CANADIAN GROUND BASED OPTICAL OBSERVATIONS OF THE CANX-7 DRAG SAIL DEPLOYMENT

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ABSTRACT

The CanX-7 nanosatellite successfully tested a unique deorbiting technology by deploying four thin-film polyimide drag sail segments in May 2017. Drag sails increase satellite cross-sectional area augmenting atmospheric drag, helping accelerate a satellite's deorbit. This small size, weight and power deorbiting technology is well-suited to small satellites as they often cannot accommodate classical chemical thruster-based systems due to their compact design. During the deployment of the drag sails, ground based observers in eastern Ontario used electro-optical telescopes to monitor the photometric (brightness) changes of CanX-7. This paper examines the detected photometric characteristics of the CanX-7 nanosatellite as detected by small telescopes in Canada prior to, during and after the drag sail deployment. The ground-based observations validated satellite telemetry from SFL indicating that the first two drag sail segments deployed successfully. The second set of sails, deployed on the subsequent orbit, was not unambiguously detected from the ground-based sensors, however their deployment was verified in CanX-7's telemetry. Weeks later, follow-up photometric measurements of CanX-7 shows an increase in its body rate between 0.6-1.7 rpm suggesting torques acted on CanX-7. This behavior was expected and will continue until the spacecraft aero-stabilizes due to increasing air density at lower orbital altitudes.

INTRODUCTION

Small satellites are showing great promise for widespread use in both private and government space systems. However, a recurring issue is that their compact form factor makes them inherently long-lived in orbit increasing their chance of becoming long-lived space debris. Due to small satellite's relatively high ballistic properties, this class of space vehicle can dwell in orbit for hundreds of years exceeding the guidelines of the Inter Agency Debris Coordination Committee (IADC) which recommends deorbiting a satellite within 25 years after the end of its mission life [1]. Given small satellites' economic appeal due to their lower cost, and a favorable market environment savoring increased data production, the possibility of increased space debris generation in Low Earth Orbit (LEO) higher than 650 km becomes a distinct possibility.

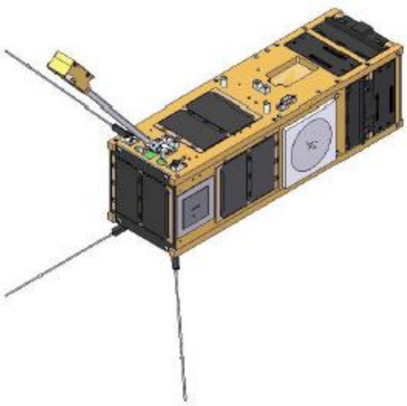
Recognizing this technology gap in deorbiting of small satellites, the University of Toronto Space Flight Laboratory (SFL), initiated the CanX-7 satellite technology demonstration. Upon the completion of its ADS-B (aircraft detection) demonstration mission [2], CanX-7 would deploy a 4 m^2 drag sail to test the suitability of sails to deorbit *nano* and *small*-satellite platforms. Drag sails are an elegant solution to deorbit small satellites as they are lightweight, do not require active attitude control or power from the satellite and do not store energetic propellants which could explode thereby adding to the space debris problem.

The CanX-7 drag sail deployment represented a unique observational opportunity for the Space Situational Awareness (SSA) community to observe a nanosatellite rapidly change shape and size in orbit. As such, Defence R&D Canada approached SFL to coordinate an observing opportunity during the deployment of CanX-7's drag sail segments. On 4 May 2017, the CanX-7 nanosatellite deployed its drag sail segments while simultaneously observed by ground based electro-optical telescopes at

DRDC Ottawa and the Royal Military College of Canada (RMC). These observations were to validate the drag sails' deployment and to characterize the phenomenology of a large drag inducing device's effect on small satellite motion. This paper describes the organization of the observing campaign working in collaboration with a small satellite operator. The detected pre-deployment photometric characterization of CanX-7 is described serving as a baseline reference for the drag sail deployment events. The photometric attributes of the CanX-7 drag sail deployment are described, and the post-deployment behavior of the nanosatellite is then indicated. A brief commentary on the orbital evolution of CanX-7 is provided which clearly shows that the drag sails are working as intended.

CANX-7 SYSTEM DESCRIPTION

CanX-7 is a 3.6 kg, technology demonstration nanosatellite adhering to the 3U cubesat standard with prismatic bus dimensions of 10x10x30 cm (see Figure 1 left). CanX-7 uses an active magnetics-only attitude control scheme where any spacecraft body vector can be aligned with Earth's natural geomagnetic field lines in orbit providing coarse attitude-control for the technology demonstration mission [2]. CanX-7 was configured with an L-band ADS-B receiver for aircraft monitoring developed by RMC. The nanosatellite is controlled from SFL's ground station using UHF/S-band based telemetry and command. CanX-7 was launched into a 700 km 10am sun synchronous orbit on 22 September 2016



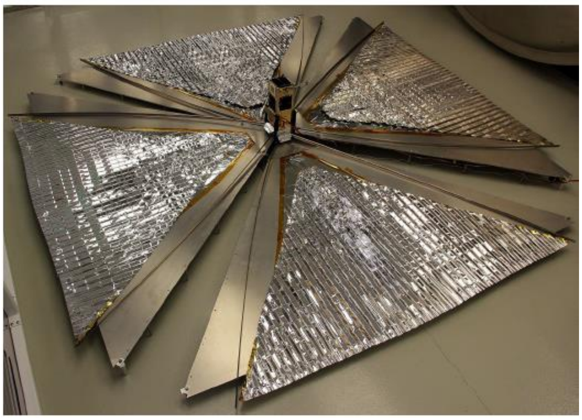


Figure 1. (Left): Artist rendering of CanX-7. (Right): Deployed drag sail segments during testing at the University of Toronto Space Flight Lab. Image credits: University of Toronto Space Flight Laboratory

The drag sail is portioned into four triangular segments each of ~1m^2 cross sectional area. Each drag sail is individually deployed by initiating a burn wire releasing spring tension deploying the sail segments outward. During sail deployment CanX-7's attitude is set in a passive configuration allowing the spacecraft body to react naturally to sails' unfurling. Each of the drag sails is instrumented recording tension and extension during the sail deployment allowing SFL engineers to validate the drag sail design in orbit. After deployment and a reduction in satellite altitude, the drag sails start a shuttlecock effect orienting the sails in the direction perpendicular to its orbital velocity.

MIXING SSA OBSERVATIONS WITH NANOSATELLITE OPERATIONS

Ground-based characterization of CanX-7 would occur in three phases in 2017. The first phase occurs months prior to the drag sail release. Repeated and frequent pre-deployment photometric observations are collected to understand the *typical* photometric behavior of CanX-7 when observed from the ground. This a-priori background knowledge helps differentiate brightness changes due to the release of the drag sails during their deployment phase.

Sail deployment is the second phase and is complex due to several observing and operating constraints and is short duration, lasting 2 orbital revolutions. This phase requires the observation of the nanosatellite while working with the satellite operator. This type of interaction is very infrequent as SSA observations are usually performed separate of operator involvement. Satellite operator requirements are added to observing requirements making the observations more complex. One such operator requirement was that the drag sail to be commanded deployed at a high elevation angle with respect to the SFL ground station. This helps ensure that the radio link between SFL and CanX-7 is maintained as the drag sails could potentially ‘shade’ CanX-7’s antennas. In addition, the four drag sails were deployed in pairs opposite one another on two separate high-elevation passes in order for SFL to downlink sail deployment telemetry (to monitor sail deployment progress) and offer two opportunities for ground telescopes to observe the deployments. This adds a time constraint for the optical observers who must ensure they acquire, detect and track CanX-7 within a small 7-minute observing window shortly after CanX-7 exits eclipse and becomes visible.

The third phase is post-deployment observations of CanX-7 after the sails have unfurled and the nanosatellite has begun its descent into lower orbital altitudes. This phase will last several years. Some initial measurement tracks collected on CanX-7 within 35 days of sail deployment are already showing some evidence of interesting dynamic motion.

The ground-based electro-optical sensors observing CanX-7 requires that they operate during night-time and that the skies are clear during acquisition. In addition, the nanosatellite needs to be sunlit such that the telescopes detect sunlight reflected from the satellite surfaces. A mechanical limitation of the observers is that the telescopes observe CanX-7 with ~ 45 degrees elevation passes. This helps eliminate the need to cross the meridian (the North-South line) causing the German equatorially mounted* telescopes to lose precious observing time during the 7 minute passes. If the passes of CanX-7 crossed the meridian the telescopes would incur 2-3 minutes of reacquisition time limiting the observation period to conduct sail deployment.

Since the sail deployments were one-time events, two geographically-close sensors to the SFL ground station were used to observe the deployments collaterally. Collateral sensors help reduce the risk of individual equipment failure or cloud obscuration during critical observations. The primary sensor configured for this observation campaign was the DRDC Ottawa Space Surveillance Observatory, a robotic SSA research sensor based on the Ground Based Optical (GBO) infrastructure developed in 2005 [3]. The instrument consists of a 35cm telescope coupled to an Andor iXon 888 EMCCD camera operating at 20 MHz. In this configuration the instrument acquires ~200 frames/minute. Tracking of CanX-7 uses the daily updated two-line orbital elements for CanX-7 available from Spacetrack.org [4] and is fed as a continuous set of azimuth-elevation corrections sent to the robotic telescope mount.

Figure 2. Defence R&D Canada Ottawa’s Robotic Space Surveillance Telescope (Image credits: Defence R&D Canada).

The collateral sensor used in this experiment was one of the three telescopes located at RMC. The RMC telescope is configured similarly to the DRDC instrument except an Apogee Alta U42 CCD detector is coupled to the prime focus of the instrument. The favorable close geographic separation of

* *German equatorial mounts* are a two-axis mechanical mount design with its declination axis offset from the hour-angle axis

SFL, DRDC and RMCC enabled the two ground-based telescopes to simultaneously view CanX-7 during its passes over Canada while TT&C was maintained with SFL (see Figure 3).

In winter-spring 2017 CanX-7's orbit flew out of eclipse during its easternmost passes over Canada. This caused a two-minute delay in observations by ground telescopes until CanX-7 was fully illuminated (optical Acquisition of Signal – AOS). Once sunlit, brightness observations of the nanosatellite were acquired. Once the satellite lowers to the horizon (~10 degrees) optical detection is discontinued (optical Loss-of-Signal - LOS). This pattern was repeated for the predeployment characterization of the nanosatellite. During sail deployment, once CanX-7 rose to maximum pass elevation the command to deploy the drag sails was issued and ground sensors monitor for brightness changes. Figure 3 shows CanX-7's pass geometry relative to eastern Canada. The green segments represent portions of CanX-7's orbit which are sun illuminated which are detectable by the ground telescopes.

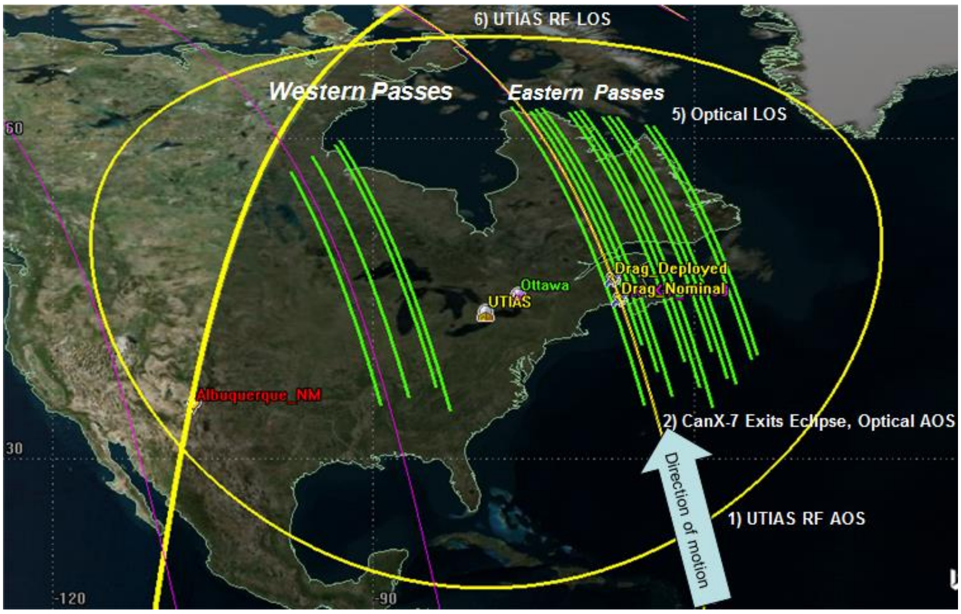


Figure 3. Orbital passes of CanX-7 (green) relative to UTIAS (SFL) and Ottawa sensors. SSRAL (not shown) is centered between UTIAS and Ottawa.

OBSERVATIONS

Photometric observations were collected on CanX-7 in three phases in 2017. The dates of observation are summarized in Table 1 with their respective eastern and western pass distribution identified. Sample imagery collected by the DRDC Ottawa telescope is shown in Figure 4. The dot in each image of Figure 4 is CanX-7 where the intensity of the detection is a measurement of the nanosatellite's photometric brightness. Background streaks are caused by stars trailing across the detector field during the short exposure (0.6 second) imagery.

Table 1 – 2017 CanX-7 Observation Summary expressed as Julian Day of year (JDay)

Observing Phase	Eastern Passes	Western Passes
Pre-deployment	J104, J113 J119	J099, J104, J109, J113, J115, J117
Sail Deployment	J124	J124
Post-deployment	-	J148, J159

Figure 4. Photometric observations of CanX-7 during eastern passes measured by the DRDC Ottawa sensor

PRE-DEPLOYMENT CHARACTERIZATION

The pre-sail deployment light curves of CanX-7 are shown during eastern (Figure 5) and western (Figure 6) passes measured with respect to the DRDC Ottawa Space Surveillance Telescope. Photometric measurements are range-normalized by adjusting the detected magnitude by $+5log_{10}(R/R_0)$ where R is the slant range in kilometres and R_0 is the normalization range. The normalization range for LEO satellites is defined to be 1000 km. The plots are expressed against Sun/Target/Observer phase angle in order to characterize different orbital passes against a common observing reference.

CanX-7's brightness is typically magnitude 12 with some glinting visible in its light curve around 55° and 90°. A noticeable contrast between the eastern and western passes is that eastern passes tend to have relatively flat, monotonic light curves while western passes exhibit significant glinting behaviour at high phase angles attributed to the Fresnel effect. As several of the western pass light curves tend to show this effect it was decided to observe the first sail deployments during the eastern passes at lower phase angles to help differentiate body induced or sail-induced photometric changes.

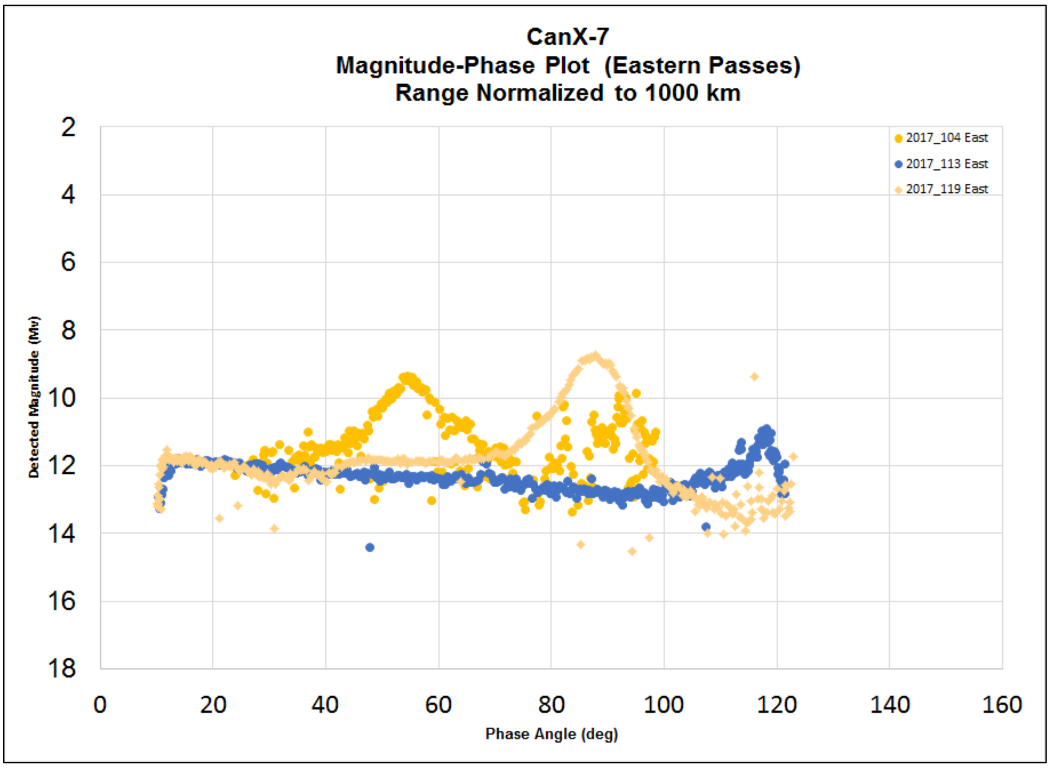


Figure 5. Photometric observations of CanX-7 during eastern passes measured by the DRDC Ottawa sensor

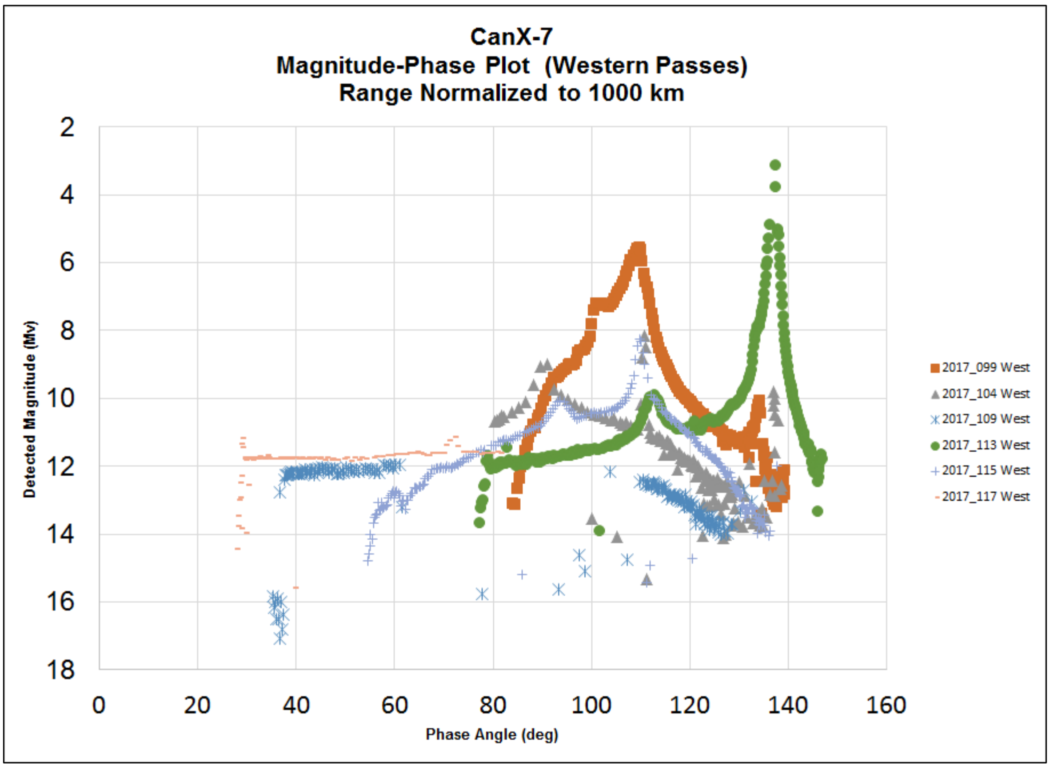


Figure 6. Photometric observations of CanX-7 during western passes measured by the DRDC Ottawa sensor

SAIL DEPLOYMENT OBSERVATIONS (2017-J124)

On 4 May 2017 clear skies and favourable pass geometry set the stage for the drag sail deployment and ground-based observations. A live teleconference between SFL, DRDC and RMCC was arranged to ensure that the SFL satellite operations team and the two ground-based observers were coordinated for the sail deployment. At 01:21 UTC, CanX-7 exited Earth's shadow and the ground telescopes measured reference photometry on CanX-7 for about two minutes. When CanX-7 neared maximum elevation, SFL commanded the first drag sail deployed. Figure 7 shows the detected photometry of the -*Z* and +*Z* drag sail deployments and Figure 8 shows the +*X*, -*X* sail deployments.

In Figure 7 the deployment of the –*Z* drag sail is very apparent as a brightness step near the 82.6-minute mark. Both DRDC and RMCC observations show this step change in brightness. The RMCC observations do not show the same detected magnitudes of CanX-7 and is attributed to the nearly 7° difference in observing geometry on any given surface facet of the nanosatellite compared to DRDC's observation line-of-sight geometry. The subsequent +*Z* sail deployment did not show an obvious step change in brightness however a small inflection in the light curve is visible possibly indicating a change of body rate of the satellite. Soon afterward, a strong increase in CanX-7's brightness was observed, and many ground-based images were saturated at both DRDC and RMCC telescopes. CanX-7's reflectivity became noticeably higher and was observed to be near magnitude 4 after the second sail deployment. CanX-7 became naked-eye visible for a short period of time until the satellite moved toward the horizon.

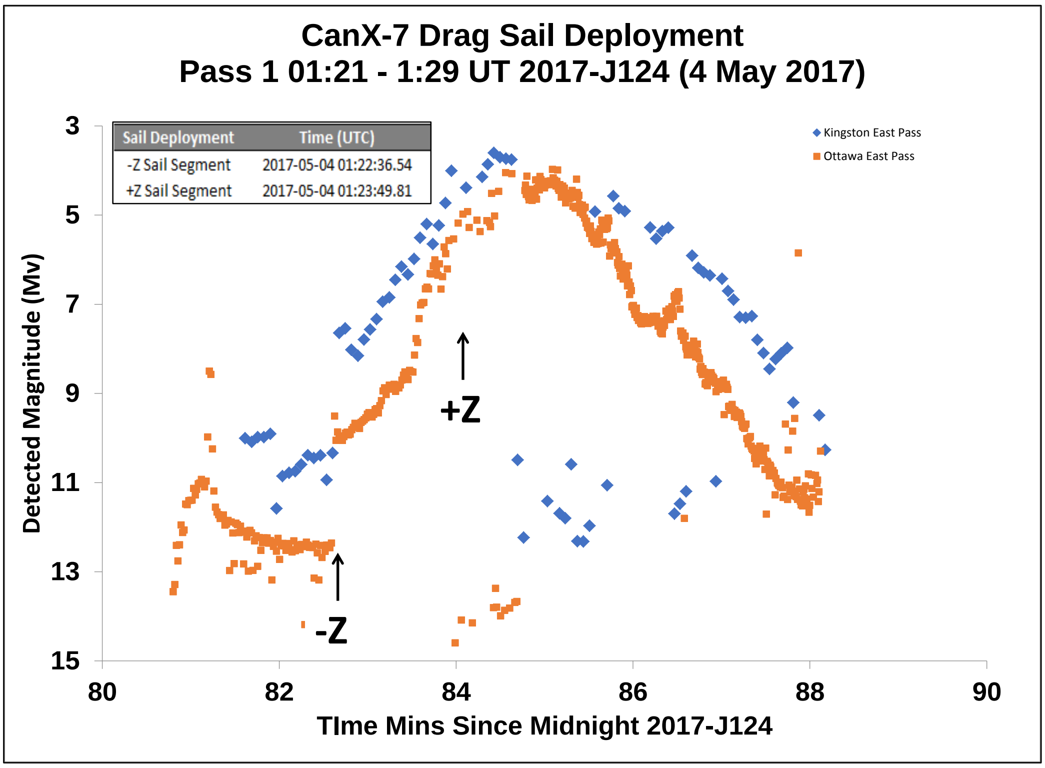


Figure 7. Photometric observations of CanX-7 during the first two sail deployments of CanX-7. Sail segment deployments are marked.

After a pause of 1 orbital revolution the ground-based observers resumed measurements on the nanosatellite where the second pass' light curve shown in Figure 8. The next two drag sails would be observed under high phase angle observing geometry. In this case, the ground-based observers are observing CanX-7 on its shadowed side, making it fainter. An interesting feature of Figure 8 is the near-periodic behaviour of the photometric measurements suggesting that CanX-7 acquired some angular rate after the first two drag sail deployments. At 180.3 minutes past midnight the -*X* sail was deployed and, 90 seconds following, the +*X* sail. CanX-7's light curve in Figure 8 shows behaviour consistent with an object with body angular rates. Both drag sails did not show the stepped behaviour apparent during the -Z sail deployment. The presence of small quasi-periodic glints suggests that CanX-7 acquired some body rotational motion causing oscillation in CanX-7's light curve. An alternative explanation for these small glints could be due to the apparent motion of reflected sunlight moving over the surface of the newly unfolded, wrinkled, drag sail causing the brightness variations.

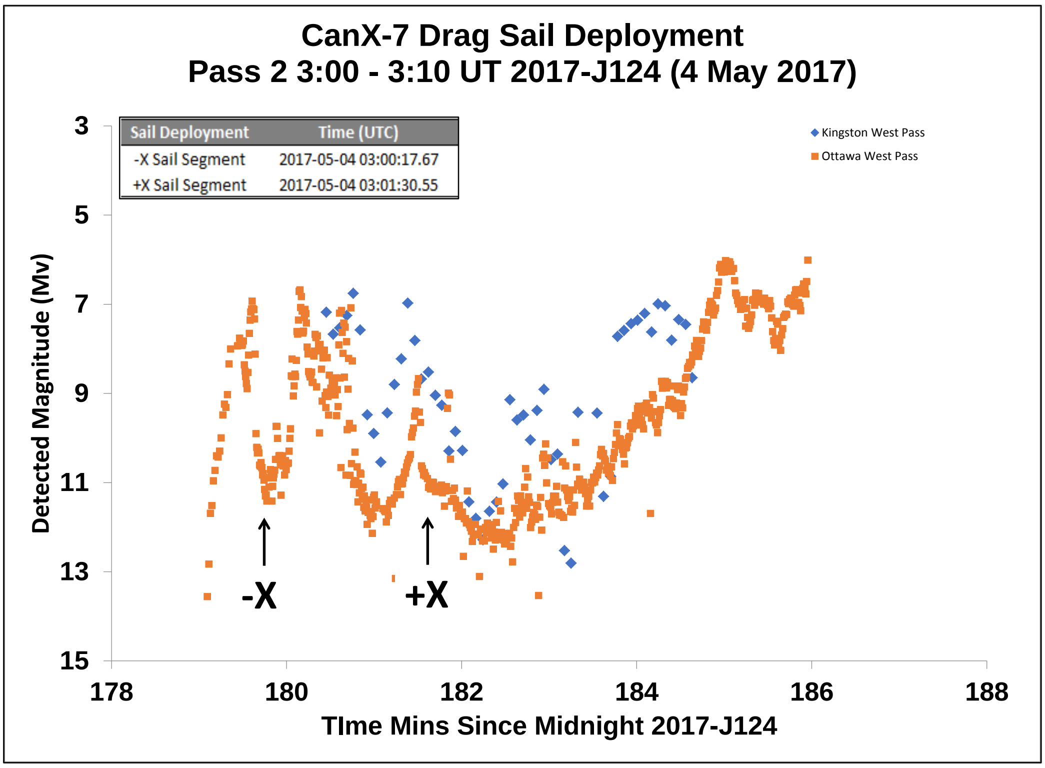


Figure 8. Photometric observations of CanX-7 during the last two sail deployments of CanX-7. Sail segment deployments are marked.

POST-DEPLOYMENT CHARACTERIZATION

Following CanX-7's successful drag sail deployment, a two-week period of persistent rain and cloud cover over eastern Canada prevented follow-up observations. Collaborating observers in the United Kingdom [5] indicated that periodic motion was observed suggesting a body rate of 1 rpm. A full 35 days after CanX-7's sail deployments DRDC Ottawa performed follow-up observations on CanX-7 resulting in the light curves shown in Figures 9 and 10. Both light curves show suggest strong periodic motion of CanX-7 as the oscillating behaviour is a clear sign of rotational motion of a LEO satellite body. Observations from J148 (Figure 9) suggests that a CanX-7's rotational period of 1.7 rpm was observed. This validated the UK observer's findings and also suggested that the vehicle was spinning up, possibly due to torques on the drag sails. Solar radiation pressure, or possibly atmospheric drag torques may have caused the nanosatellite to rotate due to these torques exerted through the cantilevered drag sails.

Oddly, 11 days later, measurements collected on J159 (Figure 10) suggested that the rotational rate of CanX-7 slowed to ~0.6 rpm. In that time, SFL's satellite operations team detumbled the satellite to help maintain a consistent radio telemetry link with CanX-7's ground segment. As such, the light curve behaviour is highly contrasted against the measurements from J148. After detumble, SFL decided to allow the satellite's attitude to evolve naturally to help understand the behaviour of a long-lived drag sail for their flight heritage characterization purposes.

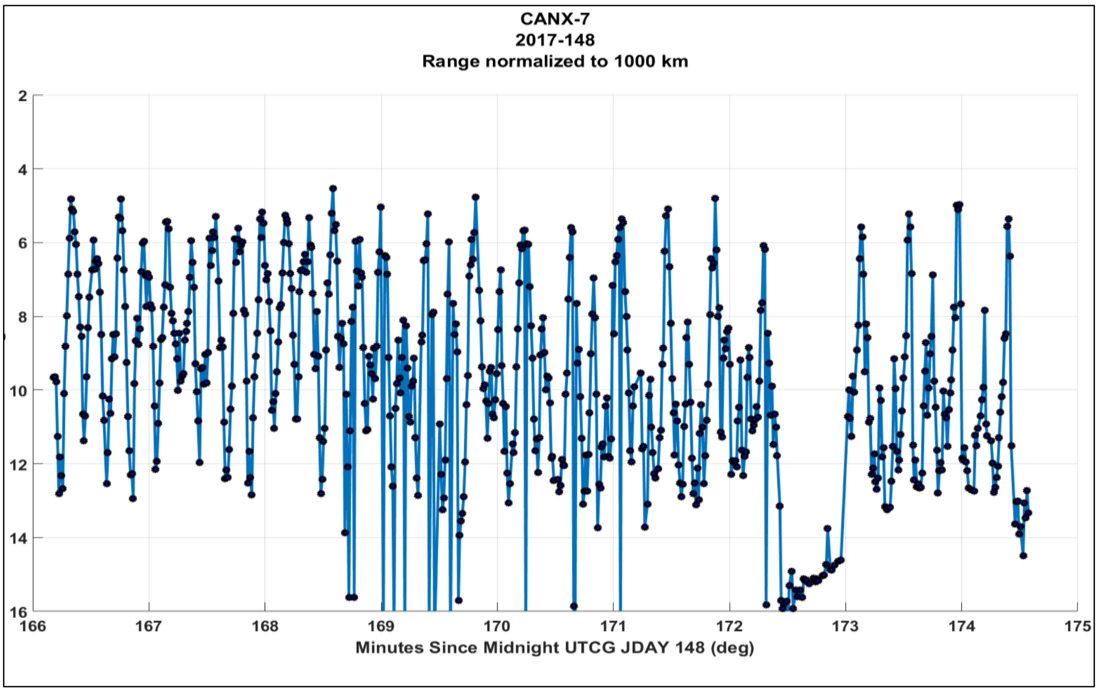


Figure 9. CanX-7 light curve measured by DRDC Ottawa on 2017-J148

Figure 10 shows an unexpected pattern of brightness behaviour from CanX-7. Two smooth glints are followed by one single, narrower, noisier glint and this pattern repeats throughout the 2017-J159 measurements. This is unexpected as the four fully-deployed drag sails should exhibit a dominant four-glint repeating pattern throughout the pass. The measurements suggest a 3-glint pattern which is unexpected. The pattern does not suggest that drag sail did not deploy as there is no lull or missing beat in the light curve. SFL's satellite telemetry does not suggest that any one of the sails did not deploy. Follow-up observations of CanX-7 are planned for spring 2018 to determine if this behaviour is still being exhibited.

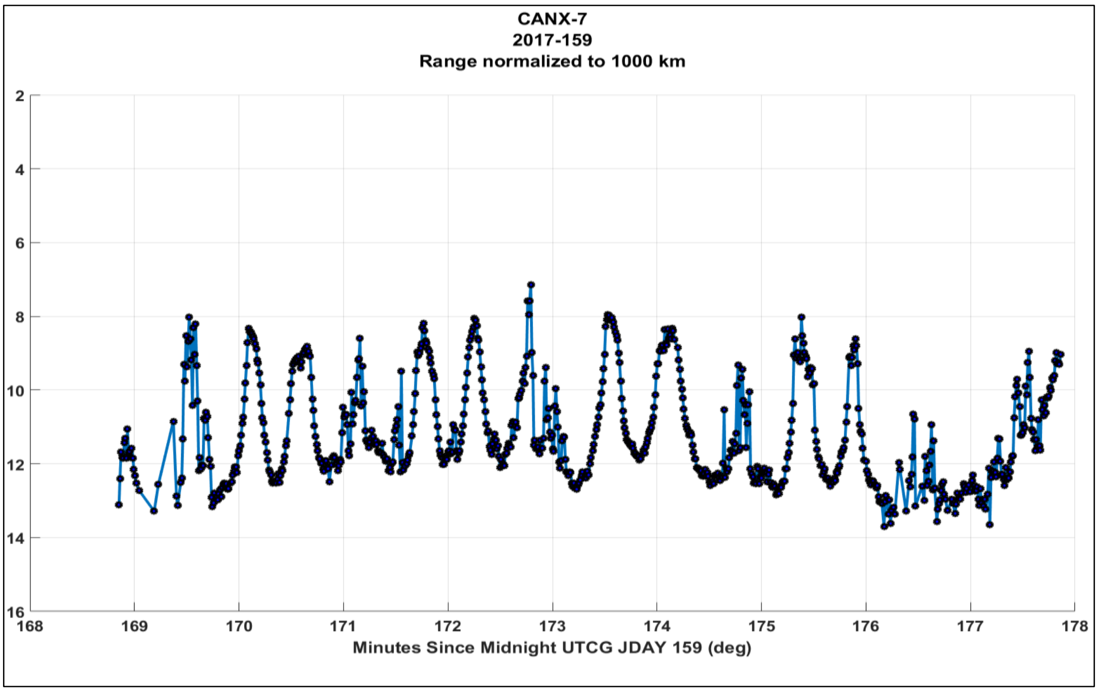


Figure 10. CanX-7 light curve measured by DRDC Ottawa on 2017-J159

ORBITAL EVOLUTION OF CANX-7

Within a few days of the drag sails' deployment the orbital decay rate of CanX-7 increased from 1 m/day to ~45 m/day. Figure 11 shows the change in CanX-7's orbital semi-major axis, a proxy for orbital energy, from October 2016 to January 2018 and Bstar - a drag term used to quantify the ballistic coefficient of an Earth orbiting object.

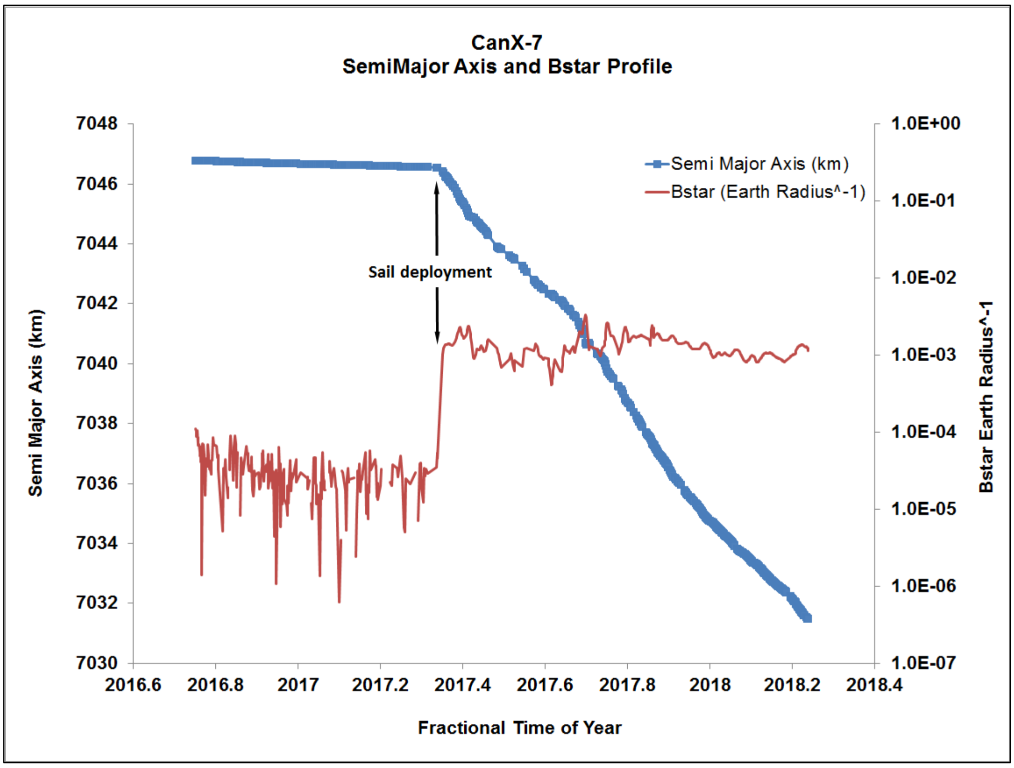


Figure 11. CanX-7's semi major axis and Bstar showing the effect of drag sail deployment

The drag sail's deployment on 4 May 2017 (marked) clearly shows the change in CanX-7's orbital decay rate marked by the knee in the semi major axis curve. The Bstar term shows a nearly 100-fold increase in its susceptibility to atmospheric drag consistent with the large increase in cross-sectional area of the nanosatellite. Today, CanX-7 continues to lose altitude and is anticipated to re-enter Earth's atmosphere sometime in the next 3-4 years. If the nanosatellite was left to decay naturally, without the assistance of the drag sails, it is predicted to take more than 100 years to re-enter Earth's atmosphere. The decay rate of CanX-7 appears relatively stable with some intervals of acceleration and deceleration of the decay rate. This behaviour is attributed to changes in thermospheric density which changes in response to times of enhanced solar activity.

CONCLUSION

Ground based observations of the CanX-7 drag sail were successfully performed in collaboration with the University of Toronto SFL, Defence R&D Canada and the Royal Military College of Canada. These were the first ground-based observations of a small satellite deploying a large sail and photometric validation of deployment of the first two drag sail segments was achieved. The last two drag sail segments' deployment was less apparent from the photometric measurements but did show some light curve inflection behaviour consistent with a change in the angular rate of the satellite-suggesting the sails' deployments affected CanX-7's motion. Subsequent observations of CanX-7 shows strong photometric evidence of angular motion at nearly 1.7 rpm and later at 0.6 rpm after SFL invoked detumble control on the vehicle. SFL will continue allowing the nanosatellite's attitude to evolve naturally enabling the SFL team to further understand and characterize the long-term behaviour of this new class of deorbiting technology. The CanX-7 drag sail is clearly demonstrating its deorbit capabilities with a 45x increase in orbital decay rate realized shortly after the sails' deployment.

The unique mix of orbital operations talent and space situational awareness tracking techniques validated the successful test of a novel Canadian deorbit technology. The mission teams looks forward to following CanX-7's orbital descent until its eventual re-entry sometime in the next few years.

ACKNOWLEDGEMENTS

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