CANADIAN ADVANCED NANOSPACE EXPERIMENT 2: ON-ORBIT EXPERIENCES WITH A THREE-KILOGRAM SATELLITE

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ABSTRACT

The objective of the Canadian Advanced Nanospace eXperiment (CanX) program is to develop highly capable "nanospacecraft," or 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 Canadian Advanced Nanospace eXperiment 2 (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 mNms nanosatellite reaction wheel as part of a three-axis stabilized momentum-bias attitude control system, and a commercially available GPS receiver. The secondary objective of CanX-2 is to fly a number of university experiments including an atmospheric spectrometer. At the time of writing CanX-2 has been in orbit for three weeks and has performed very well during preliminary commissioning. The mission, the engineering and scientific payloads, and the preliminary on-orbit commissioning 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 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 two-fold. First, offer a low-cost, quick-to-launch satellite platform upon which to execute a wide-spectrum of missions, ranging from scientific experimentation to technology demonstration for commercial exploitation. SFL develops low-cost miniature satellite systems to challenge traditional satellites in cost based performance. In addition to state-of-the-art capabilities and functionality, miniature satellites employ low cost, readily available components making them rapid to develop and significantly less expensive to launch, operate, and insure than their larger counterparts. As a result, miniature satellites show increasing potential to displace traditional satellites on a fraction of the budget, and make new applications feasible - both technologically and economically. This will allow government and industrial organizations to afford their own satellites for 24/7 use independently of third party satellite service providers.

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 engineering staff. Canada's first space telescope, the MOST (Micro-variability and Oscillation of Stars) microsatellite was designed, integrated and tested within SFL [1]. With this expertise on hand, SFL graduate students can tap into a diverse wealth of knowledge during the design of a SFL spacecraft. Thus, 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 assembled in the SFL clean room.

SFL FACILITIES

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

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

A Class-10000 clean room is used for all SFL spacecraft during final integration, spacecraft cleaning, testing and holding prior to shipping the spacecraft to the launch site.

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

CANX-2 OVERVIEW

The second satellite built under the CanX spacecraft program is CanX-2, a triple CubeSat measuring 10 x 10 x 34 cm in dimensions and 3.5 kg in mass. This nanosatellite packs enough engineering and scientific experiments to push the envelope of what has been previously attempted in 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 that were identified to be critical for the upcoming CanX-4/-5 formation-flying mission. The CanX-2/-4/-5 missions are designed to develop and demonstrate capabilities for formation flying and inspection in space on a small platform. Within this series of spacecraft, CanX-2 will serve principally as a risk mitigation mission for CanX-4 &-5. Engineering payloads to be investigated include hardware essential for centimeter-accurate GPS determination of relative satellite positions, a nano-propulsion system based on commercial off-the-shelf components, a three-axis degree-accurate attitude determination system, a CMOS imaging system for inspection and navigation, a high performance computer and a high data rate radio system.

The second objective for CanX-2 is to provide cost-effective access to space for the research and development community in Canada. Scientific experiments flown on CanX-2 include a miniature atmospheric spectrometer used to detect greenhouse gases, a GPS atmospheric occultation experiment to determine vertical profiles of electron and water vapour content of Earth’s atmosphere, a surface material experiment that will measure the effects of atomic oxygen on advanced materials, and a dynamic spacecraft networking protocol experiment.

Formation Flight Technology Demonstration

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

A group of small satellites flying in formation have several advantages when performing the same mission over a single, larger satellite. One advantage is higher reliability, as the loss of a single satellite does not terminate the mission. Furthermore individual, cheaper satellites in a formation can be easily replaced over time, gradually upgrading the system with a more spread out investment. Perhaps the most important advantage is the cost savings made possible by "mass producing" the satellites used in the formation, thus spreading out the non-recurring engineering costs.

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

Centimeter Level GPS Based Position Determination

Formation flight holds promise for many spacecraft applications, however it can only be realized if the relative states of the vehicles can be measured accurately in real-time. The CanX-4/-5 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 capabilities to measure positional accuracies on the centimeter level have been shown [2].

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

Nano-Propulsion System (NANOPS)

Formation flight applications require a propulsion system for several reasons. For applications such as sparse aperture sensing, spacecraft in formation must maintain their relative separation distances by controlling secular disturbances caused by perturbative forces. Second, different types of formation offer particular advantages, therefore spacecraft must have the capacity to maneuver in orbit to reconfigure the controlled formation.

To this end, a small experimental liquid fueled cold-gas propulsion system, the Nano Propulsion System (NANOPS), has been developed and is flown on CanX-2 [3]. 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 system uses sulfur hexafluoride (SF_6) as propellant. The nozzle is oriented such that thrusting induces a major-axis spin on CanX-2. Through a series of experiments, several performance characteristics of NANOPS will be inferred from pressure and temperature readings. The satellite angular rates achieved by NANOPS will be measured using the on-board attitude determination system. Key performance requirements of NANOPS are shown in Table 1.

Table 1: NANOPS performance attributes

Parameter	Value
Total ΔV	2 m/s
Specific Impulse (I_{SP})	35-40s
Thrust	50 mN
Minimum Impulse Bit	<0.1 mN·s

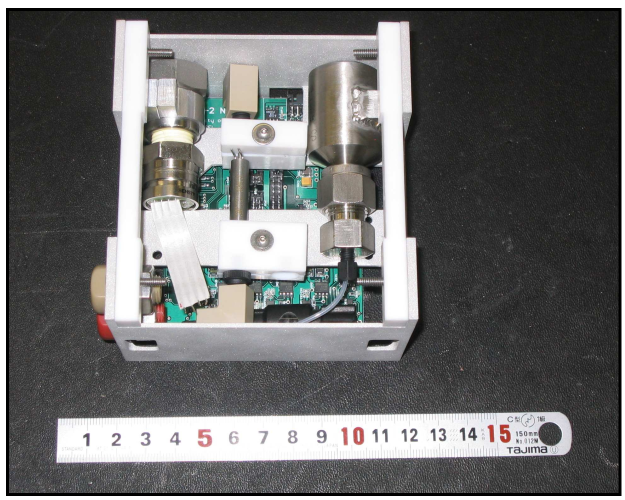

Figure 3: NANOPS system

Attitude Subsystem

Formation flight applications often demand a high-fidelity attitude determination and control subsystem (ADCS). For applications such as sparse-aperture sensing, spacecraft must maintain relative attitude with high accuracy in order to create an effective large aperture.

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. Accurate three-axis control will be achieved using a set of high precision sun sensors, a magnetometer, 3-axis rate sensors, three orthogonal nano-reaction wheels, and magnetorquer coils. As a demonstrator, CanX-2 includes all but the rate sensors.

This system has design heritage, but prior to CanX-2 has not been flight proven. To this end, CanX-2 will evaluate the performance of these actuators and sensors in a momentum-biased three-axis stabilized attitude configuration.

CMOS Imagers

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

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.

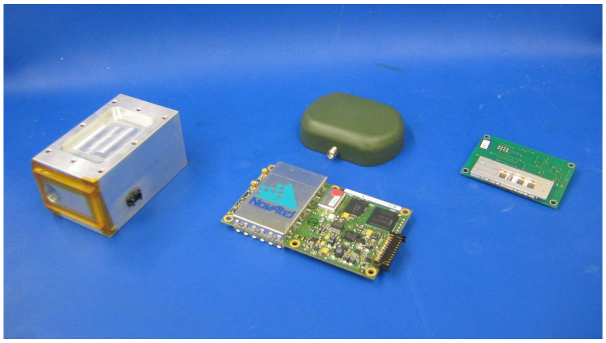

Figure 4: CanX-2 science instruments: Atmospheric spectrometer (left), GPS antenna (center top), GPS receiver (center bottom), Advanced surface material experiment (right)

Atmospheric Spectrometer

The Argus Spectrometer, developed by researchers at York University, aims to yield a better understanding of greenhouse gases in the atmosphere [4]. Specifically, this 230 g device will analyze in the near infrared spectrum, looking at the radiance response of carbon dioxide, methane, nitrous oxide, oxygen, and water around the 1.5 to 1.8 μm mark.

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

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 [5]. To study this phenomenon, CanX-2 will carry 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 compared with those from ground-based GPS stations. Using differential methods, the total electron content (ionosphere) and water vapour content (troposphere) will be mapped as a time-varying function of altitude. A successful map of atmospheric properties will allow mitigation of GPS position errors. It will also allow the monitoring of auroral activity, magnetic sub-storms, and other enhanced ionospheric activities that impact navigation and communications systems.

Surface Material Experiment

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

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

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 Al. 6061-T6 tray based design was chosen to simplify assembly and integration. A large majority of CanX-2's internal components are directly mounted to the tray, as are most of the body panels that enclose them. Externally, four aluminum rails act as contact surfaces with the deployer.

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.

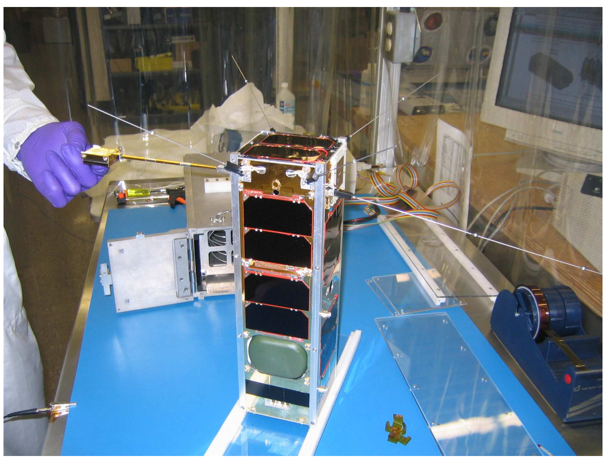

Figure 5: Integrated CanX-2 spacecraft

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 anticipated 2 to 7 W of generated electrical energy for use by the various subsystems. Power is directed 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 ±1º is achieved using a set of six SFL-developed sun sensors, supplemented by an SFL-developed three-axis magnetometer that is deployed approximately 20 cm from the satellite. Three-axis stability, to an accuracy of at least ±10º, is achieved on CanX-2 using a Y-Thompson configuration with bias in a wheel instead of the body. The wheel, developed in partnership between SFL and Sinclair Interplanetary generates a maximum torque of 3 mNm and has a maximum momentum storage of 30 mNms. This wheel is being flight tested for the first time on CanX-2. The attitude determination and control suite of components is shown in Figure 6 and Figure 7.

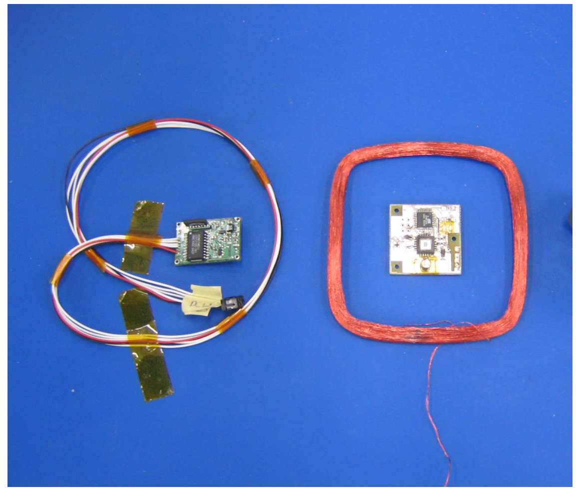

Figure 6: CanX-2 ADCS components: Magnetometer (left), Sun sensor (right-center), Magnetorquer coil (right)

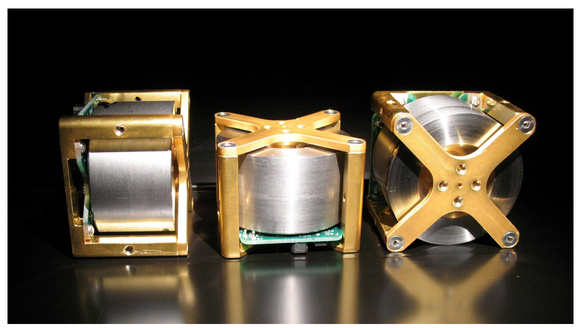

Figure 7: SFL/Sinclair Interplanetary reaction wheels

The central brain for CanX-2 is composed of two computer boards, each hosting a 40 MHz ARM7 processor (although, clocked at 12 Mhz on CanX-2) with 2MB of SRAM equipped with triple-voting error detection and correction (EDAC) and 4 MB without EDAC protection. Each computer also holds 16 MB of flash memory for storage of telemetry, science data, images and pre-positioned code. An SFL-designed pre-emptive multi-threaded operating system, CANOE, runs all of the application software and handles all internal communication with the hardware components. Moreover, 58 telemetry points will be gathered, keeping track of CanX-2's status with fine detail. One of these computers is shown in Figure 8.

The CanX-2 communication system is full-duplex. A custom-built UHF receiver (Figure 9) providing a communication rate of 4000bps through a set of quadcanted antennas serves as the uplink. An SFL-developed S-band transmitter will be used for the downlink and can operate between 32 kbps and 1.0 Mbps. An SFL-designed UHF transmitter is also on board to serve as a backup downlink radio.

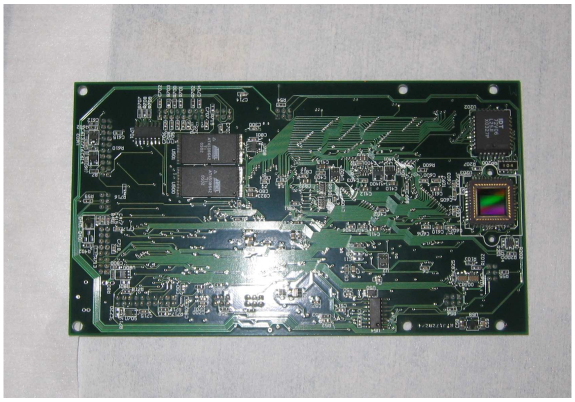

Figure 8: CanX-2 on-board computer

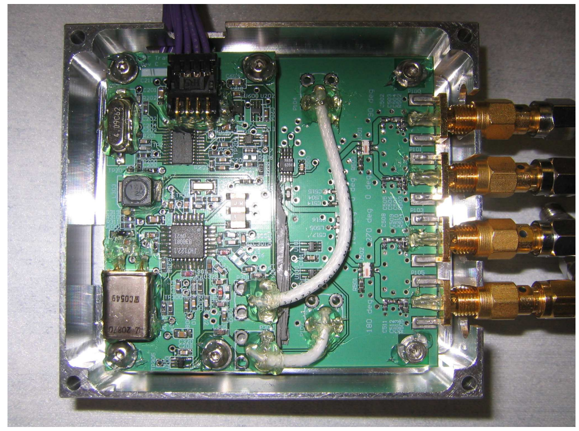

Figure 9: CanX-2 UHF Transceiver

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

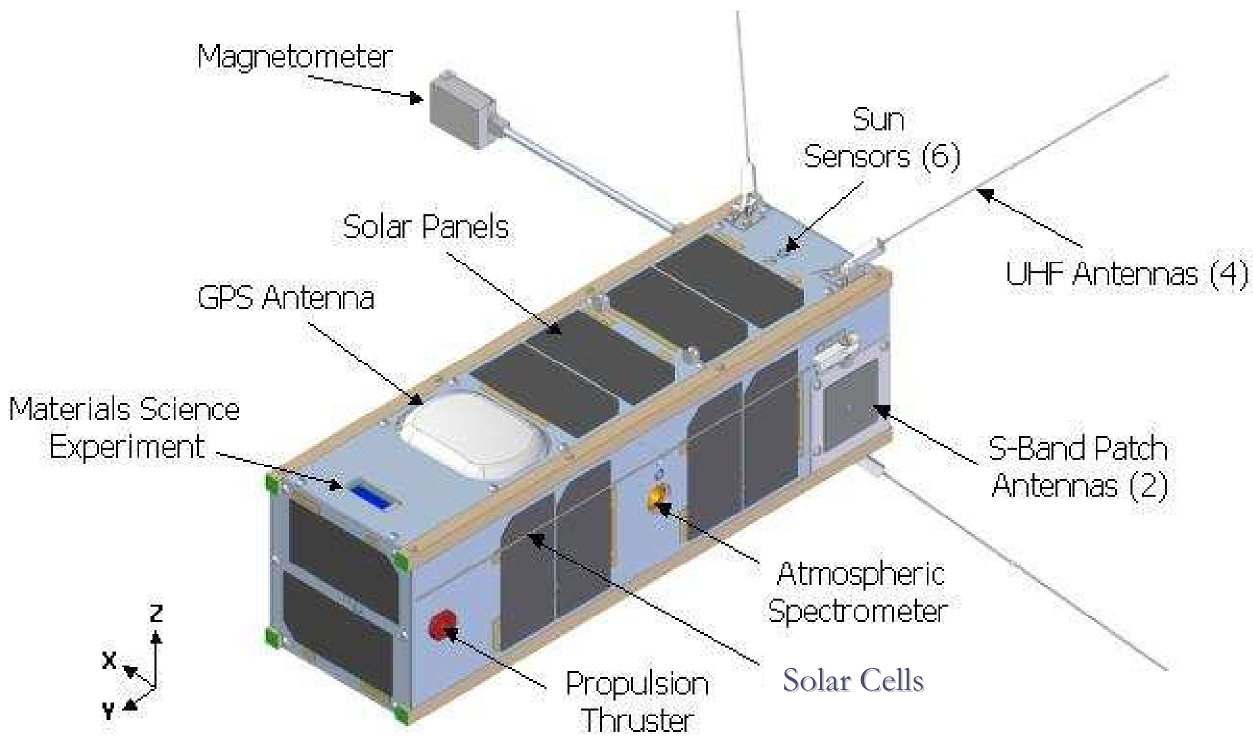

Figure 10: CanX-2 bus overview

CANX-2 LAUCH CAMPAIGN

The CanX-2 nanosatellite was launched into a 635km sun synchronous orbit with a 09:30 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. CanX-2 was part of the SFL-arranged 'Nanosatellite Launch Service-4' (NLS-4), a cluster of six nanosatellites which were launched on the same PSLV flight. 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.

NLS-5 was also launched on the same PSLV flight. NLS-5 consisted of SFL's NTS (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 and tested and launched within 7-months.

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 in deploying several spacecraft.

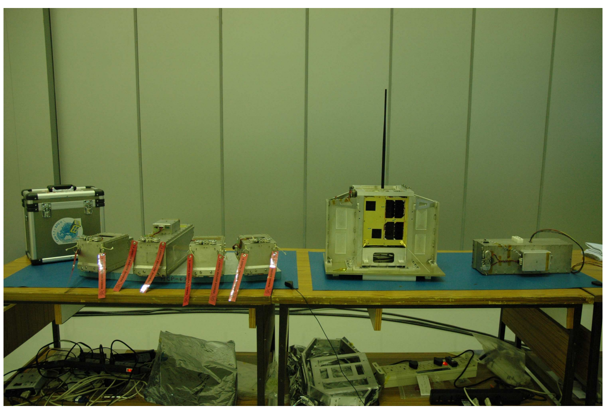

Figure 11: Several NLS-4 & NLS-5 spacecraft stowed in their respective XPOD systems

The XPOD deployment system is a jack-in-the-box type concept where, once a deployment door is opened, the satellite is pushed out of an aluminum or magnesium box-frame by a spring-loaded plate. The XPOD deployment door is secured in place during launch by a cord. This securing cord is burned and cut using a heater when a deployment signal is issued by the launch vehicle. Each XPOD is equipped with sensors which confirm spacecraft deployment.

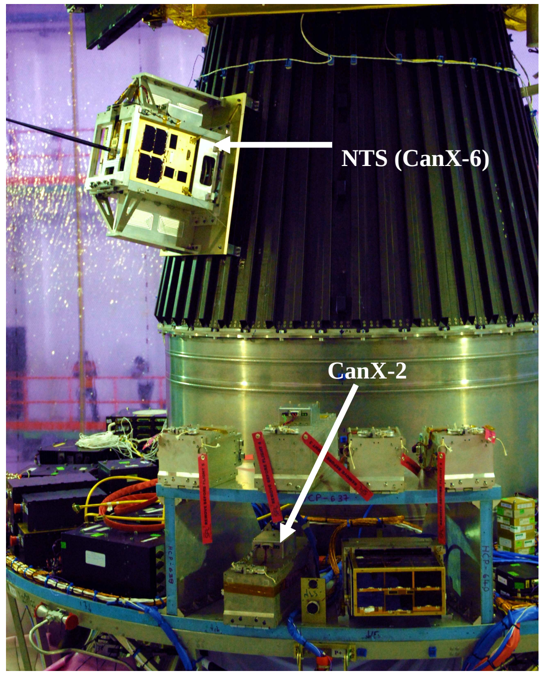

Figure 12: CanX-2 & NTS integrated along with the rest of NLS-4 & NLS-5 to the upper stage.

On the larger XPODs, minimal lateral relative motion between the spacecraft and the XPOD system is ensured by a cup-ball interface between the spacecraft and the XPOD. Motion is also constrained in the longitudinal axes by a customizable pre-load.

SFL has designed several variants of the X-POD deployment systems in order to accommodate a wide-range of spacecraft form factors, while still retaining the same deployment mechanism concept in order to maintain design heritage. Compatible spacecraft form factors include single, double and triple cubesats (including triple-cube variants), and 20x20x20cm & 20x20x40cm spacecraft. SFL also has the capacity to customize the XPOD deployment systems for any particular application.

CANX-2 ON-ORBIT EXPERIENCE

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 successfully deployed from their XPOD's as local amateur radio operators were listening to Morse-Code broadcasts from the cluster (beacon equipped spacecraft included SEEDS, Cute-1.7+APD II, AAUSAT-II, COMPASS-1, and Delfi-C3). These independent amateur radio operators were able to provide preliminary health verifications of the spacecraft which had sufficiently strong beacon broadcasts.

Confirmation that the CanX-2 and NTS XPOD deployment systems safely actuated and 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 of 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.

Within the first three weeks after launch, significant headway has been made with respect to the orbital commissioning of the CanX-2 spacecraft. The commissioning procedure involves incrementally building on the spacecraft functionality by enabling progressively more capable software modes and testing systems, actuators and sensors as they are required. At the time of writing, a large percentage of the spacecraft systems has been activated and commissioned to an extent necessary for immediate operations.

Figure 13: Antrix/ISRO PSLV-C9 launched at 03:53 UTC April 28th 2008 carrying CanX-2

Since launch, CanX-2 has operated in most software modes (several software modes of the on-board ADCS have yet to be commissioned). 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. These commissioning tasks include verifying the stability of the BL2 software and sequentially powering up each sun sensor and the magnetometer in order to verify that these sensors do not cause any shorts. This checkout is required as these ADCS equipment are powered on following a spacecraft boot into CANOE. 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.

In the first three weeks, the three operations teams (each comprised of two operators) have accomplished approximately one third of the commissioning activities. These activities include: a checkout of all ADCS sensors and actuators, including

- A spin up of the Sinclair Interplanetary/SFL reaction wheel
- A preliminary checkout of OASYS (attitude determination mode only), focusing on the validity of the sensor inputs and the attitude state vector produced by the on-board Extended Kalman Filter (EKF)
- Activation of the nano propulsion system and commencement of the fuel-leakage check
- Activation of science data collection on the material science experiment

- Demonstration of the full functionality of the S-band transmitter and UHF receiver
- Verification of the spacecraft's thermal and power models
- Confirmation that the spacecraft antenna and magnetometer deployable mechanisms have successfully deployed.

Some of these topics will be explored in further detail in the subsequent sections.

General Telemetry

From initial acquisition to the present time (05/18/08), the spacecraft has been left in a free-tumble with rates which were initially imparted by the XPOD deployment system. In this random tumble, the spacecraft power and temperature-status are within nominal expected ranges. The spacecraft bus voltage has currently been typically bounded between 3.9V and 4.1V. The spacecraft is expected to charge when the bus voltage reaches 3.9V and discharge once the bus voltage has climbed to 4.1V. The lowest recorded battery voltage was 3.64V which occurred when the 5W S-band transmitter was ON during a groundstation pass that occurred at the end of an eclipse. The power generated by the body-mounted solar cells is well within the nominal range. The maximum and minimum peak power generation recorded was 7.18W (1.79A @ 4.01V) and 3.02W (0.756A @ 4.0V), where peak-power is defined by the maximum power generated in any charge cycle. In this random tumble, the average power generation is approximately 5W (1.25A @ 4.0V). In order to provide context, the average load of the spacecraft during commissioning is 1.25W.

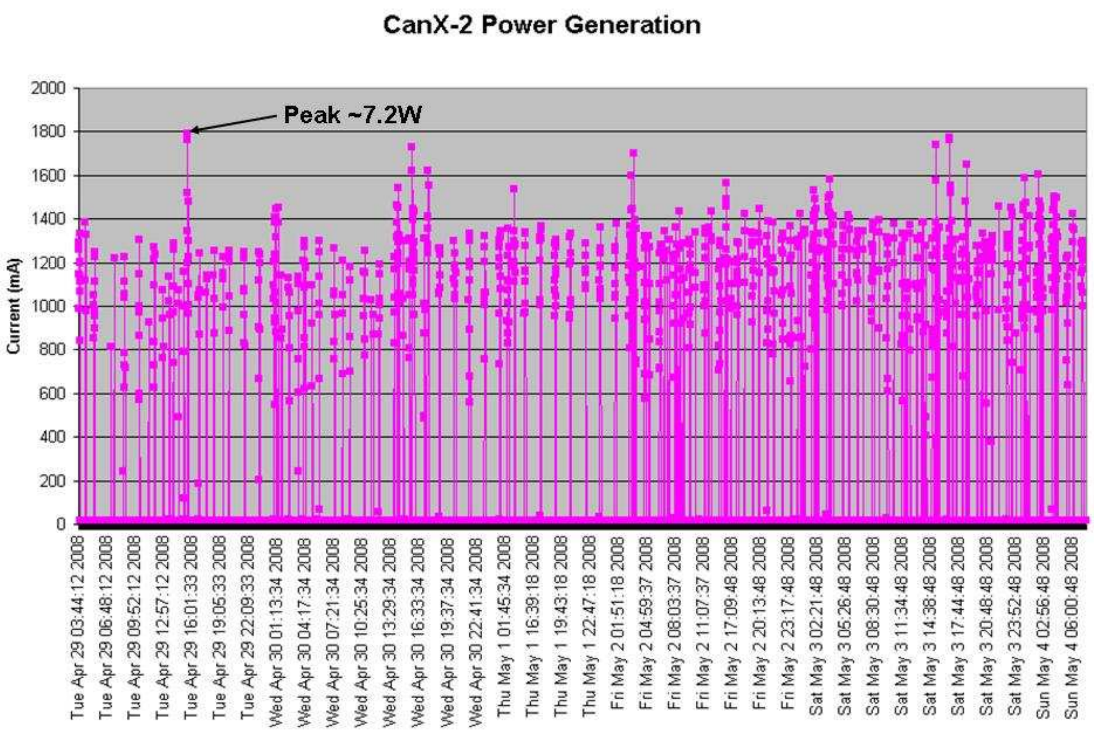

Figure 14: Power generation profile in a random tumble attitude state.

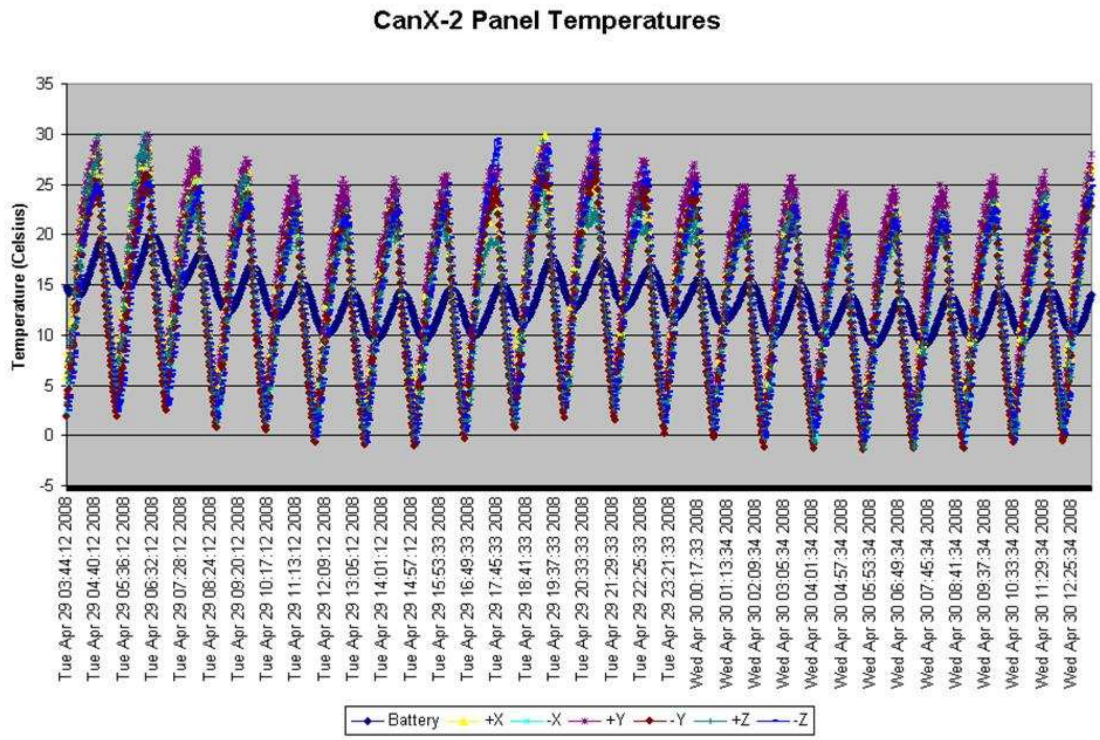

Figure 15: CanX-2 panel and battery temperatures in a random tumble attitude state

A significant albedo contribution is evident in instances of high power generation. For instance, in the case of the maximum 7.18W power generation, both opposing solar panels on the spacecraft Z-axes were recording significant current generation (500mA on the –Z panel and 250mA on the +Z panel respectively). Assuming the spacecraft -Z panel was illuminated by the sun, the 250mA generated by the Z+ panel could only be generated by albedo illumination.

The CanX-2 power and thermal state are quite related. Generally, when the spacecraft is generating plenty of power, the spacecraft temperatures are typically within ideal ranges. This is precisely the current situation on CanX-2. The spacecraft is tumbling at approximately 1.5 to 2.0^o/s with the spin vector in the body-frame precessing quickly. In such conditions, the spacecraft battery temperature is currently bounded between 10^{o}C and 20^{o}C, with a time-average temperature at 15^{o}C. This time-average ranges between 12.5^{o}C and 17.5^{o}C, resulting in a maximum battery temperature swing of 5^{o}C (see Figure 15).

This variance in the time-average battery temperature is due to the precession of the spin vector in the body frame, and thus the variance of the solar vector in the body-frame. Since the spacecraft is a rectangular prism with a length dimension 3.4 times greater than the width or depth, the orientation of the solar-vector in the body-frame will make an appreciable difference on the spacecraft temperature. For instance, the spacecraft is cooler when the solar vector is aligned near the Y-axis relative to any other direction. Therefore, CanX-2 will be cooler in a spin where the angle between the Y-axis and solar vector is minimized for a significant fraction of an orbit. The same principle applies to power generation as seen by the differences in peak power generation reported earlier.

The spacecraft structural panel temperatures are bounded between 35^{o}C and -2^{o}C, which is expected given a random tumble. In fact, in comparison between the thermal model predictions versus actual orbit telemetry, the spacecraft thermal model is accurate to within 5 deg C and typically on the order of 2 deg C in comparison with actual telemetry.

Attitude Determination and Control

Commissioning of CanX-2's attitude determination and control subsystem (ADCS) makes up a significant fraction of the overall spacecraft-commissioning procedure. The process involves ensuring a safe power-up of all sensors and actuators, ensuring that the sensor inputs to the Extended Kalman Filter are reasonable and, given these sensor inputs, confirming whether the EKF is producing an accurate state vector (body rates and quaternions) using spacecraft current generation and temperature telemetry as a coarse reference.

The performance of OASYS (and its EKF) has been sound thus far with the on-board ADCS code running stably since the operating system was loaded and attitude determination initiated. The only updates that were made to OASYS included updating the two line elements (TLEs) which are used for the on-board orbit propagator (updated on a weekly basis) and a slight tweak in the exposure time of the digital sun sensors. Both of these updates were expected and planned before launch.

It is currently estimated that the attitude determination solution is accurate to around a degree or two in sunlight and a few degrees during sun sensor drop-out where only the magnetic field vector is sampled. This indicates that the spacecraft attitude sensors and the EKF are working as designed; more accuracy is expected after an on-orbit calibration.

The sun sensors consist of two parts; a fine sensor that uses a CMOS detector for accurate (degree-mark) determination of the solar vector in the body frame; and a coarse (5 to 10 deg) sensor based on diffuse filtering of a phototransistor. The coarse sensors are primarily used to select the appropriate fine sun sensor to be sampled. This approach avoids the computational time that would otherwise be necessary to poll all six fine sun sensors (about 100 ms each for a readout).

Two small subtleties of the sun sensors are currently being examined. First, each fine sun sensor has a roughly 88 deg minimum field of view (FOV), driven by filter geometry and recession within the satellite's body. As a consequence, there are small dead bands between the fine sun sensors. During solar vector transits through these dead bands, the coarse sun sensors, with their full, hemi-spherical, fields of view, are used as the sun measurement, which means that the accuracy of the attitude solution briefly drops. This has a noticeable affect on attitude determination in the current tumble state, since these FOV boundaries are crossed often. The effect will be minimal in nominal operations since the body rates will be near zero and the attitude will see the sun within the fine sensor fields of view, by and large.

Second, the albedo contribution is, as expected, influencing the phototransistors. The result is that the sun vector estimated by the coarse sun sensors can be significantly degraded when albedo is significant. However, the impact on attitude determination is negligible since these sensors are mainly used to select the correct fine sun sensor, where the sun intensity is greater than the albedo intensity.

The magnetometer has been sampling the magnetic field measurements of Earth since the application software CANOE was loaded on CanX-2. Observations indicate that the magnetic field magnitude measurements are consistent with the expected value for the ascending node and altitude. The magnetometer is currently undergoing a full on-orbit calibration which relies on randomly-distributed measurements across the entire sensor's unit sphere. Fortunately, a random tumble is an ideal condition to capture this data. Finally, because rate measurements made with the magnetometer and sun sensors are in agreement the deployment of the magnetometer has been confirmed. Had the magnetometer not been fully deployed the measured spin-vectors would not have been aligned.

Initial testing has also been conducted on the magnetorquers and the reaction wheel. This testing has focused on low-level functionality as opposed to a full-scale performance (scheduled for the near future). The three orthogonal magnetorquers were each actuated in both polarities at maximum current output for 30s and their effect on the spacecraft state was analyzed. The test results indicate that polarity switching has been affirmed and, where evident, polarity itself has been verified.

A preliminary reaction wheel test involved spinning the wheel up to 50 rad/s in the positive and negative wheel directions in increments of 25 rad/s. The motive for this preliminary test was to verify that the wheel was in a healthy state following launch. The wheel performed very well, where at each speed step the wheel spun up and settled to the commanded value with an acceptable profile Figure 16 is a plot of the wheel speed versus time as the wheel is spun from 25rad/s to 50rad/s and back to 0rad/s. In this test, the wheel was spun up in speed-control mode, whereas torque-control will be used in nominal operations. The small ripple seen at 25rad/s is expected and is due to the fact that this speed is at the threshold of the wheel dead band.

The induced spacecraft body-rate is shown in Figure 17. The wheel, mounted on the spacecraft Y-axis imparted a 0.175rad/s (10^o/s) and 0.35rad/s (20^o/s) spin about the spacecraft Y-axis when spun up to 25rad/s and 50rad/s respectively, which was right on target. While evaluating the wheel performance, this test demonstrated that the EKF was correctly calculating the spacecraft rate. The noise in the EKF rate-measurement is in part due to the solar vector passing through the fine sun sensor (FSS) dead bands, leading to FSS dropout. This can be seen by comparing Figure 18 with

Figure 17, where Figure 18 is a FSS drop out error plot. The EKF raises a flag with number '19' when the solar vector passes through a FSS dead band and '12' when the spacecraft is in eclipse. In both cases, the determination system can only sample the magnetometer measurements. In comparison of the two figures, it can be seen that FSS dropouts lead to more inaccuracy, however the solution always re-converges when the sun sensors are exposed to the sun. Thus the EKF's ability to converge is well demonstrated

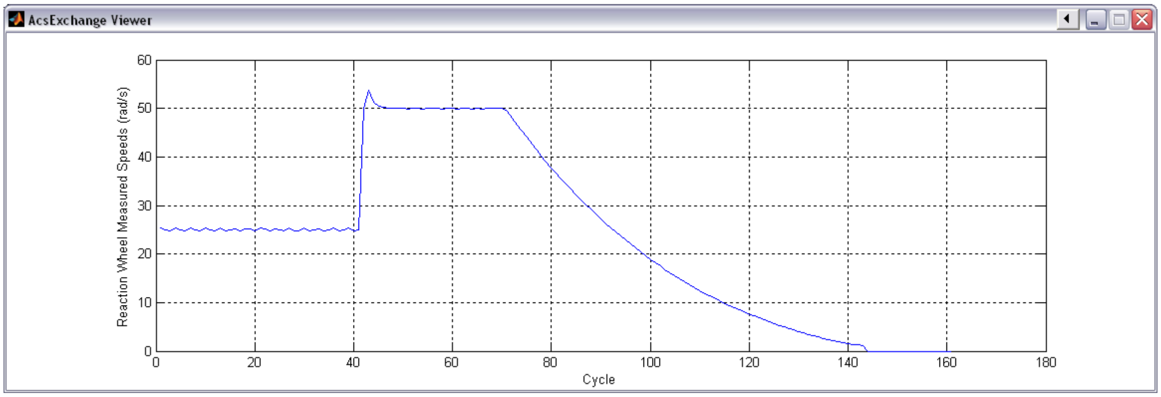

Figure 16: Wheel speed plot

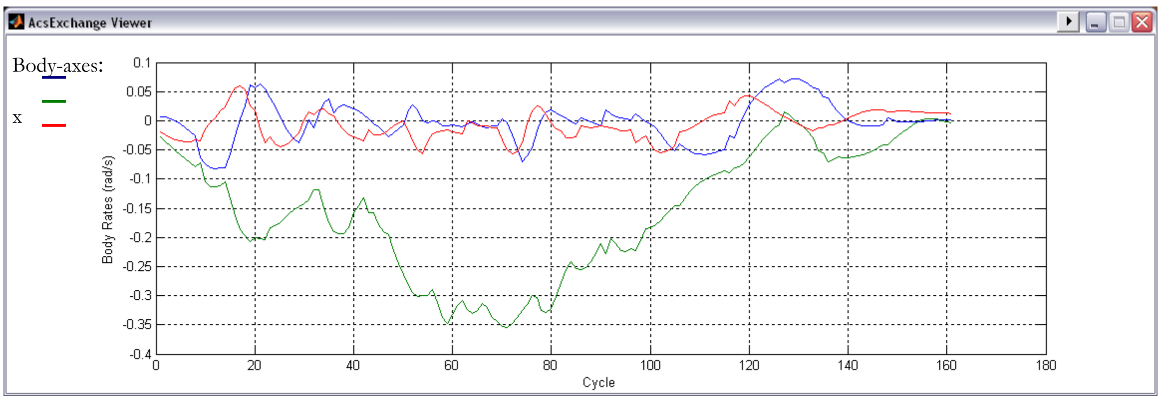

Figure 17: EKF estimated body-rate plot during wheel spin-up

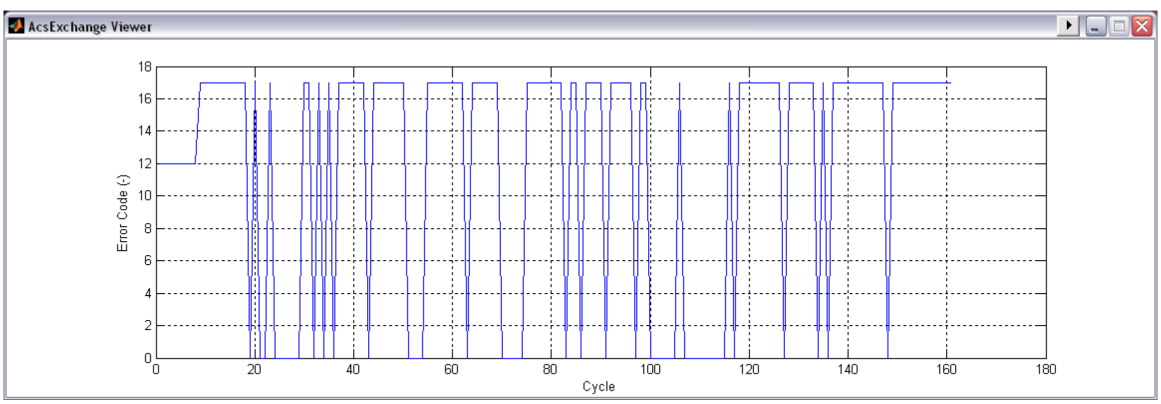

Figure 18: OASYS FSS drop out error plot during wheel spin-up

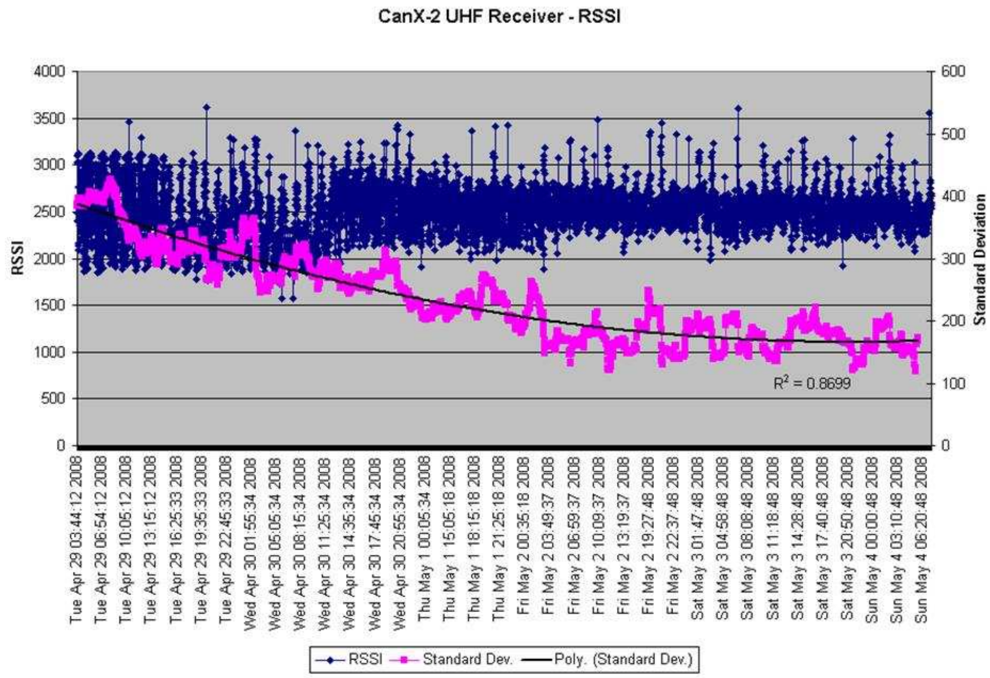

Figure 19: UHF Receiver RSSI during April 29th to May 4th. The standard deviation of the RSSI decreases with time, potentially due to spacecraft separation.

RSSI and Spacecraft Identification

One interesting observation associated with this cluster launch (and that is likely to be present in any cluster launch) was the influence 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 onboard NTS.

Further observations over the next several days showed that the, although the CanX-2 RSSI was noisier than the NTS RSSI, the noise was decreasing steadily over time (see Figure 19). The data also showed that during a period of approximately 20 hours starting on April 29, 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 design were sufficient to overcome the added noise input.

Nano Propulsion System Leak Check

At the launch site, NANOPS was filled with Sulfur Hexafluoride (SF_6) 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 solenoid 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 15.22^{o}C.) Approximately 9-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. The leak test is a long duration experiment and will continue until thrust test experiments are scheduled to begin. Thrust tests will commence following a thorough checkout of the attitude determination sensors and state estimation code.

UHF/S-band Radios & Ground Station Performance

The UHF and S-band communication system on the spacecraft have been operating flawlessly. 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. In the three weeks following launch, the CanX-2 communication system has been used to download over 16MBof data.

The ground station has been operating well, with efforts currently focused on attaining a higher level of automation as the commissioning process of CanX-2 is progressing. The commissioning of CanX-2 is occurring in parallel with NTS commissioning and MOST operations. Therefore the automated operations account for pass-scheduling between the two nanosatellites while avoiding conflicts with the MOST microsatellite

Near-Future Work

With approximately a third of the commissioning activities complete in the first three weeks, the upcoming month will be quite engaging and interesting. Following the completion of the EKF commissioning, the near-term tasks include: a detumble of the spacecraft using B-dot magnetic attitude control (rate damper). Minimal body-rates are required prior to beginning performance thrust experiments with the Nano Propulsion System. Following these thrust experiments, the spacecraft will resume the commissioning of the attitude control system and algorithms. In this process the spacecraft will transition from the B-dot attitude mode to a spin-alignment with the orbit normal using magnetic control before spinning up the reaction wheel and settling into a momentum bias-configuration and the nominal controlled attitude. At this point, science collection from the on-board spectrometer and GPS receiver will begin. Last, at opportune points during the commissioning process the on-board imagers will be commanded to take snapshots of Earth and other targets of interest.

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 ascending node. CanX-2's first three-weeks in orbit have been very successful with the spacecraft performing very well.

Commissioning of the spacecraft is well underway with nearly a third of the procedure closed-out. These successful commissioning tasks include: operating CanX-2 in the majority of the spacecraft's software modes, activating and testing all ADCS sensors and actuators, verifying that the EKF is producing an accurate state vector of body rates and quaternions, activating the nano propulsion system and commencing the leak check test, and demonstrating the full-functionality of the spacecraft S-band transmitter and UHF receiver. A significant list of commissioning activities remains prior to commencing nominal operations. Carrying-out these remaining commissioning tasks is expected to occupy a large faction of the upcoming month. Once commissioning is complete, the spacecraft will begin the atmospheric spectroscopy and GPS occultation experiments while continuing the NANOPS technology demonstration.

CanX-2 is a clear cut example of what a nanosatellite on a shoe-string budget is capable of accomplishing. CanX-2, which is approximately the size of a 2L milk carton, is a highly capable and sophisticated satellite which pushes the envelope of what can be achieved from 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 tight-budget.

CanX-2 is a trail-blazing mission for the Space Flight Laboratory. Technologies demonstrated on CanX-2 are the cornerstones of the systems, sensors and actuators that form SFL's Generic Nanosatellite Bus (GNB). The GNB bus, while built upon the heritage and experience of CanX-2, is an even more capable spacecraft. Upcoming GNB missions include the CanX-4/-5 dual-spacecraft formation flight demonstration, the CanX-3 (aka 'BRIght Target Explorer or BRITE) astronomy constellation, and AISSat-1, a spacecraft that will detect ship-based AIS signals within Norwegian waters. Each of these SFL GNB missions are well into design maturity and are fast approaching the assembly, integration and test phase. These spacecraft are expected to launch in 2009 with the first of the four BRITE spacecraft launching in the first quarter of 2009.

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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