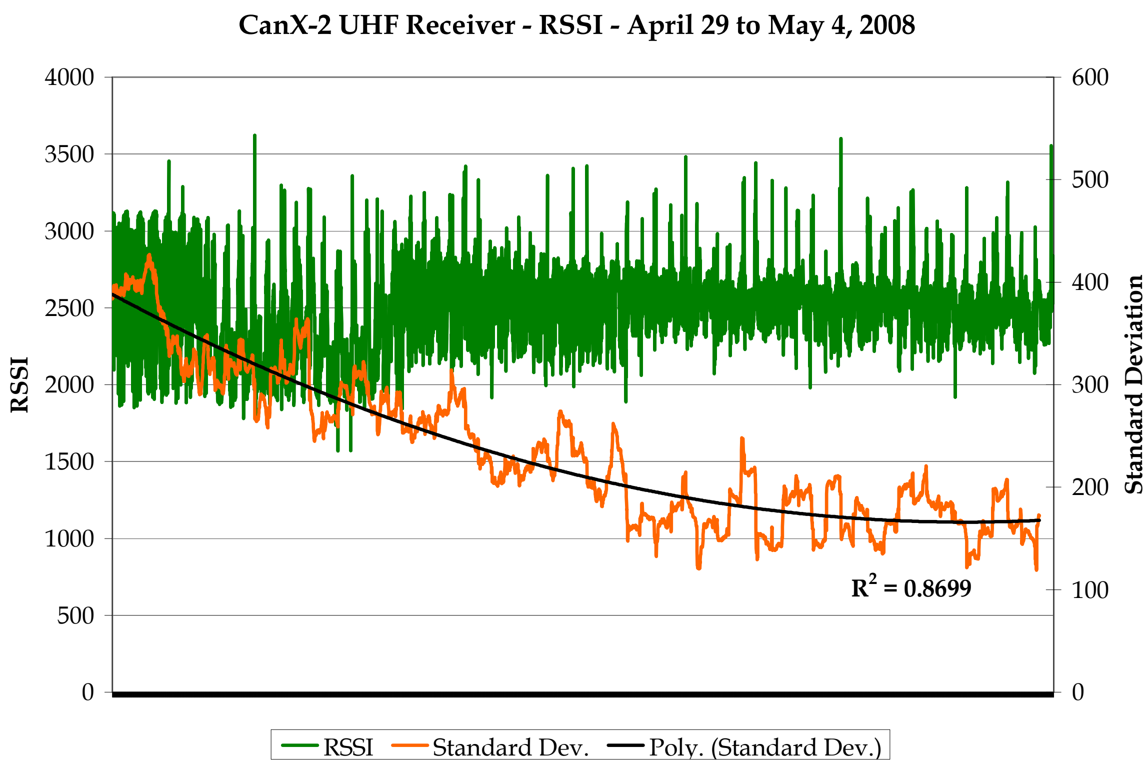

Figure 13: UHF Receiver RSSI during April 29th to May 4th. The standard deviation of the RSSI decreases with time, potentially due to spacecraft separation.

CANX-2 BUS ORBITAL PERFORMANCE

Over the last year, the CanX-2 bus has proven to be a solid platform in conducting the engineering and science mission objectives. Problems encountered (typically software or procedural) during the commissioning phase were ironed out. Upon successful completion of spacecraft commissioning, the ground-support team had been making steady progress towards meeting the spacecraft mission goals.

General Telemetry

Extremely low cost spacecraft are often designed with a requirement that the bus support the mission and payloads irrespective of the orbit's ascending node, inclination, altitude, and where possible, attitude. Designing in this way opens up as many shared-launch options as possible (launch price can be minimized as launch options increase) and simplifies the design. CanX-2 is no different; all subsystems were designed to operate in any attitude and over wide range of orbital elements. In that respect, in any attitude and spin rate, CanX-2 remains power positive, the battery depth of discharge remains low (battery voltage remains high), and temperatures are predominantly very benign.

During science operations, in which the spacecraft spends considerable time, the spacecraft's Y-axis (minor axis) is aligned with the orbit normal and can pitch about the Y-axis to point its instruments to targets of interest. In this standard orbital attitude, over the span of a day, the spacecraft's time-average power consumption is ~1.25W, where the time-average power generation is on the order of 5W, leaving the spacecraft highly power positive. As designed, the spacecraft battery voltage cycles between 3.9V and 4.1V (charge and discharge triggers respectively), with the only deviation occurring when high-power consumers (i.e. the 5W S-band transmitter) are activated in eclipse. In these instances the battery voltage is still well above the battery's load-shed limit. Over the span of a year, in this nominal attitude configuration, the spacecraft's structural panel temperatures (extreme temperatures are usually observed on the panels, aside from those experienced at local hot-spots due to high-power consumers such as the S-band Tx) range between 6°C and 45°C, and the battery temperature ranges between 19°C and 30°C, with a typical sunlight-to-eclipse change of 6°C. Typical CanX-2 power (generated vs. consumed), battery voltage, and temperature telemetry are shown in Figure 14, Figure 15 and Figure 16.

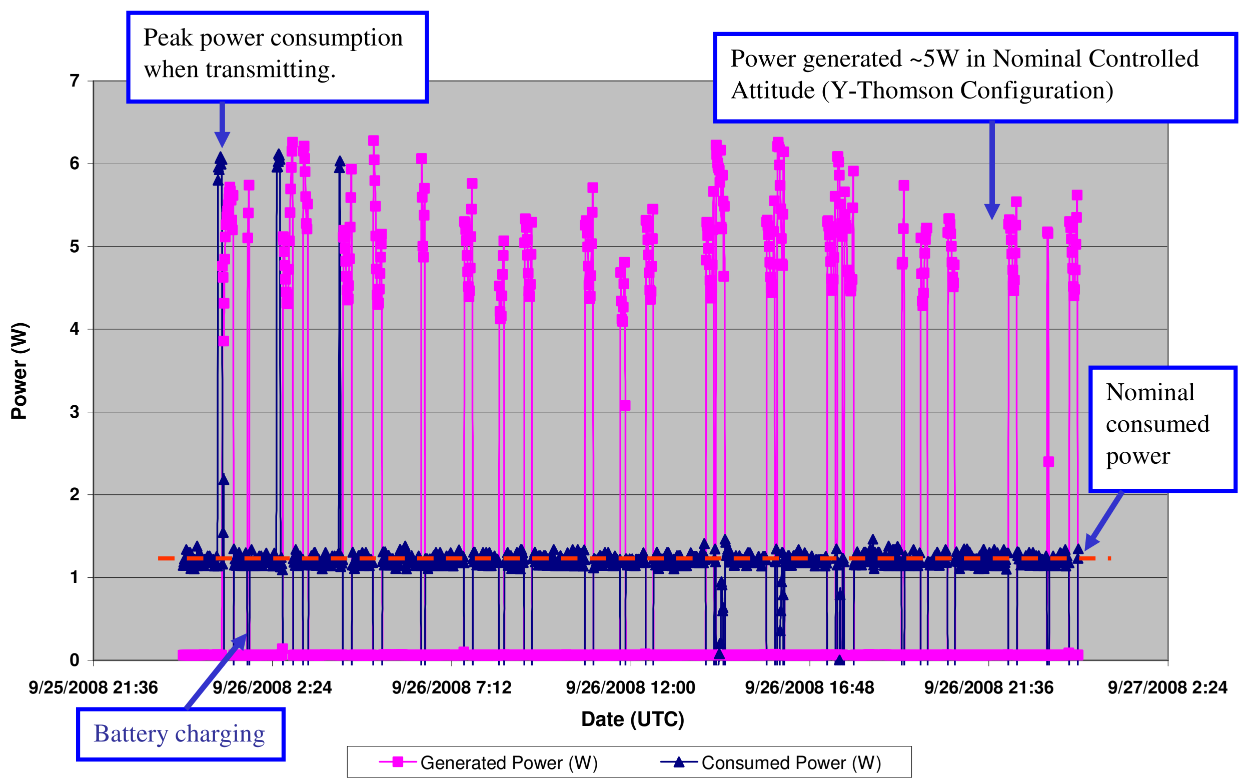

Figure 14: Power generated versus consumed on September 26th 2008, while CanX-2 was in its nominal Y-Thomson configuration attitude (Y-axis aligned with orbit normal)

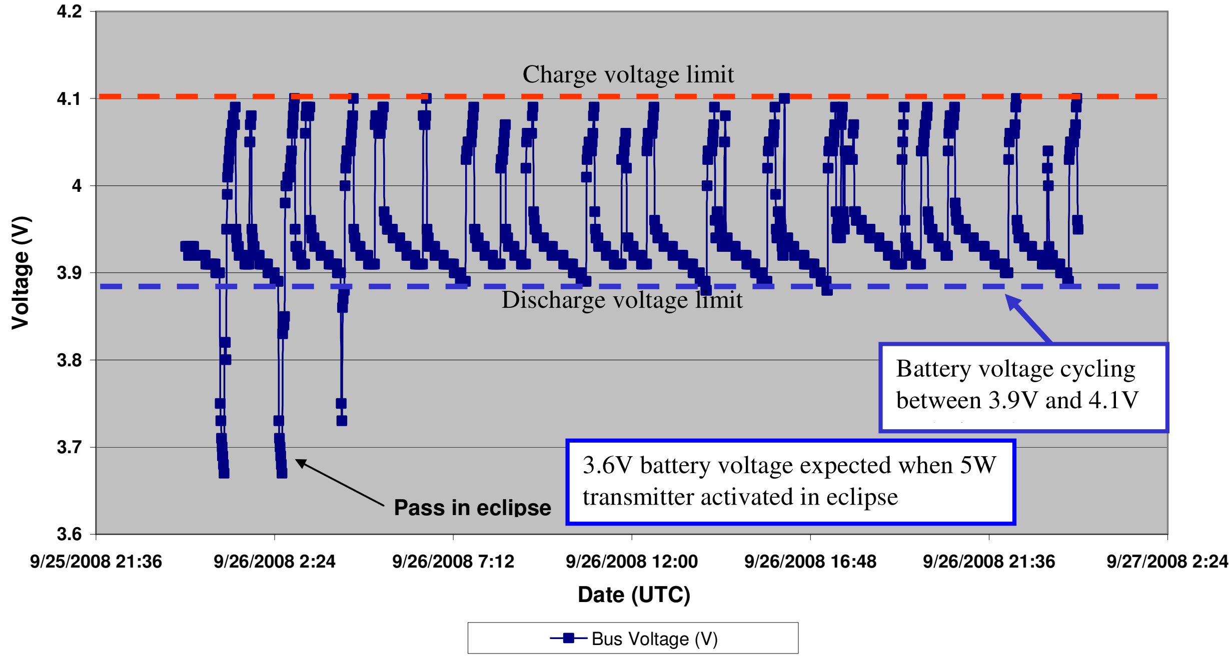

Figure 15: Battery voltage on September 26th 2008, while CanX-2 was in its nominal Y-Thomson configuration attitude (Y-axis aligned with orbit normal)

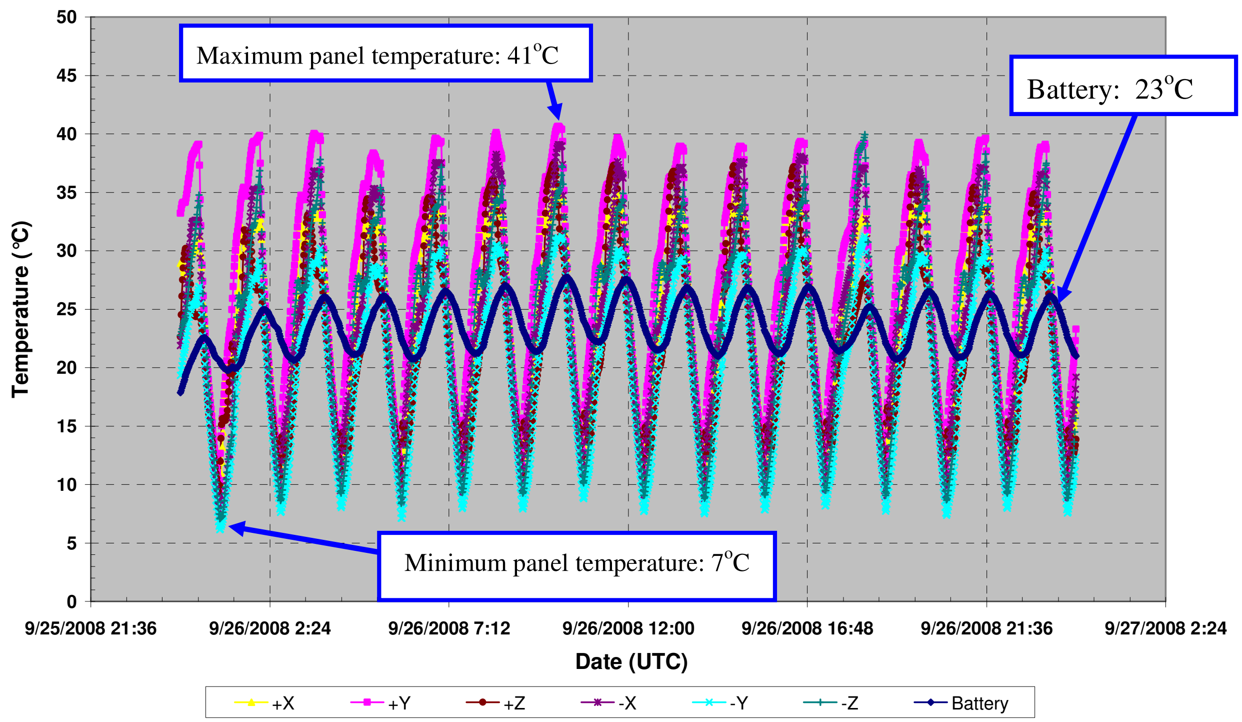

Figure 16: Structural panel and battery temperatures on September 26th 2008, while CanX-2 was in its nominal Y-Thomson configuration attitude (Y-axis aligned with orbit normal

UHF Uplink and S-band Downlink Radios

The UHF and S-band communication system on the spacecraft have been operating well. The radios have been tested through a wide range of functionality, with S-band communication data rates ranging from 32kbps and 256kbps (a data rate of 1000 kbps is possible with this transmitter design) under both BPSK and QPSK modulation schemes. Note, that a downlink rate of 256kbps is a new record for this class of spacecraft. As of June 2009, over 370MB of science data and engineering telemetry have been downloaded to date. The UHF transmitter, designated as the backup downlink radio, has not been required to date.

On-Board Computers and System Software

Upon ejection from the XPOD, CanX-2 powered up and booted up into the Bootloader-1 (BL1) software state. The BL1 software is stored on a pre-programmed EPROM and is the lowest-level software state. BL1 is also the default start-up software mode following a spacecraft power-cycle. BL1 has no automation and offers only basic functionality, such as polling real-time telemetry and powering-up most spacecraft systems and components.

Within the first few days, the spacecraft was booted into Bootloader 2 (BL2), which was stored in the spacecraft FLASH memory. BL2 builds on the functionality of BL1 and includes the ability to store spacecraft telemetry once per minute for over to 24-hrs so that the engineering team can review the spacecraft health state across several orbits.

The SFL-developed operating system, CANOE (also stored in on-board FLASH memory) was loaded upon completion of the commissioning activities in BL2. CANOE is a multithreaded operating system and is the highest-level software state on CanX-2. This operating system allows multi-tasking of operations and full spacecraft-functionality. One of the primary tasks of CANOE is running the On-orbit Attitude System Software (OASYS). OASYS is responsible for calculating the attitude state vector based on attitude sensor inputs and commanding actuators to attain a desired attitude state.

The operating system performance on orbit has been good. Four code updates have been made to date, one to increase downlink efficiency and the others to improve payload configuration capability, performance, and data collection frequency. Operating system stability has been good; software crashes have been primarily due to radiation events and operator errors. The time spent, for recovery to nominal operations following a operating system software crash, is extremely quick, requiring only 1-2 ground contacts.

Attitude Determination and Control

After a year on orbit, the performance of the attitude software (OASYS, which includes the Extended Kalman Filter) has been solid. Three flight upgrades have been made, all during the first few months into the mission. The first upgrade modified the way the operating system (CANOE) turns the torquers off while reading from the magnetometer. The second upgrade added some logic to the processing algorithms of the fine sun sensors to improve performance. The third upgrade added the ability to use the torquers to apply counter dipoles, in an attempt to combat a parasitic dipole. A fourth upload is pending, which will add more sun sensor logic, specifically enabling more than one digital sensor to be read per one second processing cycle, which will improve the EKF's performance in certain cases

It is currently estimated that the attitude determination solution is good to around 1.5 degrees in sunlight; performance in eclipse is not within the mission scope. This performance estimate is derived through comparison of flight telemetry to modeled performance. The satellite's imager may be used in the future for further research into attitude determination and control performance. It also appears that the EKF is able to correctly estimate rates up to about 145 deg/s and attitude at rates up to about 90 deg/s, beyond which the solution aliases.

Over the first year of the mission, rate damping (B-dot) control has been a handy tool, used successfully to de-tumble the satellite from high spin rates. In a number of situations, either the propulsion system or procedural anomalies have led to rates that were high enough such that application of normal rate damping would lead to spin up instead of spin down. Recovering from rates beyond the first boundary (where the B-dot controller has several boundaries, which are a function of the time between attitude sensor polling and actuator firing, beyond which gain polarity must be reversed to prevent a spin-up) has been possible by either two methods. The primary high-rate damping method involves reversing the B-dot control gain and bypassing the EKF (temporarily) to reduce the time between magnetometer reading and torquer actuation (thus increasing the boundary rate). As an alternative, high-rates have been damped by using the wheel to initially soak up the high rates and applying rate-damping control while slowly despining the wheel. Successful recovery has been made from rates of about 190 deg/s.

The wheel, being flight tested for the first time, is currently having over a year of problem-free performance on CanX-2. During commissioning, it was checked out by spinning at various speeds and watching the reaction in the body. Its on-going performance during orbit-normal alignment and pitching operations reveals solid performance that has yet to show signs of degradation. A key metric of interest is the torque ripple, which, by design, is supposed to be 1 μNm over a 1 s attitude-control frame. CanX-2 may not be able to affirm this, unless the imager can be used to provide a star-tracker-like solution, but telemetry to date appears to indicate that ripple is of the required order of magnitude. The one issue that did arise was the previously unknown presence of a parasitic dipole on the wheel, which shouldn't have been present in the design and which was, unfortunately, missed during testing due to a late change in the wheel supplier. Its magnitude is on the order of the disturbing environment, but is able to be countermanded by using the torquers to apply an opposite dipole.

Orbit-normal alignment is the nominal mode for CanX-2. The approach uses bias in the wheel combined with B-dot control to ensure that the wheel's axis aligns with the orbit normal, which represents a minimum energy solution. In CanX-2's sun-synchronous orbit, this vector is ever-changing in the inertial frame of reference and so some lag and nutation is present in the alignment tolerance. To date, CanX-2 routinely achieves alignment to 5 deg, plus or minus another 5 degrees, which is typical for this method.

Payload operations make use of the satellite's pitch controller, where the wheel (nominally in momentum mode, during orbit-normal alignment) changes to reaction mode to slew CanX-2 around its minor axis (ostensibly aligned with the orbit normal). The torquers are, here, used to trim momentum in the wheel. To date, payload pointing performance appears to be good to about 2 degrees.

By and large, the attitude subsystem is performing as expected in all modes, with excellent results during payload operations. The one ongoing issue that remains relates to the use of coarse sun sensors to select one fine (digital) sun sensor to measure the local sun vector. The non-ideal performance of the coarse sun sensors (due to a higher-then-expected albedo influence, and sensor filter effects) periodically leads to an incorrect selection of a digital sensor, resulting in an instantaneous incorrect attitude estimate. This performance was not testable, fully, on the ground; the a priori alternate was to expand the software to allow more than one fine sun sensor to be read at a time (which wasn't done initially for power and timing purposes, but which, on orbit, looks to be fine). The software to read from multiple sensors is ready, and will be demonstrated following the next code upload.

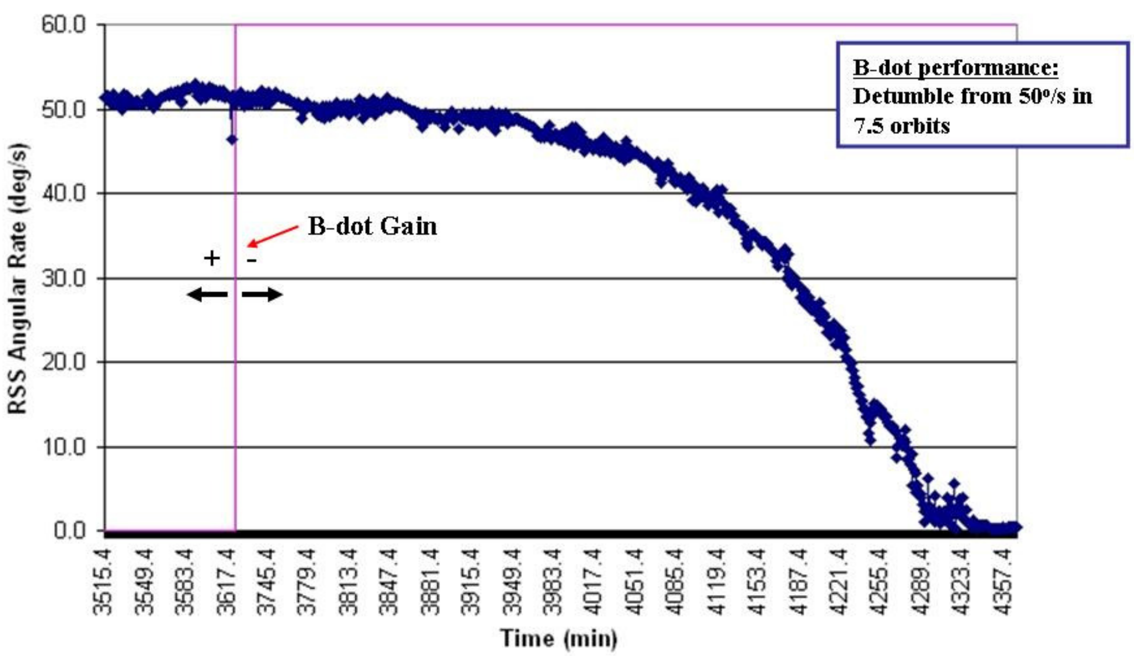

Figure 17: CanX-2 B-dot Rate Controller damping rates from 50°/s

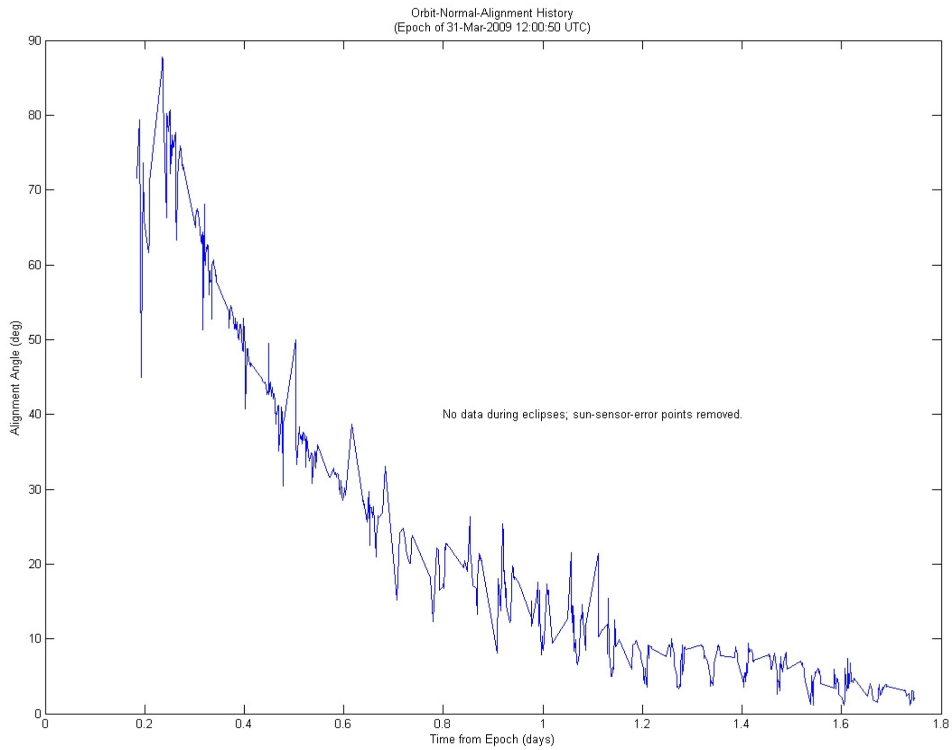

Figure 18: CanX-2 Momentum Align Controller: Alignment angle between spacecraft Y-axis and orbit normal approaching 0°

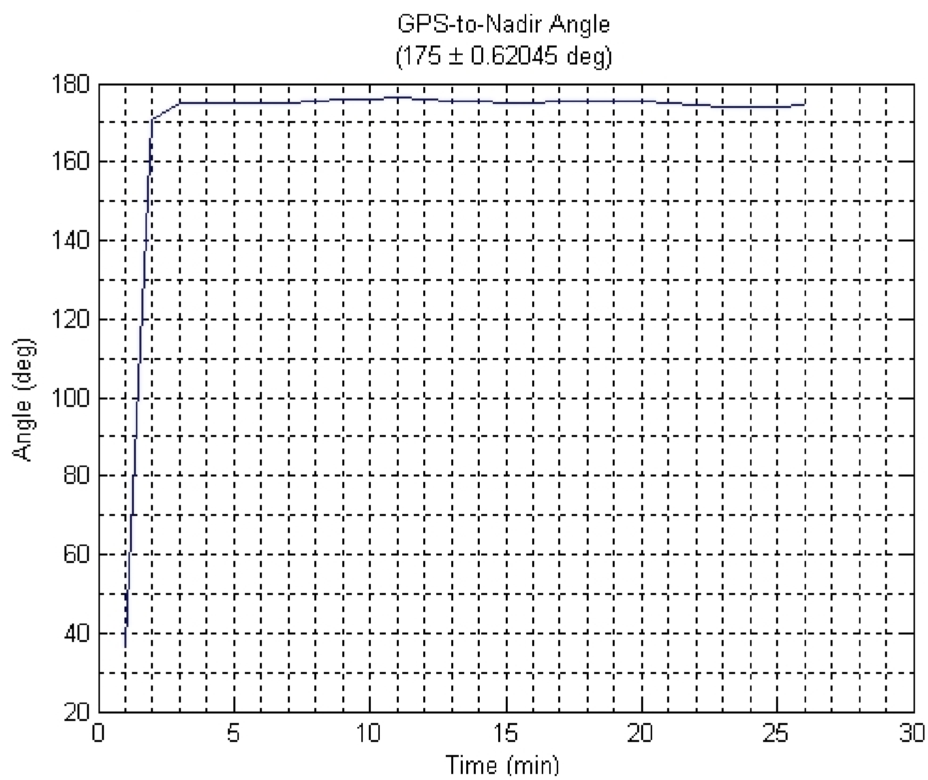

Figure 19: CanX-2 Wheel Pitch Controller: Aligning GPS antenna to zenith

CANX-2 PAYLOAD EXPERIMENTATION SUMMARY

Over its first year in orbit, a significant fraction of CanX-2's time has been spent conducting engineering and science payload experimentation. NANOPS, being the highest priority payload, was characterized through experimentation as early as possible (early-May, mere days after launch). Full-time science (GPS occultation observations and spectrometer observations) observations began in November 2008.

Nano Propulsion System (NANOPS)

After only minimal commissioning (only a subset of the entire attitude subsystem hardware and algorithms were required to perform NANOPS testing), NANOPS experimentation was performed from May to mid-August 2008. During that span, dozens of experiments were carried out to characterize the system performance. Experiments conducted to date were aimed at evaluating fuel leakage and quantifying the minimum-impulse bit of the propulsion system.

At the launch site, NANOPS was filled with sulfur hexafluoride (SF_6) fuel at 20^{o}C, yielding a fill pressure of 522 psi. This pressure is not recorded in the actual fuel tank (referred to as V1). Rather, the pressure is sampled in a secondary volume (V2) which is a volume between the regulator and thrust solenoid valves. This secondary volume is used for short term fuel storage. In order to provide context, the regulator valve is placed in series between the fuel tank (V1) and the secondary volume (V2). The thrust valve is placed in series between V2 and the thrust nozzles. When the regulator valve is actuated, the pressure of V2 equalizes to that of V1. Two and a half days after launch, the propulsion system was briefly powered on and telemetry results were well within the expected ranges (pressure at 461psi at 15.2^{o}C.) Approximately nine days following initial power-up, the regulator valve was actuated in order to begin the leak test check. The pressure in V2 equalized to the pressure of V1 and rose to 513psi at 19.3^{o}C, which indicates that there is little or no leak in the fuel tank and that the NANOPS system had withstood launch loads.

Minimum impulse bit tests are conceptually simple in nature. The aim was to establish the smallest impulse that can be imparted by the propulsion system by progressively shortening the thrust-valve actuation time, taking into account propellant pressure and temperature. During minimum-impulse bit testing, before each test, the NANOPS secondary volume was pressurized to just under the vapour pressure at the polled propellant temperature. Since a minimum-impulse bit thrust imparts an attitude rate that is well below the measurement threshold of the attitude subsystem, dozens of short-duration thrusts were sequentially conducted. Through orbit experimentation, the thrust magnitude was estimated at 35mN (max), and the minimum-impulse bit was observed to range from 0.07 mNs @ 75psi to 0.15mNs @255psi. The theoretical maximum ISP for SF_6 is 50s, and the observed average ISP was 46.7s. Through the course of testing, the NANOPS thrust valve actuation-times were varied from 1 to 500ms.

Further testing is planned shortly in order to conduct longer duration thrust experimentation that will establish impulse and thrust levels at various pressures.

GPS Position Estimation

Since launch, approximately sixty GPS trials have been executed, in order to evaluate GPS Rx data quality, performance in orbit and to evaluate single-point position determination accuracy. Dozens of parameters were varied, the key ones being the GPS antenna attitude, Rx on-time, logging frequency, and supplied initial time and position estimates (to warm-start the GPS Rx).

When experimenting with cold-starts, it was found that GPS antenna attitude held considerable importance in establishing a position-velocity-time (PVT) estimate. Pointing the GPS antenna towards zenith typically returned a position estimate (four or more GPS spacecraft locked), provided that the GPS Rx on-time was greater than 15 minutes. When the GPS antenna attitude was pointed towards the horizon (specifically, anti-velocity), PVT estimates were not obtained within 20 minutes. Position estimates were acquired when pointing in attitudes other than zenith during GPS occultation experiments (see below). This was, however, only possible after warm-starting the receiver.

The accuracy of the position solution has been investigated to a preliminary-extent, by comparing the GPS receiver estimates with NORAD TLEs as shown in Figure 20. In the figure, GPS-estimated longitude and latitude were plotted with the orbital ground track estimated by NORAD TLEs. Analysis to date has indicated that GPS position solutions are at least accurate to within the maximum TLE error of ±20 km. Detailed analysis of the PVT logs will follow in the near future, through an error characterization with respect to accurate orbit propagator models.

GPS Occultation Experimentation

The GPS signal occultation experiment, designed by the University of Calgary, aims to characterize water vapour and electron density concentrations in the troposphere and ionosphere respectively, as this information has widespread weather applications and can be used to improve GPS position estimate accuracy [6]. In order to process a GPS signal occultation event, a minimum of five GPS satellites must be tracked continuously. At least four of the observed GPS spacecraft must be in view above the atmosphere in order to avoid position estimate degradation by atmospheric effects. At least one of the tracked GPS spacecraft must be occulting through the atmosphere. Occulting spacecraft must be positioned near the peak of the antenna's gain pattern, otherwise the weak L2 signal (weakened as it passes through the atmosphere) will only provide intermittent data, or be lost altogether before the GPS spacecraft sets. Last, while obtaining a position estimate, the data acquired by the onboard GPS receiver can be logged a low frequency (0.1Hz), however the logging rate must be stepped higher (20Hz to 50Hz) during the occultation event in order to retrieve a valid atmospheric profile.

Occultation trials on CanX-2 commenced in January 2009, with the first campaign running until March 2009 and the second running from April to June 2009. The focus of these two occultation campaigns were to commission the experiment, and work out issues related to timing, GPS receiver clock drift and attitude pointing (commanding a particular GPS antenna attitude about the spacecraft minor axis in order to optimally point the GPS antenna and maximize the received L2 signal strength). Note most radio occultation missions carry two receivers and antennas, one for position estimation and the second for occultation. CanX-2's mission is particularly challenging as the spacecraft uses one set of GPS hardware to accomplish the experiment.

Steady experimentation headway was made, leading to the first successful occultation observation near the end of the second campaign. An attitude sphere plot, shown in Figure 21 below, plots five observed GPS spacecraft during a successful June 1st 2009 observance. The GPS antenna, in this trial, was pointed half-way between zenith and the anti-velocity orientation. In the plot, down is the negative-velocity direction, left is the orbit-normal, center is zenith, and the outer edge is nadir. The green circle is the earth, the blue oval is the antenna field of view, and the cyan circle is the upper-boundary of the atmosphere. The observed GPS spacecraft are shown in red, and the rapidly changing colour is time spent logging at 50Hz. In the plot, four spacecraft are observed above the atmosphere while one is occulting.

Figure 22 graphs position-difference (radial, in-track, cross-track) between the GPS receiver estimate from the same June 1st trial, relative to the TLE-estimated ground track. Note, the GPS receiver was warm started to achieve a quick position lock when the GPS antenna was pointed in the mentioned attitude.

Further GPS occultation experimentation on CanX-2 is currently underway. Accumulated data is currently being analyzed by the University of Calgary team in order to retrieve atmospheric profiles.

Argus Spectrometer Experimentation

The Argus spectrometer, developed by York University in Toronto, observes in the near-infrared band (900nm to 1700nm) in order to monitor greenhouse gasses such as CO_2 and water vapour. Approximately forty spectrometer observations have been made since launch. Most of these exposures have been observations of opportunity during the attitude experimentation/demonstration period (and hence, nadir-tracking was not yet available), or fine-tuning spectrometer parameters such as exposure time.

With the experiment setup and commissioning completed by end-2008, twelve nadir-tracking observations were scheduled and executed between late-February and early-April, leading to successful collection of valid greenhouse gas spectra at targets of interest all over the world [5]. A sample spectra, acquired over Ontario, Canada by the Argus spectrometer onboard CanX-2 is shown in Figure 23, where the coloured lines represent three different spectra readings during the same observation. Carbon dioxide exhibits a characteristic absorption fingerprint that can be seen in right hand side of the spectra.

Atomic Oxygen-Resistant Coating Experimentation

Very early in the mission (within a week from launch), CanX-2 had started collecting science data from its material science experiment. The experiment collects resistance and temperature data once a day from four aluminum samples, coated with an atomic oxygen-resistant coating developed by the Integrity Testing Laboratory of Toronto, Ontario, and the University of Toronto [7]. Since launch, little change in sample resistance has been observed, meaning minimal degradation of the AO-resistant coating samples to date. Experimentation will to continue for a longer time span before any conclusions are made on the effectiveness of this novel AO-resistant coating.

Figure 20: GPS Position Estimation: GPS estimated positions plotted relative to TLE estimated ground track

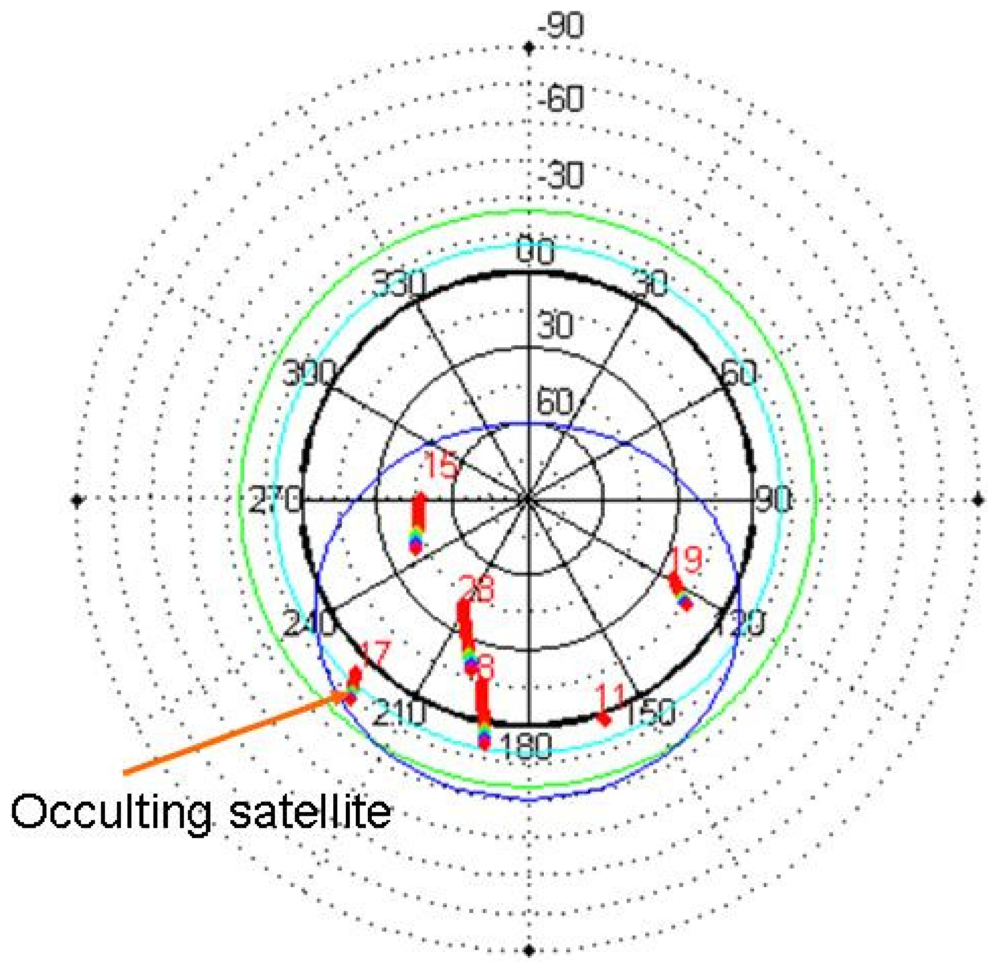

Figure 21: GPS Occultation Experiment: Attitude sphere plotting four GPS spacecraft tracked above the atmosphere, while one GPS spacecraft occults through the atmosphere. Figure provided by University of Calgary GPS occultation team.

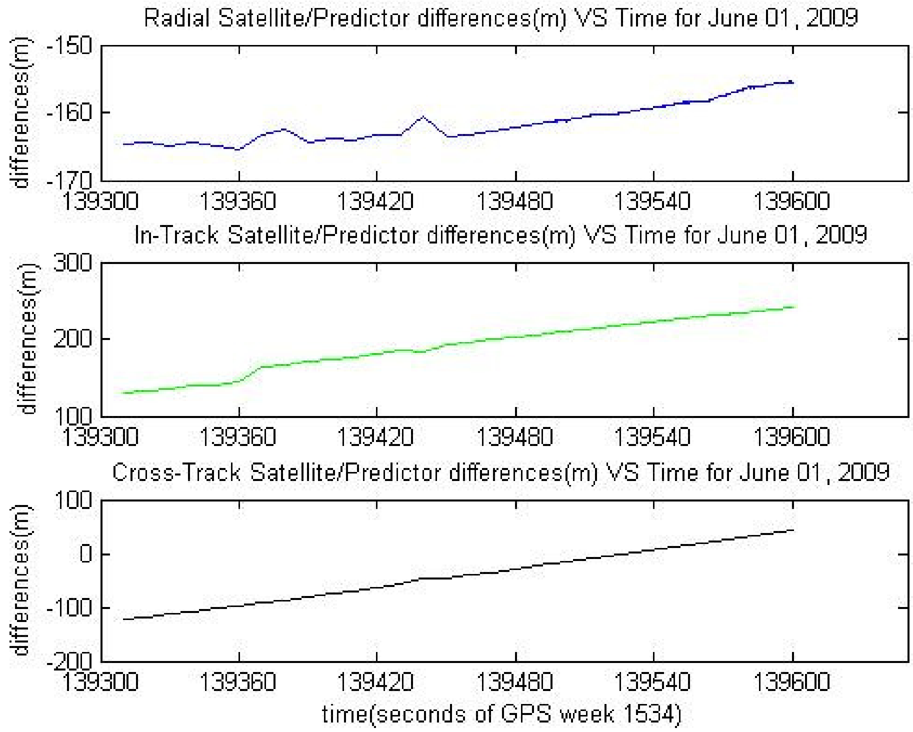

Figure 22: GPS Occultation Experiment: Estimated position differences relative to NORAD estimated TLEs. Figure provided by University of Calgary GPS occultation team.

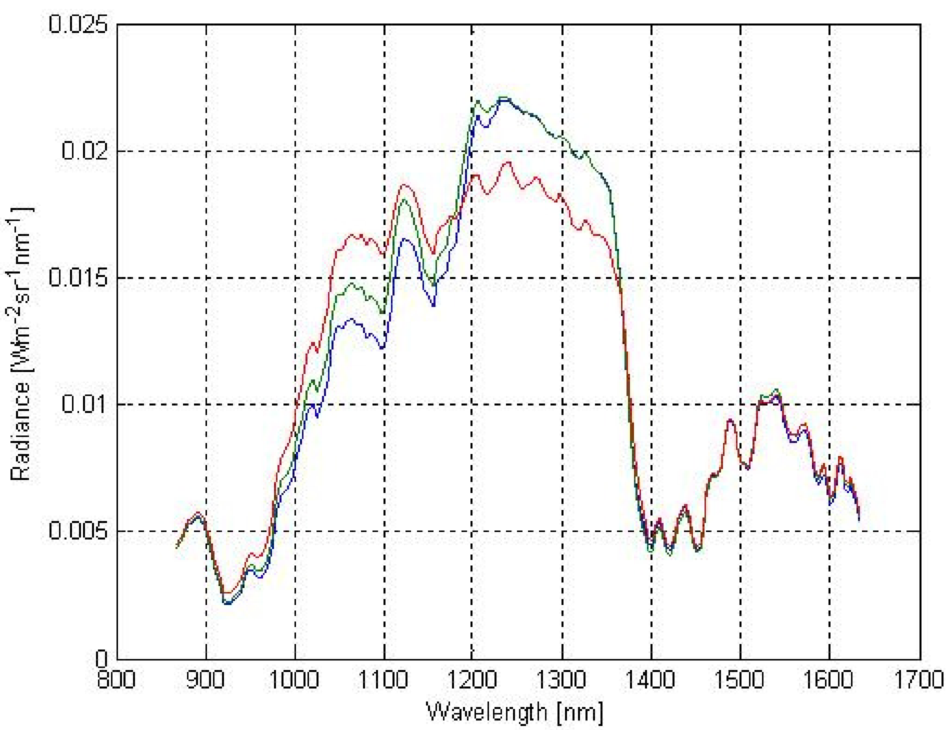

Figure 23: Spectra of greenhouse gasses taken over Ontario, Canada by Argus 1000 spectrometer. Figure provided by York University Argus spectrometer team.

NEAR-FUTURE WORK

Current CanX-2 operation activities are spent alternating between its two primary scientific payloads, conducting GPS occultation experiments, and observing greenhouse gas concentrations around the world with the Argus spectrometer.

Over the coming months, experimentation will shift back towards the engineering payloads, starting with NANOPS long-duration thrust testing, followed by GPS position determination trials. Last, a campaign with the monochrome imager is scheduled in the near future.

CONCLUSION

On April 28th at 03:53 UTC, the CanX-2 nanosatellite was launched into a 635km sun-synchronous orbit with a 9:30 am descending node. CanX-2's first year in orbit has been very successful with the spacecraft performing well.

Many achievements, some nanosatellite records, other SFL firsts, have been accomplished by CanX-2 during its first year in orbit. Notable achievements include:

- Rapid commissioning of the spacecraft hardware and software, allowing mission critical payload operation mere days from launch.
- Characterization of the NANOPS propulsion system on orbit, with experimentation results being similar to model-generated estimates.
- Accurate attitude estimation and pointing demonstrated, including solid performance of all SFL developed attitude sensors and the SFL/Sinclair interplanetary miniature wheel.
- Unprecedented radio performance for an operational nanosatellite, with downloaded data to date quickly approaching the nanosatellite record.
- Successful operation of the power, thermal and structural subsystems. Verification of the accuracy of the power and thermal models.
- Hundreds of scientific experiments executed on orbit, leading to successful spectrometer spectra of greenhouse gas concentrations and valid GPS signal occultation observations.

CanX-2 is a clear-cut example of what a nanosatellite on a limited budget is capable of accomplishing. CanX-2, which is approximately the size of a 2L milk carton, is a highly capable and sophisticated satellite that pushes the envelope of what can be achieved by this class of spacecraft. This satellite is a testament of the fact that critical technology demonstration missions and meaningful science can be accomplished in a small-frame and on a tight-budget.

CanX-2 is a trail-blazing mission for the Space Flight Laboratory. Technologies demonstrated on CanX-2 will be the cornerstones of the subsystems that form future SFL missions using its Generic Nanosatellite Bus (GNB). The GNB, while built upon the heritage and experience of CanX-2, is an even more capable spacecraft bus. Upcoming GNB-based missions include the CanX-4/-5 dual-spacecraft formation flight demonstration, the CanX-3 (aka BRIght Target Explorer or BRITE [9]) astronomy constellation and AISSat-1, a spacecraft that will detect ship-based AIS signals within Norwegian waters [10]. Each of these missions is well into the assembly, integration and test phase with AISSat-1 expected to launch in late 2009 and two BRITE satellites expected to launch in mid-2010.

The SFL-developed GNB and CanX-2 platforms are readily customizable to fit a range of payloads for commercial exploitation and scientific experiments. These platforms offer rapid and extremely low-cost access to space while providing very strong performance, as demonstrated by the successes of CanX-2 in orbit.

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