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Operational updates and optimization on Canada's resilient space telescope NEOSSat

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Abstract

The Canadian Space Agency (CSA) has been operating its innovative microsatellite-based space telescope, the Near-Earth Object Surveillance Satellite (NEOSSat), for over 12 years. Built in Canada under a collaboration between CSA and Defence Research & Development Canada (DRDC), NEOSSat is a 75kg microsatellite in a sun-synchronous 780km orbit, serving a dual mission of space astronomy and orbital space surveillance for space domain awareness. Since its 2013 launch, the operations team at CSA's Multi-mission Satellite Operations Centre has ensured continuous operations, overcoming several early-life challenges including multiple on-orbit hardware failures.

Flight software updates have allowed the vehicle to recover operations following on-orbit hardware failures through the development of new attitude determination and control system features. Innovative techniques developed and now operational on NEOSSat include using onboard global positioning system (GPS) sensors for coarse attitude determination and using the satellite's residual dipole to desaturate the reaction wheels. Analyses of flight data are driving further flight software updates to refine operational performance and address issues. Several ground segment enhancements have also improved data quality and responsiveness to science needs. Overall, experience has led to innovative new techniques to improve satellite resiliency and maximize the capabilities of an agile space telescope.

Improved flight performance and advancements in the ground segment software tools – in particular related to tasking and data processing - have allowed NEOSSat to expand the types of science that can be performed from the platform. Initially designed primarily for astrometric observations, NEOSSat is increasingly being used for photometric observations for both space astronomy and space surveillance applications. For its resident space object surveillance (space situational awareness) mission, NEOSSat now routinely observes and characterizes satellites and debris in low-Earth-orbit (LEO) and cis-lunar trajectories, both of which constitute a significant expansion from its initial mission focussed on high-Earth and geostationary orbits. NEOSSat's agility allows it to observe on-orbit events, including conjunctions, proximity operations and missions travelling to or from the Moon and beyond. For space astronomy, the original mission focused on near-Sun asteroid and comet surveys is now complemented by a variety of new science missions, including exoplanet transit photometric follow-up and observing targets of opportunity. CSA manages a Guest Observer program for NEOSSat astronomy based on Canada's Open Science policy, making astronomical data available to all observers immediately after downlink.

The paper will summarize the operational history of NEOSSat, with a focus on recent enhancements that are allowing NEOSSat to maximize its flight performance, responsiveness, data quality and resilience. Altogether, continuous improvement has allowed NEOSSat to maintain its place among the most innovative microsatellites on-orbit today and an important asset contributing to space sustainability and our knowledge of space.

Keywords: space telescope, space astronomy, space surveillance, anomaly recovery, sustainability, resiliency

Acronyms/Abbreviations

ACS: Attitude Control System
CSA: Canadian Space Agency
CDH: Command and Data Handling
C/N0: Carrier-to-Noise Ratio
DRDC: Defence Research and Development Canada

GPS: Global Positioning System
HAA: Herzberg Astronomy and Astrophysics
α: Elevation Angle
b: GPS Antenna Boresight Vector (inertial frame)
MOST: Microvariability and Oscillations of STars (MOST)
MPS: Minor Planet Center
MSCI: Microsat Systems Canada Inc.
NEOSSat: Near-Earth Object Surveillance Satellite
NRC: National Research Council of Canada
ROE: Read-Out Electronics
SEU: Single-Event Upset
SNR: Signal-to-Noise Ratio
SSA: Space Situational Awareness

1. Introduction

The Canadian Near-Earth Object Surveillance Satellite (NEOSSat), launched in 2013, is a microsatellite space telescope equipped with a 15-cm optical visible light instrument with a dual mission supporting space astronomy and space situational awareness (SSA). The mission is jointly operated by the Canadian Space Agency (CSA) and Defence Research and Development Canada (DRDC) from CSA's Satellite Operations Centre in Longueuil, Québec. At launch, NEOSSat was placed into a dawn-dusk 785 km altitude orbit to search for Near-Earth space surveillance and track asteroids/comets in the inner solar system [1] and space surveillance mission comprised the High-Earth Orbit space surveillance (HEOSS), tracking Earth-orbiting satellites and debris [2]. Observation time on NEOSSat is shared equally between space astronomy and space surveillance research advanced techniques in tracking satellites and debris in Earth orbit. Despite early challenges that threatened the mission's viability, NEOSSat has emerged as a great success for Canada in space surveillance and space astronomy through resilience and innovation, performing increasing impressive science in both domains far beyond its initial two-year design life. Furthermore, a number of recent enhancements in both flight software and ground segments tools continue improving the mission's science performance.

The astronomy component of the mission initially focused exclusively on the near-Sun surveys for the detection and tracking of asteroids and comets within the inner solar system, contributing to planetary defense, but has since expanded to cover broader celestial monitoring efforts, including variable star photometry for, among other investigations, exoplanet transit candidate confirmation. Astronomers apply for NEOSSat time through the NEOSSat guest observer program [3]. In parallel, the space surveillance research and development component, initially expected to cover only high-Earth orbit, now enables the tracking of satellites and space debris in several orbital regimes from low-Earth orbit to cis-lunar, addressing growing concerns over space traffic management and orbital debris mitigation. Observation time aboard NEOSSat is equally divided between CSA and DRDC, facilitating a collaborative framework for both scientific inquiry and national defense research. The mission continues to deliver high-value scientific and operational data, establishing itself as a significant asset in Canada's space capability portfolio in support of space sustainability. Recent advancements in both onboard software and ground segment tools have further enhanced its performance and applicability to science and space sustainability.

2. NEOSSat Satellite and Ground Segment Design

2.1 NEOSSat Satellite Design Summary

NEOSSat was designed for quick and accurate all-sky target acquisition and precision pointing to allow stable imaging of many different science targets daily. It has four reaction wheels, three torque rods managed by single controller for momentum desaturation, solar panels on all six sides, two transponders for ground communications on opposite faces, two GPS units on opposite faces, one fine sun sensor, one magnetometer, and its primary optical payload, a 15-cm aperture Maksutov optical telescope with a 0.8 degrees field of view and two sets of readout electronics sharing the optical boresight, each collecting light on identical 1024x1024 pixel CCDs at 3 arcseconds per pixel. One readout electronics set serves as the primary science payload while the second is configured as the custom narrow-field star tracker, allowing high precision pointing. The design is based on the successful Microvariability and Oscillations of Stars (MOST) space telescope [4], the first space telescope built in Canada.

In the MOST mission, the satellite would point accurately at the same target star for months, so the applicable section of star catalogue used for Fine Pointing could be uploaded at tasking. With NEOSSat, however, all-sky pointing is expected with the satellite chasing different targets across the sky every day. Consequently, the star tracker software had be significantly upgraded compared to MOST and NEOSSat maintains a complete Tycho-2 star catalogue onboard to support its operations.

Attitude determination and control begins with a coarse phase, where coarse attitude sensors are used to obtain an initial attitude solution, which then seeds the star tracker for fine attitude determination and control. In addition to providing power for the satellite, the solar panels also serve as a coarse sun sensor on NEOSSat, based on the currents detected on each panel. At the start of the mission, the solar-panel-based coarse sun sensor and the magnetometer served as the primary coarse sensors, given challenges calibrating the fine sun sensor. After a period of on-orbit calibration, these coarse sensors were sufficient to achieve coarse pointing with enough precision to acquire the star tracker and transition to Fine Point.

NEOSSat's Fine-Point mode provides a very high degree of pointing accuracy and stability, enabling long duration exposures of key astronomical targets for astrometry or photometry. For discovery and characterization of faint celestial objects, NEOSSat has demonstrated to detect targets up to magnitude 19.5 in ideal light conditions and with appropriate noise reduction through post-processing. For fast-moving objects, such as the resident space objects being tracked for space situational awareness, the attitude control system (ACS) also provides a Fine-Slew mode, allowing images to be taken while accurately tracking the moving target at a configurable rate. Fig. 1 provides a drawing of NEOSSat and its body frame coordinate system.

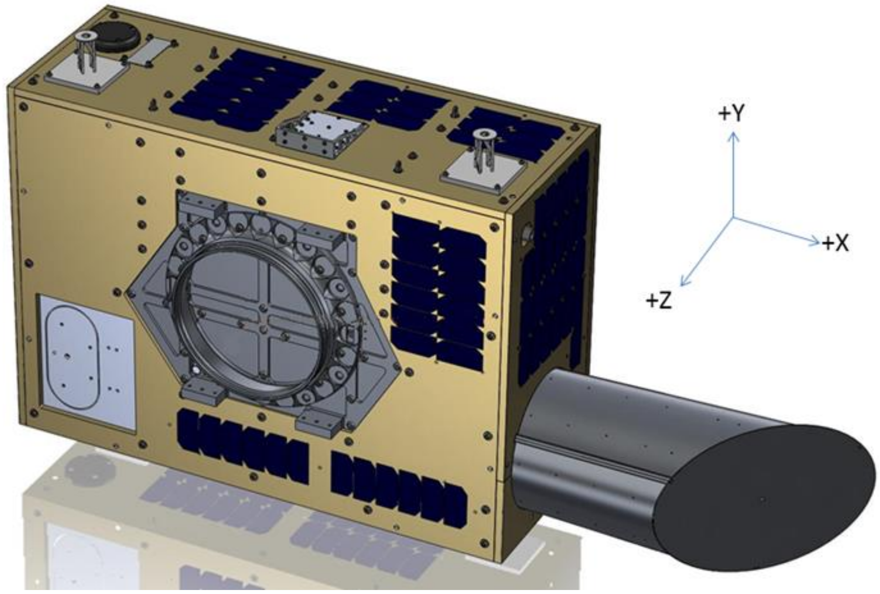

Fig. 1 NEOSSat drawing with body coordinate frame definition (Credit: CSA)

NEOSSat's extended baffle design allows near-Sun imaging, designed to allow operations down to 45 degrees solar elongation. In practice, the baffle was found to perform better than expected, with Fine Point observations successfully being taken down to 34 degrees solar elongation. During satellite eclipse periods, when the Earth can also be used as a baffle for parts of the orbit, even smaller solar elongations, down to 14 degrees, can be achieved.

2.2 NEOSSat's Operational Ground Segment

Followed a successful launch of NEOSSat in 2013, the early NEOSSat passes were supported by Canadian S-band ground stations in St-Hubert/Canada and Saskatoon/Canada as well as German S-band ground stations in Walheim/Germany and O'Higgins/Antarctica, operated by the DLR. Later, NEOSSat was also supported by new S-Band ground stations managed by Natural Resources Canada (NRCan) in Inuvik/Canada, Gatineau/Canada and

Prince Albert/Canada. These Canadian ground stations (Fig. 2) provide increased coverage and contact opportunities. Telecommands, telemetry and science data are all exchanged over the same S-Band links. The central hub for operations is CSA's Multi-Mission Satellite Operations Centre in St-Hubert, Québec. All operations are conducted from this centre, from tasking to data production and delivery. The CSA Satellite Operations Centre and associated ground stations are also used to operate other Government of Canada satellites, notably SCISAT and the three satellites of the RADARSAT Constellation Mission.

Fig. 2 NEOSSat Ground Stations and Operation Centre (Credit Background: GISGeography.com, Overlay: CSA)

2.3 NEOSSat's Tasking and Data Production Workflows

Astronomers and defence scientists share time on NEOSSat, nominally with 50% time allocation for each top level mission: space astronomy and resident space object surveillance. The astronomy time is managed by CSA, on behalf of astronomers participating in CSA's Guest Observer program for NEOSSat. The experiments supported since the start of the Guest Observer program are listed in [3]. The resident space object space surveillance mission is managed by DRDC, which also manages a variety of experiments under this program, with a summary provided in [2] and [5]. Schedule integrators representing each top level science mission prepare daily schedules for NEOSSat according to agreed-upon time windows. Each user-provided science schedule typically includes a variety of experiments related to either the space surveillance or space astronomy mission, with activities timing coordinated between different mission types on a daily basis using a shared calendar. These NEOSSat science schedules are prepared using specialized tools developed in-house to facilitate identifying the visibility to the applicable targets of interest while respecting applicable constraints. Once NEOSSat science schedules are finalized on the user side, the schedules are provided to the operations team at CSA's Satellite Operations Centre, typically a day before planned execution to maintain agility and responsiveness to emerging priorities. The satellite operators, after validating the schedules against various constraints, merge incoming schedules into one master schedule as part of the planning/tasking process. Schedules are typically uploaded once per day covering 24 hours and downlink passes are typically taken 4-5 times a day, collecting telemetry to monitor satellite health and performance and also collecting science data to be processed and delivered to applicable repositories. Astronomy data is delivered to CSA's open data portal [6] and the Canadian National Research Council's Canadian Astronomy Data Centre (CADC) [7], with no proprietary period. The space surveillance data is archived and accessible to DRDC and CSA scientists with stricter distribution controls. The CSA operations and sustaining engineering teams analyse in-flight performance and develop flight software/parameter updates to improve the spacecraft's performance and maximize the science output.

3. Commissioning Experience and Innovative Recovery Operations following Hardware Failures

3.1 NEOSSat Commissioning Experience

During NEOSSat's commissioning period, the operations team characterized the satellite and payload's performance across many parameters, as detailed in [8]. Given important design and operational changes from MOST, in order achieve routine all-sky Fine Pointing acquisition using only the onboard star catalogue and the required tracking accuracy in track-rate mode, many software updates were needed, as detailed in [5]. During investigations of the attitude control performance, the operations team discovered and characterized an important residual magnetic dipole, not previously identified in pre-launch testing and subsequently improved tracking performance in between star tracker samples by implementing this dipole torque as a feed-forward torque within the attitude control system. The residual magnetic dipole is theorized to be due to the material used in the telescope baffle. Unbeknownst to the team at the time, this residual magnetic dipole would eventually become an essential characteristic of the satellite, used to save the mission when the second of two critical hardware failures occurred.

3.2 Innovative Recovery Operations following Hardware Failures

In 2016, NEOSSat experienced two significant on-orbit hardware failures affecting its Attitude Control System (ACS): the loss of the magnetometer which was a crucial attitude sensor and a malfunction in the torque rod controller. The first failure impacted NEOSSat's ability to produce the magnetic field direction vectors used by the coarse attitude determination module to determine the spacecraft orientation. As a result, NEOSSat was unable to perform the coarse pointing necessary before transition to fine pointing for target acquisition and tracking. The second failure impeded effective momentum desaturation to make enough head room for a slew or mauver as normal science operations needed because the torque rod controller precisely regulated the current supplied to the torque rods, ensuring the generation of the correct amount of torque to adjust the spacecraft's orientation by interacting with other components like reaction wheels. While the team developed software workarounds to recover coarse pointing, a second failure occurred that again threatened the mission's viability: loss of the torque rod controller. This failure prevented the use of all three torque rods used to desaturate momentum built up in the reaction wheels to recover headroom required for slews.

Both failures, which impacted components without onboard redundancy, led to highly innovative recovery efforts through flight software updates. The software team developed creative solutions that leveraged existing onboard equipment to revive critical Attitude Control System (ACS) functions, specifically orientation sensing for coarse attitude determination and a creative new strategy for reaction wheel momentum desaturation. The first imaginative solution was to make use of onboard Global Positioning System (GPS), normally used only for orbit determination, to build a new GPS orientation vector as a coarse attitude measurement to replace the lost magnetic field measurement vector in the coarse attitude determination module. The second innovation utilized the satellite's internal residual dipole to dump momentum for desaturation implemented through a newly developed DESAT control mode, with the newly developed GPS attitude sensor, sun sensor and rate sensors aiding in the process. These efforts not only recovered NEOSSat science operations, but also expanded the knowledge base in attitude determination and control systems, demonstrating flight heritage for satellite attitude determination using GPS data and introducing a novel momentum dumping strategy.

3.3 Magnetometer failure and building a new attitude sensor using NEOSSat's GPS

NEOSSat's magnetometer was the first on-orbit failure that risked ending the mission. Based on timing, this failure was attributed to the harsh space environment at the South Atlantic Anomaly. Efforts to reboot, recover, or recalibrate the magnetometer were unsuccessful, confirming that the instrument was irrecoverable. Per the original design, the single-string magnetometer, in conjunction with the sun sensors, delivered the coarse orientation measurements required by the Extended Kalman Filter (EKF) for initial attitude determination required to seed the star tracker search algorithms before transitioning to the fine pointing mode for all mission science operations. After NEOSSat lost utilize of its magnetometer, all attempts at routine coarse pointing operations failed, and the satellite could only be left in a tumbling state. Fortunately, communications with the satellite remained, as all-sky pointing requirements meant that NEOSSat transponder configuration could allow it communicate with its ground stations from any arbitrary orientation. Operators would carefully monitor satellite temperatures during contact opportunities and induce spins manually by commanding the wheels to change the tumble towards a safer, more favorable tumble, particularly to avoid batter overheating. With no closed loop pointing control, no science could be performed and simply maintaining satellite health and safety was onerous. To recover attitude determination and restore closed-loop Fine Pointing for mission science operations, a new in-flight solution had to be developed.

After numerous innovative solutions were considered by the NEOSSat engineering team to recover coarse attitude determination, the final decision was to repurpose the onboard GPS units as a coarse attitude sensor in order to replace the failed magnetometer. This approach, building off research from Wang [9] and Axelrad [10], leveraged data logs on the position and signal strength of the space vehicles (SV) contributing to the GPS solution, along with knowledge of the GPS antenna orientations in the body, to estimate the pointing direction, effectively creating a new attitude sensing method. A simplified view of this approach is illustrated in Fig. 3, where three GPS SVs are visible. NEOSSat's antenna boresight $\mathbf{b}$ is arbitrarily oriented in an inertial reference frame, creating elevation angles α between the boresight and the sightlines to each SV. The measured Carrier-to-Noise ratio (C/N0) from each SV primarily exhibits a cosine relationship with the elevation angle, being maximized when the boresight is directly pointed at an SV. However, this angular relationship is not a perfect cosine due to antenna gain pattern irregularities and mounting effects. Azimuthal variations in the antenna gain pattern are typically small but can become significant in the presence of multipath effects. Consequently, constructing a map of α as a function of C/N0 is necessary. A mapping function was developed to correlate C/N0 with elevation angle, creating a calibration map that accurately represented the antenna gain pattern of NEOSSat's onboard GPS receivers. This map allowed creation of a reference attitude vector that could pair with the GPS antenna mounting vector in body frame. Full details on the new GPS attitude sensor algorithm are provided in [11], which includes many innovations beyond the initial concepts proposed in [9] and [10].

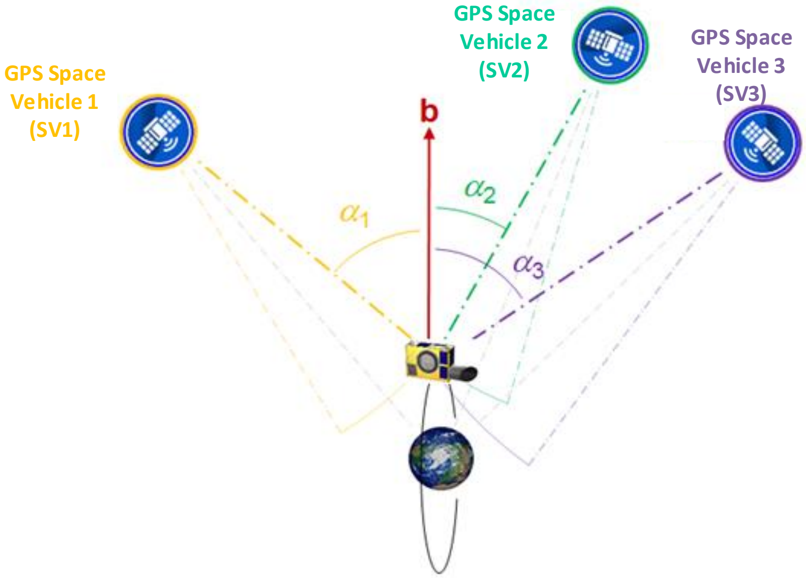

Fig. 3 NEOSSat's Lines of Sight and Angles to GPS Space Vehicles (Credit: CSA)

This new GPS attitude sensor was integrated into the existing attitude determination flight software and flight performance demonstrated that the GPS attitude vector pair served as a suitable replacement for the attitude vector pair provided by the magnetometer. This algorithm's performance within the flight software's attitude determination modules ensured that sufficiently accurate attitude solutions for coarse pointing could be consistently generated using only the coarse sun sensor and the new GPS attitude sensor.

Once the flight software was finalized, uploaded, and activated on orbit, the new attitude control system successfully restored coarse pointing with the necessary accuracy for star tracker acquisition, allowing for the transition to Fine-Point mode and resumption of mission operations. The GPS attitude sensor has been a critical component of NEOSSat's attitude control system, fully replacing the failed magnetometer. It provides attitude vectors with root mean square (RMS) errors within 10 degrees and is generally applicable as a coarse sensor for any satellite equipped with at least one GPS receiver and antenna. Further details on this innovative strategy to repurpose onboard GPS as attitude sensor algorithm and its implementation in flight software are available in [11].

3.4 Momentum dumping through innovative Residual Dipole Desaturation control mode

While the engineering team still was building the new GPS-based attitude sensor algorithm in flight software, NEOSSat was hit with the second major hardware failure when the STM32 microcontroller controls all three torque rods failed. This anomaly resulted in a permanent loss of communication with the torque rods, effectively eliminating the satellite's ability to perform active momentum desaturation required to dump momentum built up in the reaction wheels. Nominally, the attitude control system uses the magnetorquers, energized at the appropriate time and intensity, to provide continuous momentum dumping torques. Without momentum dumping, NEOSSat could not maintain controllability due to momentum buildup in the reaction wheels. Once again, the ability to reliably point to targets was compromised and the NEOSSat mission’s viability was further threatened.

The software engineering team again brainstormed methods to recover the ability to dump momentum. Unlike the case with the GPS attitude sensor, in this case, there was no background literature found with ideas to solve the problem. Reaction wheels operate on satellites by exchanging momentum between the reaction wheels and the body, allowing the attitude control system to generate slews and desired pointing. During these control operations, external disturbance torques continue to apply on the system, induced from residual magnetic dipole and other environmental effects, and the control system absorbs the torque in the reaction wheels to maintain pointing. Reaction wheels having limited momentum carrying capacity, they eventually saturate, leaving the attitude control system with no control authority. Due to conservation of momentum, disturbance torques applied to the system necessarily stay within the system and reaction wheels alone can only transfer momentum, not dump it. Additional external torques are required to reduce/dump the momentum built-up in the reaction wheels. But now the magnetorquers were out of commission due to the failed microcontroller. A new momentum desaturation strategy was needed and no literature presented concepts for this issue.

After much brainstorming, the NEOSSat team developed a novel momentum desaturation strategy known as “Dipole Desaturation”. Recognizing that the dominant disturbance torque was the inherent residual magnetic dipole torque characterized during commissioning, the team proposed to take advantage of this same torque for momentum desaturation. Given NEOSSat’s residual magnetic dipole is fixed relative to the satellite body, the proposed solution required reorienting the spacecraft relative to the Earth's magnetic field such that a torque is applied in a direction that opposed the stored angular momentum vector. This effectively subtracts momentum from the system, creating the required momentum dumping or desaturation effect. Orienting the satellite in the desired direction was feasible because coarse attitude determination and control had been recovered through the innovative GPS attitude sensor and still-functional coarse sun sensor. Because “Dipole Desaturation” requires continually orienting the satellite towards an optimal desaturation target, which changes throughout the orbit as the magnetic field changes, a new control mode would be needed where the control system continually calculates the stored angular momentum vector and the optimal desaturation target vector, and then commands the satellite to continually maintain pointing near the desaturation target to dump momentum. Visually, one can imagine the satellite “swimming” within the magnetic field to optimize desaturation based on the residual dipole.

A key requirement for the “Dipole Desaturation” control mode to be able to maintain continuous pointing towards an optimal desaturation target is for the control system to have enough control authority (low enough momentum in the wheels) to affect the required slews using the reaction wheels. If the reaction wheels are already saturated because the system has too much built-up momentum, a different strategy is needed. To address this situation, the algorithm is augmented as follows: when there is insufficient control authority for closed-loop pointing (knowable by keeping track of the momentum), the “Dipole Desaturation” control mode still calculates the optimal desaturation target vector, but instead of attempting closed-loop control, it simply either reduces or increases in the satellite body tumble, exchanging momentum between the reaction wheels and the body in an open-loop fashion such that more time is spent in orientations close to the desaturation target (i.e., “favorable” orientations) and less time is spent in orientations far from the desaturation target (“unfavorable” targets). The control system reduces time spent in “unfavorable” orientations by transferring momentum to the body and increasing tumble speed and increases time spent lingering in “favorable” orientations by transferring momentum into the wheels and reducing the tumble speed. This open-loop method is clearly slower than closed-loop method, but remains effective to dump momentum and allow transition to closed-loop control for faster desaturation.

Following implementation of this innovative new desaturation method in flight software, simulation and flight performance demonstrated the effectiveness of the method, as shown in Figure 4. Starting from a high-momentum state where this insufficient control authority for closed-loop targeting of the optimal desaturation target, the control system uses the open-loop algorithm alternating between strategically fast and slow tumbles to slowly dump momentum. Once momentum has been sufficiently reduced, the control system is able to switch to closed-loop control and optimize the pointing towards the optimal desaturation vector, resulting in faster desaturation.

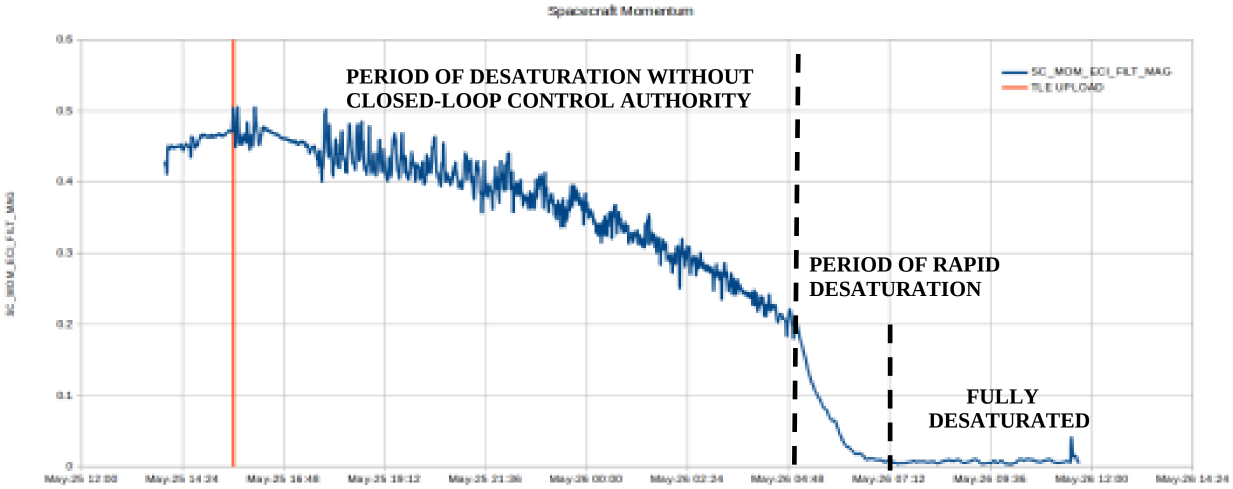

Fig. 4 Flight Performance of NEOSSat “Dipole Desaturation” to dump momentum without torque rods (Credit: CSA)

Since it requires specific pointing targets, the new “Dipole Desaturation” control mode must be deconflicted from regular science operations (pointing at science targets). The new control system can no longer perform continuous desaturation during science operations as it did with the torque rods. “Dipole Desaturation” must be regularly interspersed with science operations to ensure that control authority is recovered for coarse and fine pointing at science targets. But because re-saturation at science pointing targets occurs sub-optimally (due to the arbitrary direction of science targets relative the magnetic field) and desaturation during “Dipole Desaturation” occurs optimally (by pointing towards the continually recalculated optimal “desaturation target”), the majority of the satellite’s time can still be devoted to science activities. Furthermore, scheduling of “Dipole Desaturation” can be scheduled during periods where science targets are either not visible or not desirable due to other constraints. Consequently, although the required addition of regular desaturation periods is not ideal, it does not greatly impact NEOSSat’s science productivity. The new "Dipole Desaturation" control mode introduced to NEOSSat operations is frequently used as a "parking" mode. The user-submitted science schedules for both space astronomy and space surveillance now routinely include periods of "Dipole Desaturation" inserted in between science activities to gain efficiency. Figure 5 shows total spacecraft momentum over two different 12-hour periods featuring routine science activities interspersed with routine “Dipole Desaturation” periods chosen at the scientists’ discretion based on their science activity schedule. Most major decreases in momentum correspond to the “Desaturation” periods, while science activity periods build momentum at different rates based on the satellite’s pointing relative to the magnetic field while pointing at the selected science target. Some targets increase momentum quickly while others are either more stable or might even decrease momentum. In practice, it is rare during nominal science operations with routine “dipole desaturation” for the control system to lose control authority, but it does still happen for some targets at some times. New tools have been developed to better predict the momentum impact of specific schedules to help avoid those situations.

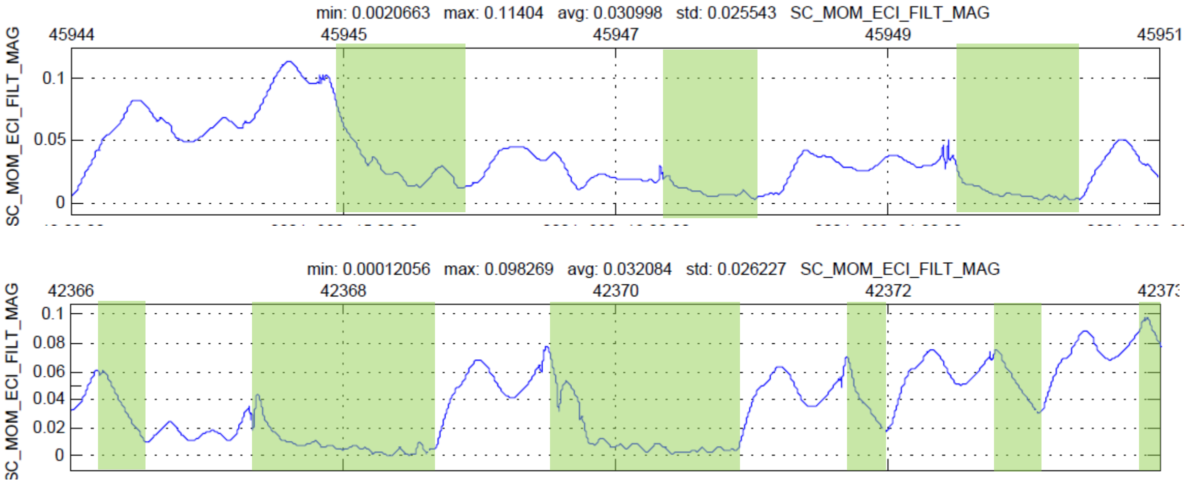

Fig. 5 Total satellite momentum over two 12-hour periods alternating between science periods (uncolored) and “Dipole Desaturation” periods (in green) at user-selected desaturation times (Credit: CSA)

Overall, the development and operational success of the highly innovative “Dipole Desaturation” control mode was a highly commendable achievement for the NEOSSat engineering team. This mode leverages the spacecraft’s inherent residual magnetic dipole to enable momentum desaturation without active torque rods control. The solution has general applicability to other satellites that may lose its ability to desaturate momentum using torque rods or that simply wish to avoid having torque rods on their satellite to reduce mass. The algorithm does depend on retaining some onboard residual dipole (which is normally minimized in design) and having knowledge of the magnetic field throughout the orbit. It should be noted that the algorithm doesn’t require a very strong residual dipole to be effective as long as the resulting torque at the optimal desaturation target is greater than other disturbance torques built up during these operations. However, a smaller residual dipole torque would result in slower desaturation using this method, which might have a greater impact on science. Finally, given the reliance on a sufficiently strong magnetic field, the method is more suitable for low-Earth orbiting satellites (which experience greater magnetic field strength) than geostationary or interplanetary satellites, where magnetic field strength is minimal.

3.5 Further flight software improvements for autonomous anomaly recovery

Inspired by the success of two highly innovate flight software updates to recover NEOSSat functionality, the team continued to explore flight software improvements to improve NEOSSat’s science performance and address some new types of anomalies associated with the new GPS attitude sensor and the new “Dipole Desaturation” control mode. Subsequent flight software, now flying on-orbit, introduced many features and fixes, including:

- Autonomous recovery from certain single-event upset recurring anomalies
- Improved support for detecting and mitigating against the intermittent loss of GPS solutions, as missing or invalid GPS solutions could negatively impact the attitude determination and control system performance, including the new “Dipole Desaturation” mode
- Improved calibration of the GPS attitude sensor by considering individual GPS SV transmitter gains
- Improved performance of the coarse sun sensor by including Earth albedo compensation in its algorithm
- Faster image transfer times from payload to main onboard computer, allowing faster imaging cadence
- Support for exposure times as low as 10 milliseconds

On top of flight software updates, the NEOSSat team has developed an innovative annealing technique to improve the hot pixel and dark noise characteristics of the two CCDs, science and star tracker. Given no onboard temperature control, the CCDs are warmed up during annealing campaigns through satellite orientation control, carefully selecting pointing attitudes that warm up the CCD while maintain battery health and safety.

Implementation of these features and operations improved attitude control performance in both science and desaturation pointing modes, further allowing the expansion of NEOSSat's scientific experiments.

4. Expanding NEOSSat science

The successful on-orbit implementation in NEOSSat flight software of the GPS-based coarse attitude sensor, the "Dipole Desaturation" mode and more features allowed NEOSSat to be saved from cancellation and not only return to its originally planned missions, but also significantly expand on the science activities supported. On the space astronomy aside, CSA established a new NEOSSat Guest Observer program, allowing astronomers across Canada to propose experiments. CSA also committed to a new open data policy for NEOSSat, where all space astronomy data would be published on CSA's open data portal [6] and the Canadian Astronomy Data Centre (CADC) [7] managed by Canada's National Research Council (NRC). On the resident space object surveillance side, the initial NEOSSat mission focusing on high-Earth orbit space surveillance was expanded to start monitoring resident space objects in different orbits, from low-Earth orbit to cislunar orbits. Details of the innovative science experiments supported by NEOSSat are available in [3], [5], [12], [13], [14] and [15]. Figure 6 shows two examples of processed NEOSSat imagery. The left image, taken June 15th, 2019, demonstrates NEOSSat's capability for imaging resident space objects even in low-Earth orbit. From its 800km altitude, NEOSSat was able to image the three satellites of CSA's RADARSAT Constellation Mission (RCM) at 580km altitude, shortly after their launch and before their final orbital phasing. The right image demonstrates the space astronomy mission, shows a processed image of Comet Tsuchinshan-ATLAS (C/2023 A3), from a stack of seventeen raw images taken on October 23, 2024.

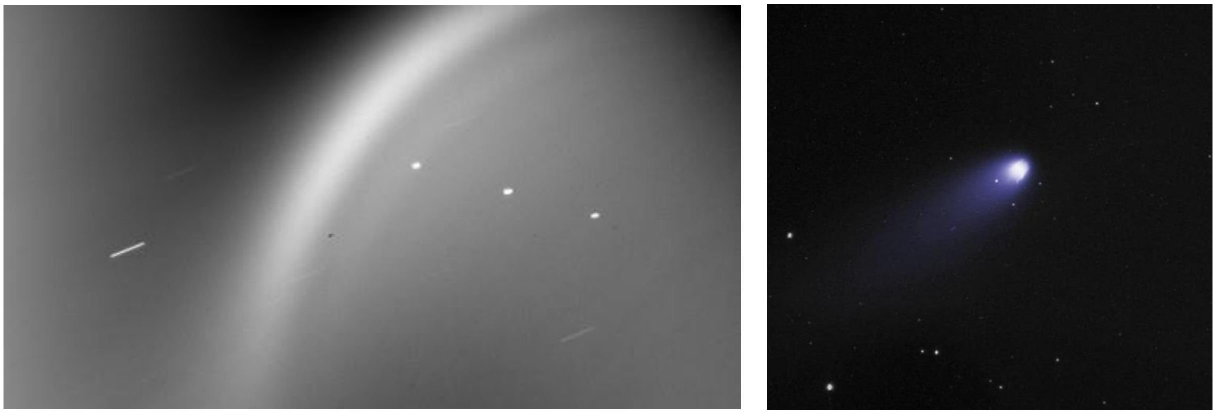

Fig. 6 NEOSSat image of RCM satellites taken June 15, 2019, after launch and before phasing (left), and NEOSSat image of Comet Tsuchinshan-ATLAS (C/2023 A3), processed from October 23, 2024 image stacking (right) (Credit: Canadian Space Agency, Defence Research and Development Canada)

Among the key innovations stemming from the Guest Observer program was experimentation to evaluate NEOSSat's capability for photometry with a view towards follow-up and confirmation of exoplanet transits. In the process, guest researchers developed improved image processing and data production software packages, which led to continuous improvement in NEOSSat's ground segment. These innovations are described in the next sections.

5. NEOSSat Data Production Enhancements for Improved Science Performance and User Experience

5.1 Enhanced FITS Processing Pipeline (n1Fits)

Ground-based image processing to eliminate noise, bias, dark current and artifacts is a normal part of any space telescope mission. NEOSSat is no different, delivering two types of FITS files since the beginning of the mission, labelled "raw" and "clean". However, the original cleaning software from early in the mission had some specific constraints and did not perform all the potential corrections to yield the highest quality imagery. The cleaned imagery was generally suitable for astrometric applications but more would be needed for photometric applications.

Following the launch of NEOSSat's Guest Observer program in 2019, investigators at Bishop's University evaluated NEOSSat's capability for photometry and the detection of exoplanet transits. Starting from the raw imagery, the principal investigator developed new Python code to perform advanced cleaning on NEOSSat images [16]. The new code better removes instrument noise, bias, electronic interference and dark correct through overscan correction and dark processing. The code was used to demonstrate NEOSSat's ability to observe and confirm short period exoplanet transits [14] and long period exoplanet transits [15].

To allow all NEOSSat users to benefit from the enhanced cleaning software, the NEOSSat developed a new image processing pipeline within the CSA Satellite Operations centre, incorporating the photometric Python software package [16] as its central component. The implementation perform the following on all NEOSSat products, when both light frames and dark frames are available:

- Overscan correction for all overscan types (discontinuous or otherwise)
- Clipping (removing the overscan region, post-correction)
- Dark subtraction (when there are matching raster size / exposure length darks)

The new image cleaning pipeline operates after every downlink from NEOSSat, immediately after production of the raw images. The enhanced workflow of the new cleaning pipeline involves many steps, as follows:

1. Sorting the lights and darks into appropriate directories for use in processing ("n1sort.py") and identifying the lists of images to be cleaned in this run. This is also the step that builds the library of darks for a given raster size and exposure length in order for the next step to be able to select the appropriate darks corresponding the lights.
2. Calling the master cleaning process ("n1clean.py") to produce the "cor" and "cord" files
3. Publishing the data to the appropriate image repository ("n1publish.py")
4. Compiling statistics on the NEOSSat's performance in delivering planned imagery ("n1stats.pl")

A more detailed workflow of "n1clean.py" is provided in Figure 7. A key innovation in this pipeline is the ability to carefully select the right set of dark images to produce the best master dark for a given dark correction. In addition to limiting the darks to those with the same raster size and exposure length, the algorithm also avoids using dark frames taken in the South Atlantic Anomaly and applies various filters (that are configurable via a configuration file) to create bins based on temperature, time difference from the light and other quality control checks. By applying these checks before building the master dark, the dark subtraction step is optimized to yield improved image quality.

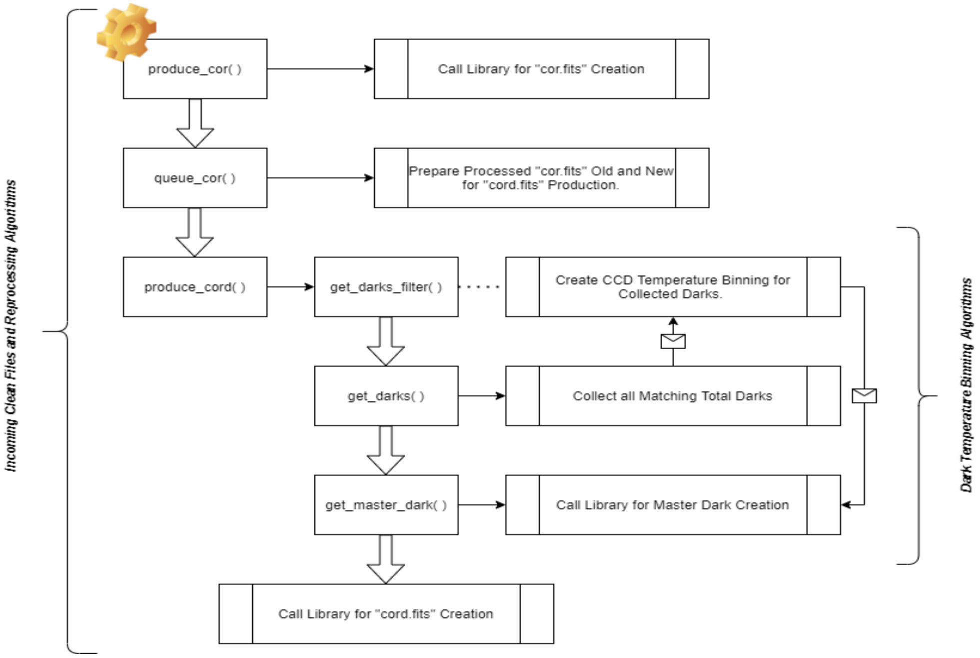

Fig. 7 Workflow for enhanced imaging pipeline to produce "cor" and "cord" images (Credit: CSA)

Figure 8 below demonstrates the newly integrated Python-based image cleaning pipeline by showing side-by-side comparisons of raw, "_cor.fits" (an intermediate product featuring only overscan correction and clipping), and the final "_cord.fits" files, which adds dark correction. The original observation was an image named "NEOS_SCI_2021043141700.fits", observing target exoplanet TOI 1823.01.

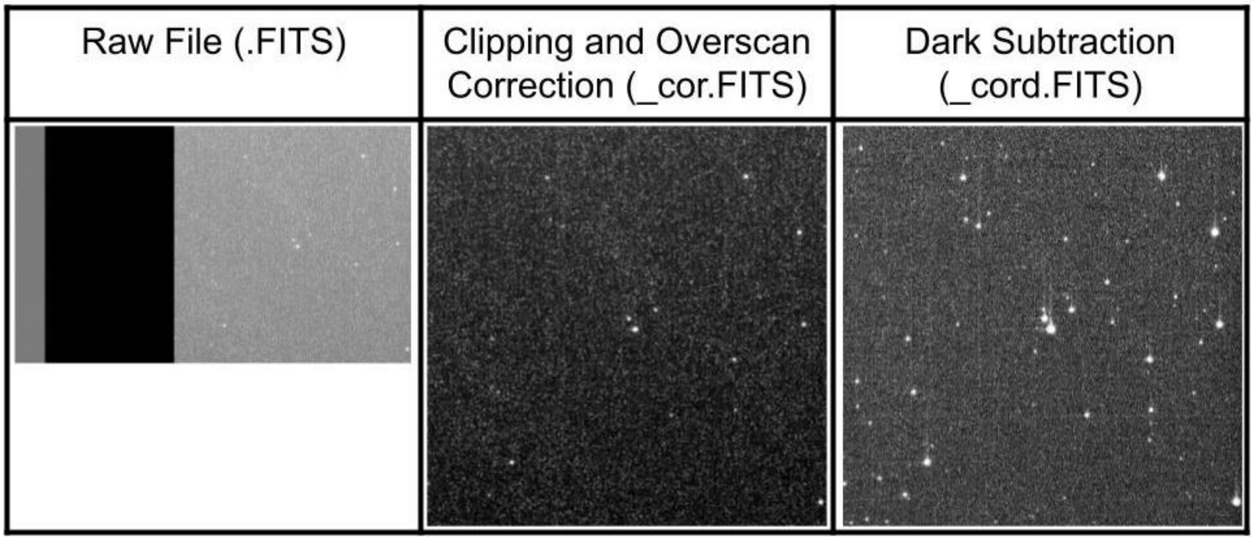

Fig. 8 Comparison of raw, cor and cord FITS images from enhanced image cleaning pipeline (Credit: CSA)

The enhanced cleaning on all products allows more precise observations, making exoplanet transit studies are now feasible directly from the product publications, without the need for users to first perform custom algorithmic cleaning in the products.

5.2 N1Phot: A Photometric Pipeline for NEOSSat Image Processing

N1Phot (short for *NEOSSat Photometry*) is a Python-based pipeline developed to automate the production of enhanced photometric data products from NEOSSat imagery. Initiated in May 2024 and nearing completion as of April 2025, n1Phot is designed to streamline data processing and make photometric measurements accessible to external researchers via the CSA Open Data portal [6] and the Canadian Astronomy Data Centre (CADC) [7].

The pipeline begins by retrieving NEOSSat images from a designated directory and generating a master image through stacking, significantly improving the signal-to-noise ratio (SNR). Source identification is performed on this high-SNR composite (Fig. 9), and the right ascension and declination of each detected source are recorded.

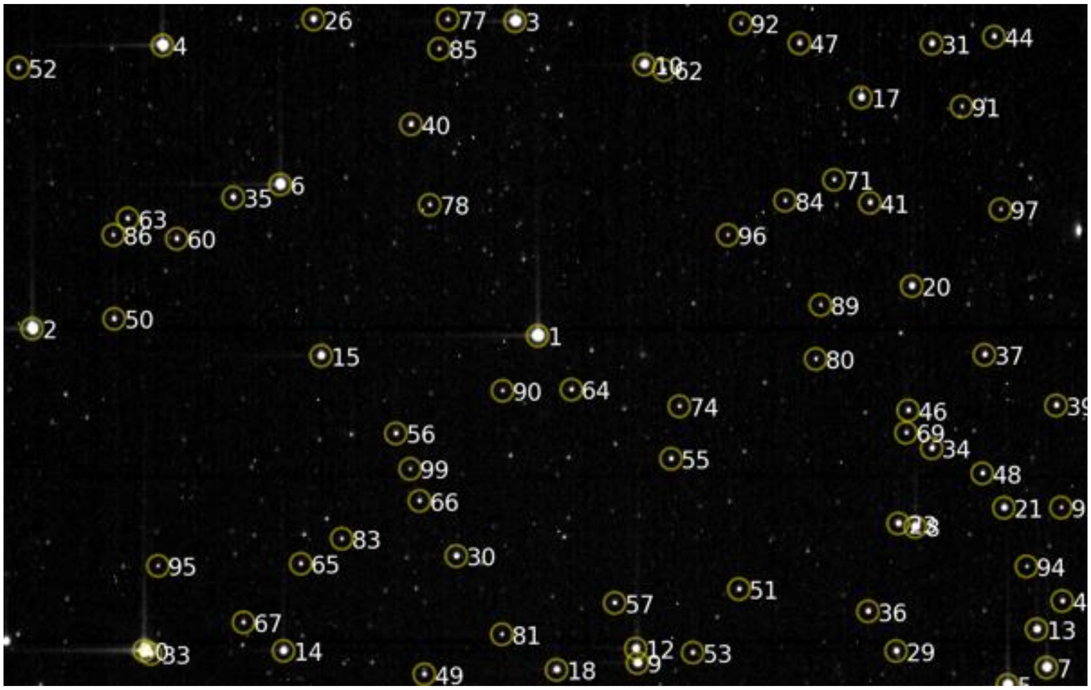

Fig. 9 Master image of a T CrB observation and the brightest detected sources in the field, observed by NEOSSat on Feb. 19, 2025. (Credit: CSA)

Subsequently, n1Phot extracts flux measurements from individual images by creating cutouts centered on each source. Background subtraction is applied, and flux counts are computed within a 14-pixel diameter aperture, which is empirically selected to optimally capture the point spread function (PSF).

To mitigate noise and systematic trends in the extracted light curves, n1PHOT incorporates a principal component analysis (PCA) routine. This step reduces the dimensionality of the data and isolates dominant patterns, effectively removing instrumental noise, systematics, and sky background variations. The PCA correction is based on the Python package originally developed by Bishop's University [16], which has been adapted to integrate seamlessly into the n1Phot framework (Fig. 10).

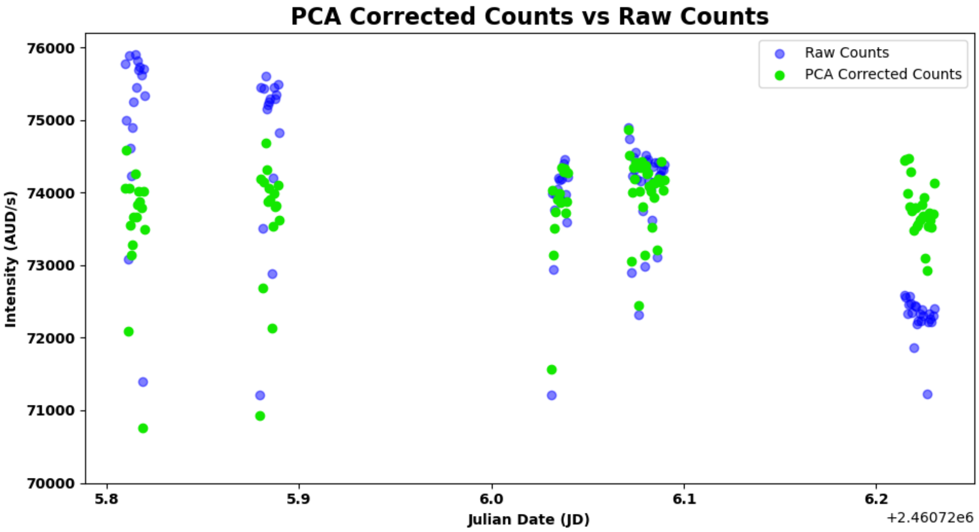

Fig. 10 Lightcurve of raw counts and PCA corrected counts, showing the reduction in spread and variation throughout data from a T CrB visit. (Credit: CSA)

Measurement uncertainties are estimated using the signal-to-noise ratio (SNR) formalism described by Merline & Howell [17]. In this framework, the signal N_* corresponds to the total number of photons collected from the target, while the noise term accounts for contributions from photon statistics, background estimation errors, dark current, read noise, and digitization effects. Specifically, the total noise is computed as:

$$\frac{S}{N} = \frac{N_*}{\sqrt{N_* + n_{pix}\left(1 + \frac{n_{pix}}{n_B}\right)\left(N_S + N_D + N_R^2 + G^2\sigma_f^2\right)}}$$

where n_{pix} is the number of pixels in the aperture, n_B is the number of background pixels, N_s is the background photon count per pixel, N_D is the dark current per pixel, N_R is the read noise, and $G^2\sigma^2$ is the gain and 1-sigma error for digitization noise in the analog-to-digital converter.

The final phase of n1Phot's development involves automating the ingestion of "cleaned" images—produced by the *n1FITS* processing module described earlier—and integrating processed FITS tables onto the Open Data Portal and CADC with ‘raw’, ‘cor’, and ‘cord’ images. This will ensure that end-users have seamless access to both calibrated image data and photometric measurements.

5.3 Science User Communication Improvements with n1FAN

FITS Availability Notification (n1FAN) is a new service provided for NEOSSat Guest Observers. N1FAN is a Python program designed to retrieve NEOSSat image metadata from the Canadian Astronomical Data Centre (CADC) and create emails to notify Principal Investigators (PIs) in the current cycle of the NEOSSat Guest Observer program, when they have new data available. This program is scheduled to run every day and retrieve information about NEOSSat FITS files from the past week using a query in the Astronomical Data Query Language (ADQL). The obtained filenames are then compared to an archive of past files, which allows for the new files to be identified and prevents previous files from being counted again. After the new files have been written to the archive, n1FAN extracts important details such as image count, fine point count, oldest image date, and target names. This information is written to a new xml file for each NEOSSat program and then sent to the CSA Satellite Operations email alerting service to be converted and sent as an email. Apart from the image counts and program details, the email also provides a link to CADC containing a query string which automatically applies the filters relevant for the user's new data. With the help of n1FAN, NEOSSat users will now be informed more frequently about the status of their observations and will be able to access their data in a more convenient way.

6. Automated NEOSSat Tasking for improved responsiveness to space events

All the previously described ground segment updates relate to improving the data delivered by NEOSSat, either in terms of data quality, measurement, or user experience. However, NEOSSat scientists must still submit their desired targets as tasking requests, based on the science goals and available planning tools. Those tasking requests are reviewed, deconflicted and ultimately scheduled alongside other users’ tasking requests. In general, daily routine NEOSSat planning covers a 24-hour period starting the next day, with uploads feasible in one of the 4-6 daily ground station passes. Putting these processes together, the routine tasking chain goes as follows:

- Science users review targets, prepare and submit tasking schedules, before a known daily deadline
- Operators review, deconflict and plan science schedules for upload at ground station contacts
- Satellite controllers upload science schedules at schedule ground station contacts

There are certain NEOSSat missions that require greater response agility than can be achieved by the routine process, where time taken on user-side planning, operator-side planning and upload execution all take up valuable time that delays rapid observation of a priority target. For new asteroid/comet discoveries, if new observations are not taken quickly, the uncertainty in orbital trajectory grows quickly and the new objects can quickly become lost. Similarly, other space events like fragmentation events and close approaches could require rapid tasking in order to capture useful data quickly. NEOSSat’s on-orbit agility is somewhat mitigated by a slow tasking process.

To address this problem for the new asteroid and comet discoveries, the Canadian Space Agency developed a new automated tasking system to autonomously produce tasking schedules with user intervention, the Near-Earth Object Candidate Observation Planner (NEOCOP).

6.1 Autonomous tasking of new asteroid and comet discoveries with NEOCOP

CSA's Near-Earth Object Candidate Observation Planner (NEOCOP) is new automated tool developed to allow NEOSSat to quickly perform follow-up observations of candidate NEOs. The process centres on the International Astronautical Union (IAU) Minor Planet Center (MPC) [18], specifically its Near-Earth Object Configuration Page (NEOCP) and Probable Comet Confirmation Page (PCCP). NEOCOP monitors the Minor Planet Center NEOCP and PCCP databases at a configurable frequency and checks every candidate object against a chosen set of parameters, including desirability score and number of observations. If a candidate passes initial checks, then NEOCOP identifies the next possible NEOSSat pass and further checks additional characteristics of candidate NEOs at that time and their rates of change of those parameters: apparent magnitude, solar elongation, sky motion, and plane-of-sky uncertainty, all of which are fully configurable. NEOCOP can also be configured to ignore the maximum solar elongation parameter if a target is predicted to be passing within a configurable proximity to Earth, allowing increased priority for potentially hazardous objects.

If a NEOCP and PCCP candidate target meets all set conditions, NEOCOP prepares a complete and constraint-verified observation schedule for the target beginning immediately after the next scheduled ground station pass, even if it was not scheduled for new tasking upload. The new "fast-tasking schedule" is automatically created and distributed to the NEOSSat operations team within approximately five minutes after identifying a suitable target. The NEOCOP reports include human-readable information to facilitate decision-making about whether the active NEOSSat schedule should be interrupted by this fast-tasknig request. If the NEOSSat team chooses to prioritize this target and upload this new proposed schedule, this will overwrite any previously uploaded tasking for this period. Parameters are selected to ensure that high-value candidates are quickly observable from NEOSSat, while attempting to minimize constant disruptions to chase NEOCP and PCCP candidates.

Given the potential uncertainty region around candidate targets requiring confirmation, which can extend well beyond NEOSSat's 0.8 degree field of view, a 'mosaic' search pattern tool was developed in NEOCOP's scheduling algorithms and is used automatically by NEOCOP to effectively search the sky for NEO candidates with higher plane-of-sky (POS) uncertainty. The tool generates a series of pointing angles for NEOSSat to efficiently cover as much of the POS uncertainty region as possible within a given timeframe, therefore maximizing the probability of imaging the target. Figure 11 provides a visualization of a mosaic search pattern generated from the MPC's 2000 Monte Carlo simulated orbits for a candidate NEO. The axes represent offsets in right ascension and declination (in arcseconds) from the nominal predicted position of the object. Each blue dot represents a possible location of the asteroid for a given simulated orbit, and the red squares indicate the fields NEOSSat will observe per the NEOCOP-generated schedule.

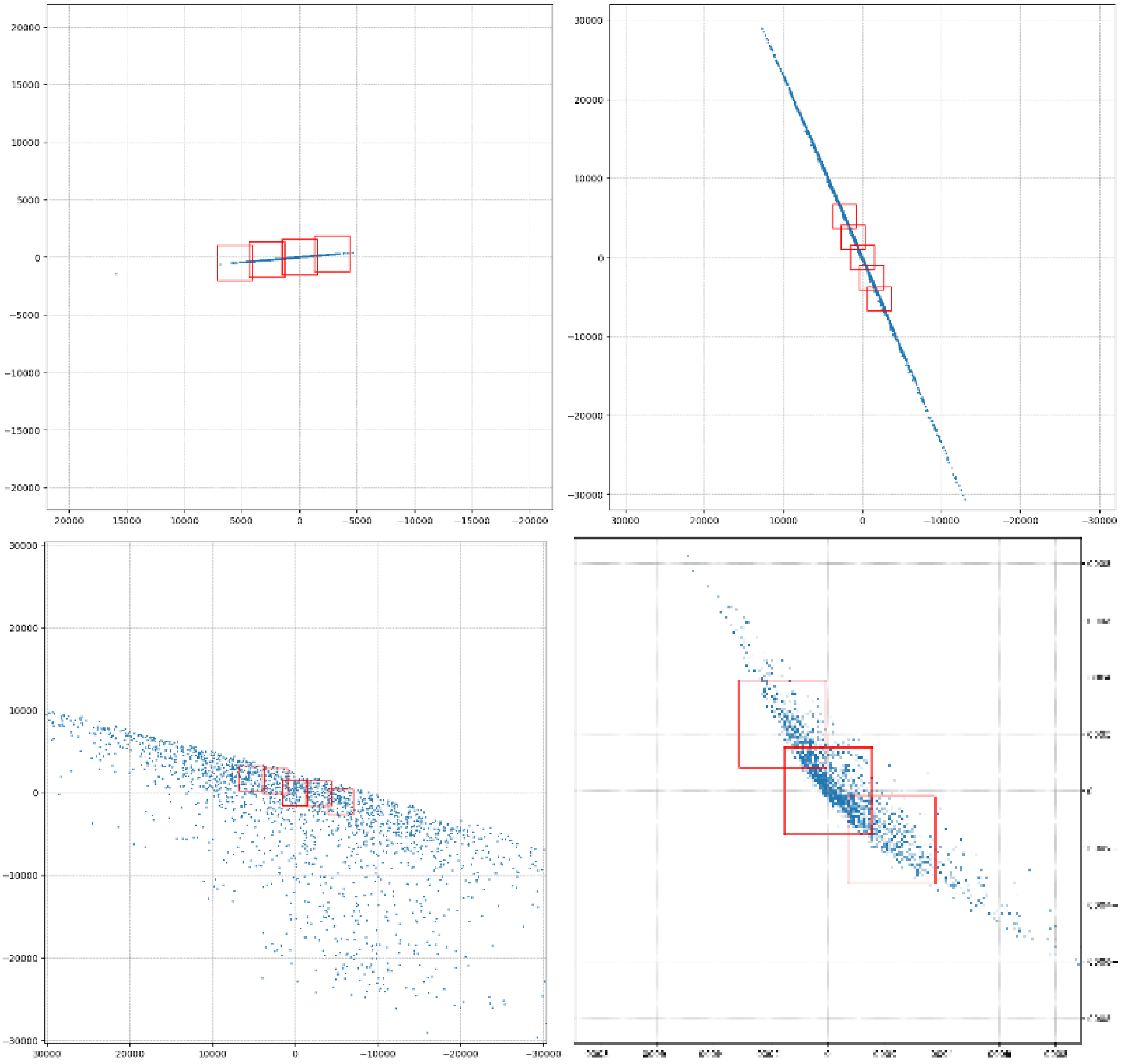

Fig. 11 NEOCOP mosaic search patterns used to image targets with plane-of-sky uncertainty greater than NEOSSat's field of view (Credit: CSA)

The implementation of NEOCOP in NEOSSat operations adds another layer of agility in NEOSSat's mission operations. The satellite itself is already highly agile, observing many different targets daily, switching between astronomical targets and tracking fast-moving resident space objects in various Earth orbits. With NEOCOP, the ground segment tasking chain also becomes more agile, enabling rapid turnaround to build observation schedules for discovery candidates that need follow-up quickly, all without end-user intervention.

6.2 Next Steps in NEOSSat Fast Tasking

NEOCOP's fast-tasking concepts around autonomous target selection and observation schedule submission have general applicability in a variety of domains of interest to CSA, DRDC and other NEOSSat users. The following applications where ground segment tools to autonomously build NEOSSat observation schedules based on high-priority and new-discovered are being considered and/or developed:

- Creating observation schedules for space objects involved in priority conjunction events (close approaches) identified through CSA’s Conjunction Risk Assessment and Mitigation System (CRAMS) [19], particularly when those objects have a relatively high-level of uncertainty, leading to an increased conjunction risk
- Creating observation schedules for newly identified variable stars to investigate possibilities for exoplanet transit or supernovae, with data feed from applicable variable star database, such as [20]
- Creating observation schedules for satellite or space debris fragmentation events or other anomalous or abnormal behaviour, with data from applicable space surveillance and tracking entities, such as [21] and [22]

A key challenge in such autonomous applications producing schedules for fast tasking is to consider prioritization with existing targets already. To this end, the NEOSSat team is introducing a prioritization schema within its scheduling pipeline, such that every target/observation within a particular schedule is marked with its priority. Initially, this will help satellite operators to identify whether an interrupt schedule generated by NEOCOP or similar tools should or shouldn’t be uploaded. But the ultimate goal is to automate the insertion of interrupt schedules, by parsing what is on the satellite and what is proposed, and always doing the right thing. This will be a focus on the next steps of automated fast tasking.

Finally, often fast tasking schedules not only require that the observations are scheduled and executed onboard the satellite as soon as possible, but also that the observations are downlinked as soon as possible. As-built, the NEOSSat science data buffer operates as a first-in, first-out queue. Consequently, stored image data from previous observations will typically be downloaded before newly inserted priority targets. If the backlog is large and there is no way to accelerate the downlink through additional ground station contacts, then the priority data downlink will be delayed. To address this issue, the NEOSSat team has designed a new solution linked to the prioritization scheme, where data marked as high priority could be stored within the telemetry buffer, to ensure it is downlinked at higher priority, ahead of lower priority images in the science buffer.

7. Conclusion and Discussion

Canada’s multi--mission agile space telescope, NEOSSat, continues to improve its services to its customers, increasing its data quality, its responsiveness to rapidly evolving space events, and its ability to work around hardware failures. Important updates in the flight software and ground segment software have enabled NEOSSat’s continuous improvement. Despite hardware failures that could have ended the mission, NEOSSat has emerged a Canadian success story in several domains: microsatellite technologies, space astronomy, space situational awareness and satellite resilience. With every new improvement, new avenues for further improvement are uncovered, inspiring the team to keep innovating. The mission serves as a model for future microsatellite-based space telescope programs. Given that redundancy remains on most critical hardware subsystems, the NEOSSat team is hopeful that the microsatellite will continue to serve the community while continuing to innovate and improve its services for years to come.

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