CANADIAN ADVANCED NANOSPACE EXPERIMENT 2 ORBIT OPERATIONS: TWO YEARS 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 atmospheric spectrometry. After two successful years in orbit, CanX-2 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 orbital achievements and experiences from CanX-2 are presented in this paper.

1. 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 clients and to 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 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.

Second, SFL provides Canada with a continuous supply of highly-skilled and experienced spacesystem 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 scientific and commercial exploitation.



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

2. THE CANX-2 MISSION

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

The mission objective for CanX-2 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 flight 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-based determination of relative satellite positions [3,4], an SFL-designed cold-gas propulsion system called NANO-Propulsion System (NANOPS) based on commercial off-the-shelf (COTS) components [4,5], a three-axis degree-accurate attitude determination subsystem, a miniature reaction wheel, and 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 [4,6], a GPS atmospheric occultation experiment used to determine vertical profiles of electron and water vapour content of Earth's atmosphere [4,7], and a surface material experiment that will measure the effect of an advanced material coating [4,8], designed to resist the erosive effect of atomic oxygen on spacecraft materials.

3. CANX-2 BUS

CanX-2 is a rectangular prism measuring $10 \times 10 \times 34$ 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 treatments. The thermal control strategy was designed to be effective over a wide range of orbits and then customized once the final orbit was known.

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 convey the generated electrical energy (2 to 7 W) to the battery. Power is distributed to the units on the satellite via an unregulated power bus nominally operating at 4.0 V.

Attitude determination and control of the satellite centres on a conceptually simple system. Determination, with an accuracy of about $\pm 1.5^{\circ}$, 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 (Y) axis, is achieved through simultaneous application of wheel bias and rate-damping control. Pitching, around the minor axis, is accurate to about 2°. The reaction wheel (Figure 2), used by CanX-2, was developed in a partnership between SFL and Sinclair Interplanetary. It generates a maximum torque of 3 mN·m and has maximum momentum storage of 30 mN·m·s. Three hand-wound magnetorquers provide rate-damping control and wheel-momentum management, as necessary.



Figure 2: 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. The Main OBC 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 of its tasks at a nominal clock speed of 11.6 MHz thereby reducing 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 pre-positioned in Flash and loaded into RAM 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.

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 3, illustrating the location of externally mounted and exposed components.



Figure 3: CanX-2 bus overview

4. 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 the 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 [9].



Figure 4: 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 [10].

5. CANX-2 EARLY OPERATIONS

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. Telemetry indicated that both spacecraft were perfectly healthy following launch and ejection from the XPOD. With confirmation that core subsystems (power, communications, deployables, thermal and computer) were functioning correctly, commissioning of the spacecraft began. The CanX-2 commissioning procedure involved 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 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.

6. CANX-2 BUS ORBITAL PERFORMANCE

Over the last two years, the CanX-2 bus has proven to be a solid platform for conducting the engineering and science mission objectives and 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 attitude, over the span of a day, the spacecraft's average power consumption is ~1.25W. The average power generation is ~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 two years, in this nominal attitude, 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 5, Figure 6 and Figure 7.



Figure 5: 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 6: Battery voltage 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 March 2010, over 550MB of science data and engineering telemetry have been downloaded. 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 24-hrs so that the engineering team can review the spacecraft state of health 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 and four upgrades 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 an operating system software crash, is extremely quick, requiring only 1-2 ground contacts.

Attitude Determination and Control

After two years in orbit, the performance of the attitude software (OASYS, which includes the Extended Kalman Filter) has been solid. Three upgrades have been made, all during the first few months of 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 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.

Since launch, 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 (B-dot controller boundaries are a function of the time between attitude sensor polling and actuator firing) 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 despinning the wheel. Successful recovery has been made from rates estimated to be as high as 190 deg/s.

The wheel, being flight tested for the first time, currently has almost two years of problem-free performance on CanX-2. During commissioning, the wheel was checked out by spinning at various speeds and watching the reaction in the body. Today, 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 in the wheel is the torque ripple, which, by design, is supposed to be 1 Nm 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 of the expected accuracy 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 8: CanX-2 B-dot Rate Controller damping rates from 50°/s



Figure 9: CanX-2 Momentum Align Controller: Alignment angle between spacecraft Y-axis and orbit normal approaching 0°



Figure 10: CanX-2 Wheel Pitch Controller: Aligning GPS antenna to zenith

7. CANX-2 PAYLOAD EXPERIMENTATION

Since very early in the mission, 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 2008, mere days after launch) and again in Sept/Oct 2009. Full-time science (GPS occultation observations and spectrometer observations) observations began in November 2008 and have continued on an alternating and regular basis since then.

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 (SF₆) fuel at 20°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° 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° C, which indicates that there is little or no leak in the fuel tank and that the NANOPS system had withstood launch loads.

The first set of tests planned for NANOPS was aimed at evaluating the minimum impulse bit of the system. 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 SF₆ 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.

In September of 2009 a second round of NANOPS experimentation was started. At that time NANOPS had been unused for more than a year. This prolonged downtime was intentional and was meant to test the ability to store fuel for long durations without significant leakage and to actuate the valves after a long period of disuse. Both of these abilities will be essential for missions like CanX-4/-5 and future formation flying missions with longer lifetimes. The results of these tests indicate that after almost 1.5 years in orbit the propulsion system still retains a significant amount of liquid SF₆. Further, no issues

were observed with either the thrust valve (stored with minimal pressure differential) or the regulator value (stored with ~500psi pressure differential) when actuation was attempted.

Testing in this second round of propulsion experimentation began with a repeat of the minimum impulse characterization. The aim was to confirm the results from the first campaign, and evaluate whether long-term storage of the device lead to performance degradation. Long duration constant thrust experimentation followed, with the aim of establishing impulse and thrust levels at various thrust-valve actuation durations. This campaign is complete, and data reduction is currently underway.

GPS Position Estimation

Since launch, approximately eighty GPS trials have been executed, in order to evaluate GPS Rx data quality, performance in orbit and to evaluate single-point position determination accuracy. Cold-start experimentation, involved evaluating the effect of manipulating several important variables including the GPS antenna attitude, Rx on-time, and logging frequency. Warm start experimentation required further customization, with experimentation focused on issuing initial time and position estimates, and assigning GPS channels to particular GPS constellation spacecraft.

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 20 minutes. When the GPS antenna attitude was pointed towards the horizon, however, (forward, or anti-velocity), PVT estimates were obtained after 55 minutes.

Warm-start experimentation lead to significantly improved time-to-solution performance. It was found that issuing a time input and an initial estimate of position had very little or no effect in warm starting the receiver. On the other hand, configuring the GPS receiver channels (by assigning each channel to a particular GPS satellite and specifying the corresponding L1-frequency Doppler offset), lead to rapid locks, and PVT solution estimates within 1-minute. In fact, on CanX-2, the calculated Doppler offsets could range as high as +/-45KHz, whereas the GPS receiver is designed to acquire the L1/L2 frequency within only a +/10KHz tolerance. Therefore, the reason why cold-start performance was so poor is because, in order to acquire a PVT solution, at least four GPS spacecraft with a Doppler offset within +/-10KHz were required within the GPS antenna field of view.

Upcoming GPS experimentation will focus on further characterizing warm-start performance. In particular, long duration GPS experimentation will be conducted, with slews introduced following a PVT acquisition in order to gauge how well the solution is maintained as GPS spacecraft are dropped and others are acquired. This experimentation is of critical importance to the upcoming CanX-4/-5 formation flying mission which will depend on continuous GPS position estimation.

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 11. 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 [7]. 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. A third campaign was run from December 2009 to January 2010. The focus of the first two occultation campaigns was 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 headway was made, leading to the first successful occultation observation near the end of the second campaign. An attitude sphere plot, shown in Figure 12 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 13 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.

The third GPS occultation campaign was the first dedicated almost entirely to the consistent collection of science-quality data as exposed to commissioning. In that campaign more than 85% of the datasets collected contained at least one occulting satellite and all contained at least six GPS satellites. Further GPS occultation experimentation on CanX-2 is currently underway. Accumulated data is 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 eighty spectrometer observations have been made since launch.

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 [6]. A sample spectra, acquired over Ontario, Canada by the Argus spectrometer onboard CanX-2 is shown in Figure 14,

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 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 [8]. Since launch, little change in sample resistance has been observed, meaning minimal degradation of the AO-resistant coating samples has occurred to date. The slow degradation of the samples can be attributed largely to the altitude of the satellite which, at 635km, is high enough that atomic oxygen is not present in very high concentrations. However, experimentation will continue as long the satellite continues to operate in order to maximize the possibility of detecting a significant change in this novel AO-resistant coating.



Propagated orbit from NORAD TLE

Figure 11: GPS Position Estimation: GPS estimated positions plotted relative to TLE estimated ground track



Figure 12: GPS Occultation Experiment: Attitude sphere plotting seven GPS spacecraft tracked above the atmosphere, while two GPS spacecraft occult through the atmosphere. Figure provided by University of Calgary GPS occultation team.



Figure 13: GPS Occultation Experiment: Estimated position differences relative to NORAD estimated TLEs. Figure provided by University of Calgary GPS occultation team.



Figure 14: Spectra of greenhouse gasses taken over Ontario, Canada by Argus 1000 spectrometer. Figure provided by York University Argus spectrometer team.

8. NEAR-FUTURE WORK

Currently CanX-2 is operating on a three-phase cycle in which approximately one month is spent on each of GPS occultation observations, Argus spectrometer observations and engineering experiments such as NANOPS, GPS engineering experiments and imager tests.

In the summer of 2010 work will begin on a database of CanX-2 telemetry. This database will enable the analysis of long-term trends in CanX-2 data so that the effect of the space environment on various subsystems can be quantified. Examples of parameters that will be assessed using this data will include:

- Degradation of thermal control coatings based on external panel temperature data.
- Reduction of battery capacity based on charge and discharge characteristics.
- Increase in power consumption based on unit-level current and voltage telemetry.
- Degradation of optical filters based on sun sensor telemetry.

Designers of future SFL nanosatellites will then use this information as inputs in their designs thereby closing the loop and fulfilling the primary mission goal of CanX-2, which is risk mitigation for future missions.

9. 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 two years in orbit have been very successful with the spacecraft performing well.

Many achievements, some nanosatellite records and other SFL firsts, have all been accomplished by CanX-2 during its first two years 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 and undegraded functionality after 1.5+ years in orbit.
- 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.
- 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 to the fact that critical technology demonstration missions and meaningful science can be accomplished in a small form factor, short time 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 [11]) astronomy constellation and AISSat-1, a spacecraft that will detect ship-based AIS signals within Norwegian waters [12]. Each of these missions is well into the assembly, integration and test phase with AISSat-1 expected to launch in April 2010 and two BRITE satellites expected to launch in early 2011.

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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