17th International Conference on Space Operations, Dubai, United Arab Emirates, 6 - 10 March 2023.

SpaceOps-2023, ID # 498

# Canada's NEOSSat Space Telescope – Ten Years of Resilience and Innovation

**Viqar Abbasi [a]*, Lauchie Scott [b], Stefan Thorsteinson [b], Nathaniel Cziranka-Crooks [a], Tyler Hrynyk [a], David D. Balam [c], Michel Doyon [a], Denis Laurin [a]**

[a] *Canadian Space Agency, 6767 route de l'aeroport, St-Hubert, Quebec, J3Y 8Y9, Canada* viqar.abbasi@asc-csa.gc.ca
[b] *Defence Research and Development Canada, 3701 Carling, Nepean, Ontario K2K 2Y7, Canada*
[c] *Dominion Astrophysical Observatory, National Research Council of Canada, 5071 West Saanich Road, Victoria, British Columbia, V9E 2E7, Canada*
* Corresponding Author

## Abstract

Launched in February 2013, Canada's Near-Earth Object Surveillance Satellite (NEOSSat) has been operational for 10 years, having overcome many challenges that could have resulted in an early end to the mission. Jointly operated by the Canadian Space Agency (CSA) and Defence R&D Canada (DRDC) from CSA's Multi-mission Satellite Operations Centre, NEOSSat continues to demonstrate incredible resilience, with new flight software enhancements to work around hardware failures, while expanding the types of science that can be performed from an agile space telescope on a microsatellite platform.

The paper summarizes NEOSSat's operational journey, which includes three major satellite recoveries led by the NEOSSat operations team, after the satellite experienced important failures impacting critical components of the satellite's attitude determination and control system. First, the magnetometer failure led to the creation of a new coarse attitude sensing algorithm using onboard GPS sensors initially intended only for orbit determination. The new algorithm uses the signal-to-noise ratio from each contributing GPS space vehicle to estimate the axis of the onboard GPS units, and then using this vector along with the sun sensor vector to calculate the satellite orientation and recover three-axis coarse attitude determination. Subsequently, while the GPS attitude sensor was still being finalized, a new hardware failure occurred as a failed microcontroller prevented use of the torque rods for desaturation of built-up momentum in the reaction wheels. This inability to desaturate was recovered by developing an innovative new desaturation control mode that would orient the satellite such that momentum desaturation could be achieved using the satellite's inherent residual dipole. Most recently, NEOSSat was beset with another hardware failure when one of its four reaction wheels failed. The operations team was able to quickly reconfigure the flight software to use three-wheel configuration. In spite of permanent hardware failures, the satellite continues to out-perform its design requirements, generating important lessons learned for satellite redundancy and operational resilience.

The innovative recoveries through flight software updates allowed NEOSSat to return to and expand upon its unique dual mission, splitting time between space astronomy and space situational awareness observations. On the space astronomy side, NEOSSat has expanded from its initial near-Earth object (NEO) survey mission towards a cross-Canada guest observer program based on an open data model, supporting a variety of astronomical experiments including exoplanet transit follow-up confirmation and characterization. For its space situational awareness mission, it now routinely observes and characterizes resident space objects and on-orbit events in low-Earth-orbit (LEO), a significant expansion from its initial mission focussed on high-Earth and geostationary orbits. Recent experimentation has also tested NEOSSat on Cislunar observations. Innovations in the ground segment for data processing and data distribution have allowed the mission to expand its user base and scientific applications supported. Operational improvements and lessons learned on NEOSSat time-sharing, open data, science data processing and distribution all demonstrate the innovation potential for small space telescopes in low-Earth orbit.

**Keywords:** Satellite Operations, Space Telescope, Space Astronomy, Space Situational Awareness, Flight Software, Resilience

**Acronyms/Abbreviations**

ACS: Attitude Control System
ADCS: Attitude Determination and Control System
CADC: Canadian Astronomy Data Center
CCD: Charge-coupled device
C&DH: Command & Data Handling
CSA: Canadian Space Agency
DLR: Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DRDC: Defence Research and Development Canada
GEO: Geostationary Orbit
GPS: Global Positioning System
HEOSS: High-Earth Orbit Space Surveillance
IAU: International Astronomical Union
LEO: Low-Earth Orbit
MOST: Microvariability and Oscillations of STars (MOST)
MPC: Minor Planet Center
MSCI: Microsat Systems Canada Inc.
NEOSSat: Near-Earth Object Surveillance Satellite
NRC: National Research Council of Canada
NRCan: Natural Resources Canada
RMS: root-mean-square
ROE: Read-Out Electronics
SAA: South Atlantic Anomaly
SEU: Single-Event Upset
SNR: Signal-to-Noise Ratio
SSA: Space Situational Awareness
SV: GPS Space Vehicle
WCS: World Coordinate System

## 1. Introduction

The Near-Earth Object Surveillance Satellite (NEOSSat) is a Canadian space telescope launched in 2013 with a dual mission supporting space astronomy and space situational awareness (SSA). The initial astronomy mission was dedicated to Near-Earth space surveillance to search for and track asteroids/comets in the inner solar system [1] and SSA mission comprised the High-Earth Orbit space surveillance (HEOSS), tracking Earth-orbiting satellites and debris [2]. NEOSSat was jointly funded by the Canadian Space Agency (CSA) and Defence Research and Development Canada (DRDC) as a low-cost microsatellite demonstration platform with minimal redundancy. The 75kg platform was based on the design and technology of the microsatellite, Microvariability and Oscillations of STars (MOST) space telescope, funded by CSA and built by Microsat Systems Canada Inc (MSCI) [3]. 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.

## 2. NEOSSat Design & Key Features

### *2.1 Key Operational Modes*

NEOSSat was designed for quick and accurate all-sky target acquisition and precision pointing to allow stable imaging of many different science targets daily. For observations of faint celestial objects, 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 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. Fine Point and Fine Slew modes utilize custom narrow-field star tracker and an onboard star catalog. Attitude determination and control begins with a coarse pointing 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. Fig. 1 provides a drawing of NEOSSat and its body frame coordinate system.

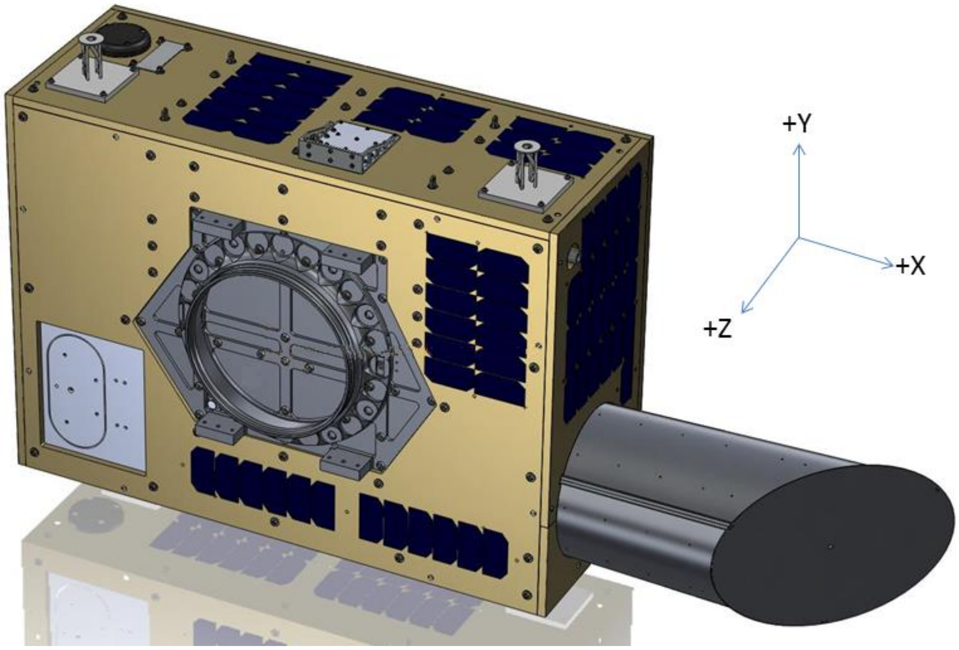


Fig. 1 NEOSSat drawing with body coordinate frame definition (Credit: CSA)

### *2.2 Design Summary*

The satellite's primary payload is a 15-cm aperture Maksutov telescope with 0.8° field of view, featuring two E2V 1024x1024 charge-coupled devices (CCD) and associated read-out electronics providing 3 arcsecond/pixel resolution. One CCD unit is used for science imaging and the second is used by the attitude determination and control system (ADCS) for the collocated narrow-field star tracker, which shares the optical boresight with the payload. NEOSSat was designed to perform coarse attitude determination using its three-axis magnetometer and coarse sun sensing derived from the solar panel output on each face. The magnetometer and coarse sun sensor are used for coarse attitude determination, whose solution is then used to seed the narrow-field boresight-aligned star tracker for fine attitude determination. Attitude (pointing) control would be performed using four reaction wheels with integrated rate sensors (X, Y, Z, Skew) and three torque rods (X, Y, Z) were used for momentum desaturation. Two Global Positioning System (GPS) receivers are also included for orbit determination, one on the +Y face and another on the –Y face. A key feature of NEOSSat is its large baffle (seen in Fig. 1 and Fig. 2), which is designed to allow the telescope to make observations near the Sun, in regions difficult to image with ground telescopes. While the design specification was to achieve down to 45° solar elongation, operationally the limit has been pushed further, with successful near-Sun imaging near 35° solar elongation routinely achieved, and during satellite eclipse periods, where the Earth can be used as an extended baffle, solar elongations below 15° can be achieved.

Fig. 2 NEOSSat satellite during integration testing (left) and artist's rendition on-orbit (right). Credit: CSA

## 3. NEOSSat Launch and Early Operations

### *3.1 Launch and Ground Station Support*

NEOSSat was launched on February 25, 2013, on the Indian Space Research (ISRO) Polar Satellite Launch Vehicle (PSLV) Flight C-20 (Fig. 3 left), as one of six secondary payloads. Another secondary payload on the same launch was the Canadian space surveillance satellite Sapphire (Fig. 3 right), owned and operated by the Canada's Department of National Defence (DND) as a dedicated contributing sensor to the United States Space Surveillance Network (SSN). The successful launch placed all satellites in 780 km sun-synchronous orbits. 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. 4) provide increased coverage and contact opportunities.

Fig. 3 PSLV C-20 launch (left, credit ISRO) and NEOSSat & Sapphire launch configuration (right, credit CSA)

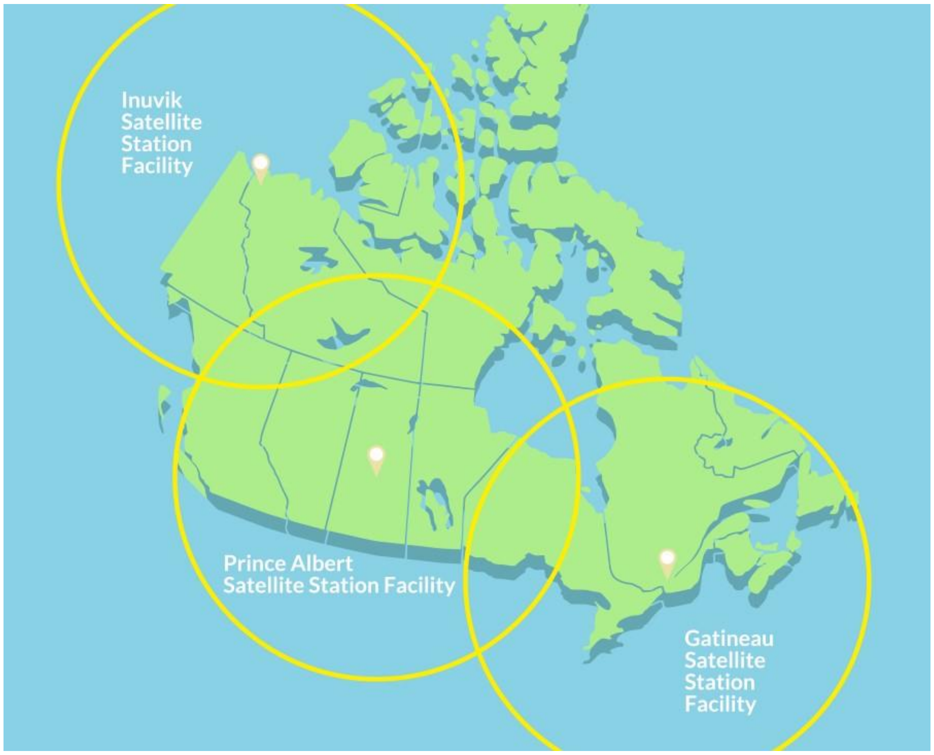


Fig. 4 Natural Resources Canada (NRCan) ground stations supporting NEOSSat (credit: NRCan)

## 4. Operations Evolution through Flight and Ground Software Updates

### *4.1 Flight software updates to achieve Fine Pointing*

Although satellite communications with NEOSSat were robust and reliable from the outset, several flight software updates were needed during the commissioning period before reliable all-sky fine pointing could be achieved. The collocated payload/star-tracker optical design on NEOSSat required significant software upgrades compared to its predecessor MOST, where star tracker parameters would be configured on the ground and uploaded to the satellite for a given science target used for months. By contrast, NEOSSat required rapid autonomous all-sky acquisition for both the space astronomy and SSA missions. While commercial star trackers typically have fields of view in the range of 8 to 35 degrees and operate mostly with bright stars, NEOSSat's boresight-aligned star tracker operates with a miniscule 0.8 degrees field of view, working autonomously with an onboard star catalog featuring 2 million guide stars down to visual magnitude 14. These features allow NEOSSat to achieve a high degree of pointing accuracy, but several flight software iterations were required to make the system operational, addressing issues such as optimal lit pixel lists and star catalog management and elimination of false positives under a variety of in-flight conditions. In addition, various updates were done to various elements in the ground segment software to improve constraint checking on tasking to maximize successful imaging while maintaining satellite health and safety. Ultimately, reliable all-sky star tracker acquisition and fine pointing was achieved, typically providing better than one arcsecond stability in Fine Point mode as well as maintaining star tracker custody during fine slews to enable highly accurate tracking of fast-moving objects.

### *4.2 Updates for image quality and electronics interference*

Another important effort during commissioning was to eliminate interference from the satellite electronics that were found to be contributing noise on the payload CCD imager [4]. To address this, the CCD readout electronics flight software was updated with new features to synchronize the operations of the science and star tracker CCD to eliminate one source of interference. Pixel over-sampling during readout was also integrated into the flight software to reduce noise effects. Another source of interference correlated with the battery charge regulator operations, which contributed a consistent background pattern apparent on the images. This interference was addressed by updating the raster settings in payload setup to include an overscan region, and updating the ground image processing software to automatically analyse the overscan region using Fourier transforms to identify the major interference frequencies, to subtract those noise contributions and to produce clean images.

Dark current and hot pixels are a challenge to any space-based astronomy mission. The effect becomes more pronounced as mission duration and the related radiation damage increase. The traditional technique to deal with this is annealing where the temperature of the CCD is increased in order to remove some of these hot pixels. NEOSSat's lack of onboard heaters meant that an alternative method for thermal control was needed. NEOSSat strategically uses its attitude control system to maintain onboard subsystem temperatures within applicable safety ranges in a form of passive thermal control. The same method is used for CCD annealing on NEOSSat to heat the onboard CCDs to required temperatures. The chosen attitude is designed to direct the sun onto the closest surface to the CCDs, while respecting other applicable satellite constraints. As the entire spacecraft attitude is changed, other components and their operating temperatures also need to be balanced against the temperature of the CCD. This process has been carried out several times in order to successfully reduce the dark current present on the CCD and thus improve image quality for both the science CCD and the star tracker CCD.

### *4.3 Updates for auto-recovery from routine anomalies*

As is typical with satellites in low-Earth orbit, NEOSSat is subject to single-event upsets (SEUs) resulting in hardware or software glitches. Many of these SEUs would occur when crossing through the South Atlantic Anomaly (SAA), an area with a high flux of radiation and charged particles that affect electronic components. The magnetometer, torque rod controller, GPS, reaction wheels, and payload/star-tracker read-out electronics units all exhibited occasional anomalies, as did the main command and data handling (C&DH) bus. In general, the solution would be to power cycle the affected unit, which normally recovered the unit but still caused an impact to operations due to the need to first detect the anomaly in a scheduled downlink pass and then upload the power cycle commands. While a variety of components could be impacted by these SEUs, some units, notably the Read-Out Electronics (ROE) for the payload and star tracker, exhibited more sensitivity and disruption than others. As anomalies might typically occur during pass gaps, there could be long periods of science lost due to routine anomalies. An important optimization to ensure NEOSSat maximizes the time it devotes to science – and minimizes the time it spends on anomaly recovery – was to implement autonomous auto-recovery from certain routine SEU-related anomalies in the flight software. Certain signatures were identified and programmed into the main bus flight software, which controls all the units. Logic was implemented for the bus flight software that controls the payload and star tracker ROE to identify the anomalous signature, confirm it over a period of time (to avoid triggering on a false positive), and then initiate recovery procedures, i.e. power cycle of the unit. This innovation greatly increased NEOSSat's resilience and brought the anomaly recovery time for frequent routine anomalies down from hours to less than a couple of minutes. Auto-recovery of common ROE anomalies in flight software had an important impact in maximizing the likelihood that scheduled tasks would deliver the images as planned, while also ensuring that the operations team did not waste time on "very routine" anomaly recoveries. Over time, more anomaly auto-recoveries were programmed, both into the ground software and flight software to maximize the mission's "up-time" and science performance. All of these updates contributed to more science data collection, less outages for maintenance and more user satisfaction. However, in 2016, major hardware failures almost resulted in a sudden end to the mission.

## 5. Recovery from major hardware failures through innovative flight software

### *5.1 Surviving a failed coarse sensor: Sun Point mode*

In early 2016, not long after several flight software updates had led to robust fine pointing and science execution, NEOSSat suffered a failure of its magnetometer. Although the anomaly was linked to the effects of the space environment, attempts to reboot, recover or recalibrate the magnetometer all failed and the magnetometer failure was deemed permanent. The magnetometer and coarse sun sensor had been the primary sensor pair providing coarse attitude determination, which was a prerequisite for star tracker acquisition and fine pointing operation. Prior to the failure, NEOSSat was able to routinely acquire its pointing targets, transitioning from coarse pointing to fine pointing as required to perform its tasked operations. With magnetometer failed, the attitude determination system could no longer reliably solve for an attitude solution. Consequently, the failure resulted in a complete loss of attitude determination and control and left the satellite in a tumbling state, essentially lost and uncontrollable. Faced with this critical failure, all mission activities were halted and the focus shifted to maintaining satellite health and safety. The communications subsystems remained functional, so thermal safety during this period was maintained by the operations team by monitoring battery temperatures and inducing a "desirable" spin through direct open-loop commanding to the wheels as required to keep the +Z face away from the Sun. It was a manual effort that required regular monitoring and intervention.

In order to optimize the team's efforts and improve satellite safety while a more complete recovery path was being explored, a new flight software build was developed to provide a new "Sun Point" control mode that would allow attitude control relative to the Sun using only the coarse sun sensors and rate sensors. This new mode would be used to stabilize NEOSSat relative to the Sun, allowing the operations team to maintain battery temperatures within safety limits. In addition, the mode would allow software engineers to stabilize the vehicle and take images, which could then be used to help in the development of new solutions to recover full coarse attitude determination with sufficient accuracy to work around the failure and return to science operations.

### *5.2 New GPS attitude sensor for renewed coarse attitude determination*

Many solutions were conceived to attempt to recover coarse attitude determination. Ultimately, the team settled upon a solution which would create a new GPS-based attitude sensor for use in the satellite's coarse attitude determination, based on the signal-to-noise ratio (SNR) of contributing space vehicles, a methodology proposed by Axelrad [5] and Wang [6]. A new GPS-based attitude vector pair derived from assembly-and-integration knowledge of the GPS antennas in the body frame and an estimated orientation of the GPS receivers in the inertial frame would replace the attitude vector pair provided by the magnetometer. This solution would require detailed information on the signal-to-noise ratio of all GPS signals being received and the inertial positions of those same contributing GPS space vehicles. The flight software that introduced "Sun Point" had also included updates to the GPS interface to collect these advanced logs on the GPS space vehicles being tracked, providing all the raw data needed to develop and validate the GPS attitude sensor algorithm on the ground before flight software implementation. Truth data on NEOSSat attitude was obtained by solving starfield images taken from the camera, allowing testing and calibration. A mapping function was developed between the signal-to-noise ratio and elevation angle to create a calibration map, representing the antenna gain pattern for NEOSSat's onboard GPS receivers with reasonable accuracy to get an effective solution [7].

The next flight software build finalized the implementation of the GPS-based attitude sensor. As detailed in [7], the NEOSSat implementation of a GPS-based attitude sensor made important improvements over earlier concepts, including the combined use of both onboard GPS antennas, loss compensation and filtering for multi-path effects. Once the flight software build was finalized, uploaded and activated on-orbit, the new attitude control system was able to successfully recover coarse pointing with the accuracy required for star tracker acquisition and transition to Fine-Point for mission operations. The new GPS attitude sensor is now a key component of the NEOSSat's attitude control system and has fully replaced the functions of the failed magnetometer for coarse attitude determination. The GPS attitude sensor provides an attitude vector with RMS errors within 10 degrees, and is generally applicable as a coarse attitude sensor to satellites with at least one GPS receiver.

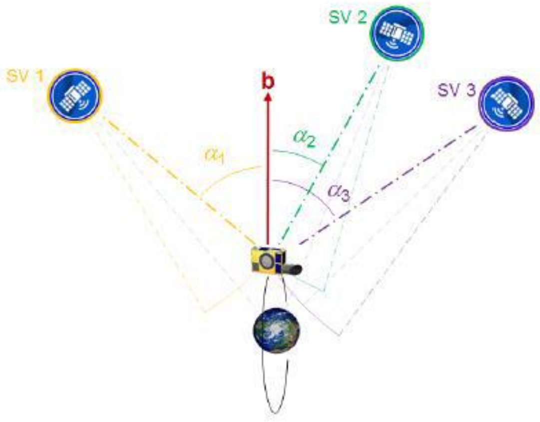


Fig. 5 GPS attitude sensor concept, using contributing SVs to estimate GPS antenna direction (credit: CSA)

### *5.3 Desaturation using Residual Dipole instead of Torque Rods*

In another dramatic turn later that same year, just as the new GPS attitude sensor was in its final validation testing prior to an upload that was expected to bring about a return to routine science operations, NEOSSat was hit with another major hardware failure that once again threatened to put an end to the mission. This time, the anomaly was a communication failure with the STM32 microcontroller controlling the torque rods. This type of loss of communication failure between the main flight computer and the torque rod microcontroller had previously been encountered during the mission but unlike previous occurrences, the typical recovery approach of performing a power cycle of the microcontroller was unsuccessful. The STM32 microcontroller remained unresponsive. After a variety of unsuccessful recovery attempts, the unit was deemed failed, resulting in the permanent loss of all three torque rods. The impact of this new failure was that, once again, NEOSSat could not maintain controlled pointing, this time due to the loss of the ability to desaturate momentum from its reaction wheels. Without a desaturation strategy, even the interim "Sun Point" control mode, used to maintain safe orientations in the absence of full three-axis attitude control, could not be used consistently, due to momentum build-up leading to wheel saturation. At this point, NEOSSat operations toggled between "carefully monitored tumbling" (during which momentum would slowly dissipate) and short periods of "Sun Point", driven by the need to regulate temperatures on batteries and other subsystems. In parallel, the team once again brainstormed for a recovery strategy, this time to regain desaturation capability in the absence of torque rods.

To solve this latest problem, the team developed an innovative new control mode called "Dipole Desaturation", a brand new concept first conceived for NEOSSat. It had previously been established that NEOSSat's primary disturbance torque was the torque produced due to the satellite's inherent residual dipole torque and that this residual dipole was fixed and characterized in the body frame. In the newly proposed Dipole Desaturation mode, the satellite makes use of the residual dipole of the spacecraft in order to reduce total momentum. Utilizing a closed loop algorithm, this mode continually calculates the on-board momentum and NEOSSat's attitude relative to the magnetic field of the earth. The control system then points NEOSSat in such a manner that the disturbance torques from the residual dipole reduce the total spacecraft momentum. Dipole Desaturation is either commanded from the ground or activated as an automatic transition when the spacecraft has insufficient momentum headroom to perform a scheduled operation. Once activated, the algorithm operates autonomously on board within the attitude control system, as detailed in [8]. Once the efficacy of the new algorithm was validated in simulation, the modified flight software was uploaded to NEOSSat and the Dipole Desaturation mode was commanded. Fig. 6 shows the spacecraft flight telemetry tracking the momentum after first activation of Dipole Desaturation mode from a hyper-saturated initial conditions.

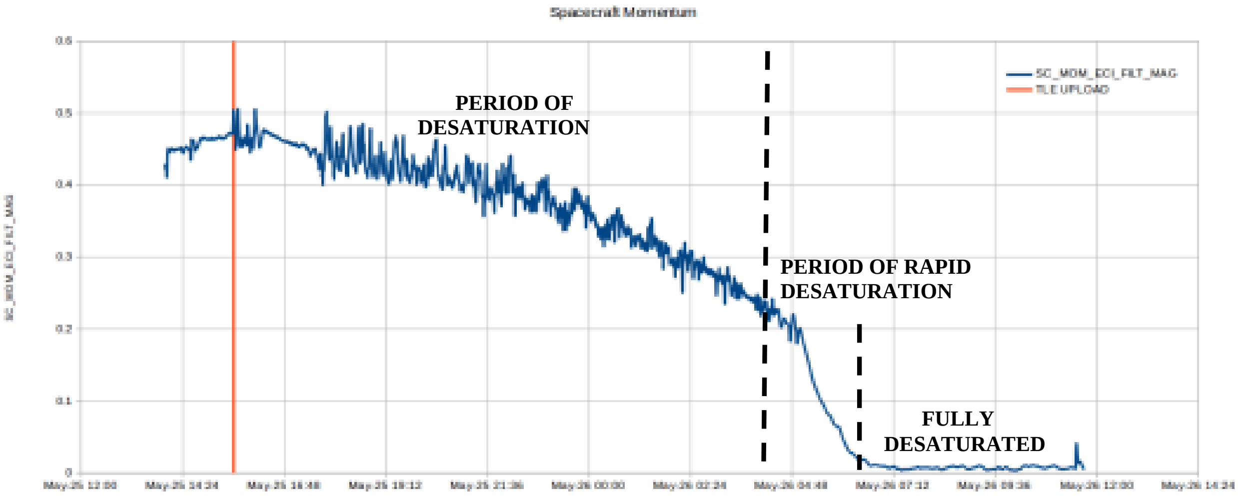


Fig. 6 Flight telemetry showing momentum reduction in Dipole Desaturation mode (Credit: CSA)

Normal science operations are paused during dipole desaturation and re-saturation of the reaction wheels occurs during routine science pointing control due to disturbance torques. However, since desaturation is done at the optimal attitude for desaturation and science pointing targets are essentially random, desaturation periods under Dipole Desaturation control takes significantly less time than re-saturation during science operations. Furthermore, the major disturbance torque is well characterized for NEOSSat and therefore, the expected momentum build-up for user-commanded attitudes is easily modeled and simulated. To optimize NEOSSat's duty cycle, planning functions in the ground segment were updated to predict momentum buildup and allow the configuration of timelines that alternate between periods of science pointing operations and periods for desaturation as needed between operational targets. The insertion of desaturation periods helps to ensure that user tasks are performed with sufficient control authority to complete successfully and that saturation never (or rarely) occurs. Desaturation periods are often planned during orbits that are otherwise ineffective for observations (such as orbits crossing the South Atlantic Anomaly or when the target is not visible), further limiting the effect of the new desaturation requirement on the satellite's productivity. Although the maximum possible duty cycle is reduced compared to the original baseline configuration with functional torque rods, the ability to schedule desaturation in otherwise unplanned time slots and the efficiency of dipole desaturation allows a majority of the available time to be available for scientific target observations and tracking. Consequently, despite the loss of inline continuous desaturation, the majority of time of NEOSSat's operational time is still devoted to science and NEOSSat users are getting more useful data than ever before.

With this innovative new recovery strategy and concept of operations, NEOSSat science operations were relaunched. The post-recovery period starting in 2017 would see a renaissance of NEOSSat science, with renewed SSA experimentation that pushed the limits of the vehicle and a new Guest Observer program for space astronomy that greatly expanded the variety and quality of science data collected. Innovation through flight and ground software continuous improvement continued in support of these new missions over the next few years. When NEOSSat's next major hardware failure occurred, a lengthy break in science activity was averted by a well-architected attitude control system software that was written with resilience in mind.

### *5.4 Three-wheel re-configuration*

In 2021, NEOSSat lost one of its four reaction wheels in what appears to be an electrical failure but is still under investigation. Fortunately, the attitude control system flight software was programmed with a high degree of configurability through easily-updated configuration parameters. To quickly recover science operations, the team made the necessary flight software parameter table modifications for a 3-wheel configuration, performed simulation testing, and uploaded the new parameters to the satellite. Within two weeks of the wheel failure, nominal operations resumed and science operations began to be performed at the same frequency as before the wheel failure.

For the most part, users do not notice an impact due to the change from 4-wheel to 3-wheel configuration as the satellite maintains full three-axis control and accurate pointing. The change from 4-wheel to 3-wheel configuration has some minor drawbacks as the wheels in a 3-wheel configuration cannot maintain the directional bias they can in a 4-wheel configuration. With no directional bias implemented, the satellite can experience more "zero crossings" when a wheel has to change its direction from positive spin to negative spin which can induce instability in an image taken during the zero-crossing. At most, this affects one image in a set of images. For all other images in a set, pointing stability is generally maintained as well as it was in a 4-wheel configuration.

## 6. NEOSSat Astronomy Evolution and Summary

Early science plans for NEOSSat-based space astronomy focussed on near-Sun surveys in the range of 45-55 degrees from the Sun [9]. While such surveys continue to be performed occasionally, in 2019, CSA launched the NEOSSat Guest Observer program to improve astronomers' access to NEOSSat data and maximize the scientific return from the mission. Under the new program, NEOSSat astronomy images are automatically pushed to the CSA Open Data portal [10] and the Canadian Astronomy Data Centre, managed by Canada's National Research Council (NRC) [11]. Through these portals, the astronomy data is freely available with no proprietary period. The NEOSSat Guest Observer program for space astronomy has enabled NEOSSat to be more useful and more responsive to the needs of the astronomy community, supporting many more astronomers in many more fields of study, including domains not initially planned, such as photometric applications for exoplanet transit follow-up. Through five cycles, ten different principal investigators and their teams have used NEOSSat for their investigations under this program [12].

Overall, more than 500,000 non-dark images from NEOSSat are available through the CADC platform. In 2022, the satellite downloaded more than 200,000 images totalling approximately 230GB of astronomy and SSA image data. This is a substantial increase over NEOSSat's initial planned cadence of 288 images/day, based on 24 images/orbit and 12 orbits/day. A summary of key observations and experimentation is provided in this section.

### *6.1 Near-Earth Asteroids and Comets*

Early on after establishing Fine Point capabilities, NEOSSat performed observations of known asteroids and comets. Successful observations and submission of astrometry for these asteroids and comets led to the assignment of observatory code C53 for NEOSSat by the International Astronomical Union (IAU) Minor Planet Center (MPC) [13].

Since the launch of the Guest Observer program, the comet and asteroid astrometric processing pipeline initially developed for the Dominion Astrophysical Observatory (DAO/NRC) [14] has been adapted to include NEOSSat as part of its sensor bundle (which includes the 1.82-m Plaskett telescope and the 0.76-m Baker-Nunn Schmidt telescope of the Rothney Astrophysical Observatory at the University of Calgary). MPC submissions are performed through this workflow with data processed and delivered shortly after downlink. In this pipeline, each series of images is processed (bias and dark subtracted) and the world coordinate system (WCS) is determined for each using on-line astrometric catalogues. All images in the stack are then re-sampled, using both linear and non-linear terms to a common tangential projection with constant scale and the boresight is at the central pixel. Since the aperture of NEOSSat is relatively small (0.15m) compared to ground telescopes, it is necessary to compensate for the orbital motion of the target comet, the earth in its orbit and the spacecraft in its 99 minute (polar) orbit to ’freeze’ the object on the detector. The technique is straight-forward for ground based sensors and results in the background stars becoming long, linear trails. The technique for a spacecraft is complicated by parallax effects from both the nearby comet and the spacecraft in its orbit. Motion compensation is achieved by the numerical integration of the equations of motion of earth, comet and spacecraft resulting from the heliocentric equatorial coordinates of the earth and comet and the geocentric equatorial coordinates of the spacecraft for the mid exposure time of each image in an image stack. Image stacks of two near-Earth objects are shown in Fig. 7 to illustrate the effects of parallax. The image stack of Apophis was obtained as the spacecraft traversed the earth’s pole and this is reflected in the arc-like appearance of the background star trails. The images for comet C/2020 F3 were captured one month post-perihelion and inside the Earth’s orbit.

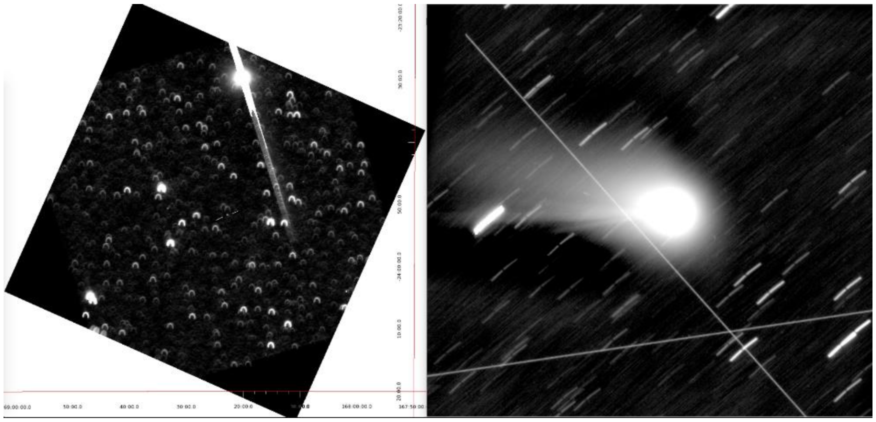


Fig. 7 Image stacks of hazardous asteroid (99942) Apophis (left, based on co-addition of 32-66 second exposures on UT 2021 Feb. 18) and long-period comet C/2020 F3 (right based on co-addition of 26-28 second exposures on UT 2021 Feb. 18). The parallactic effect of NEOSSat’s polar orbit is clearly seen. (Credit: DAO/NRC & CSA)

The distribution of 308 field ‘visits’ are shown in Figure 6 as a histogram of the solar elongation, apparent magnitude and motion rate. There are 25 successful visits to fields with solar elongation less than 40 degrees, demonstrating the near-Sun capabilities. Several of the more extreme values were reached during eclipse season, when it is possible to use the earth limb to occult the sun. The archive of motion-compensated comet image stacks are available for public access via the International Comet Quarterly, a publication devoted to comets since 1978 [16].

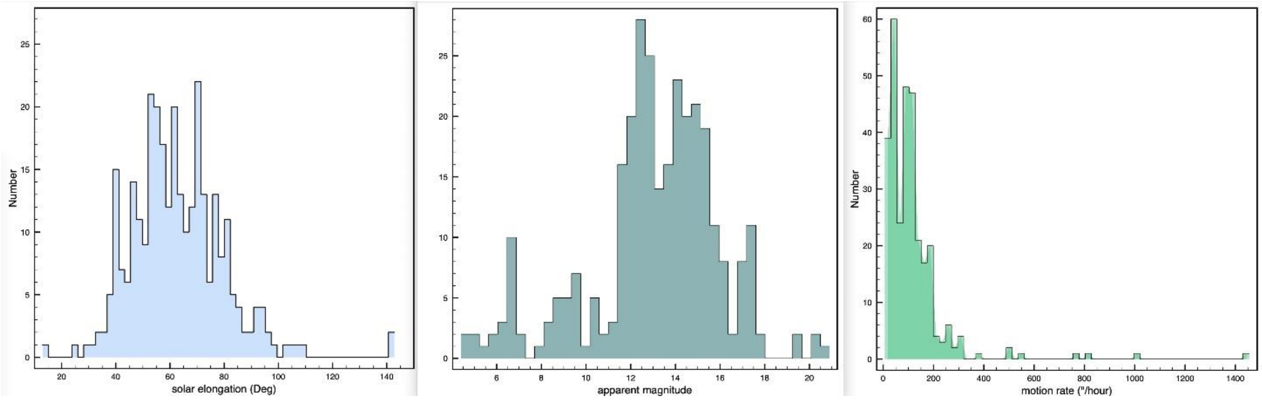


Fig. 8 The distribution of 308 NEO targets as a function of solar elongation, apparent magntitude and motion rate (Credit: DAO/NRC)

One of the most interesting objects NEOSSat observed was the interstellar comet 2I/(Borisov), which NEOSSat started observing shortly after its entry through our solar system until its exit. This was only the second interstellar object to be discovered in the solar system. The in-bound light curve of this unusual object was investigated and a tentative rotation period of 13 days was found from more than 6000 images obtained between September 2019 and February 2020 [16].

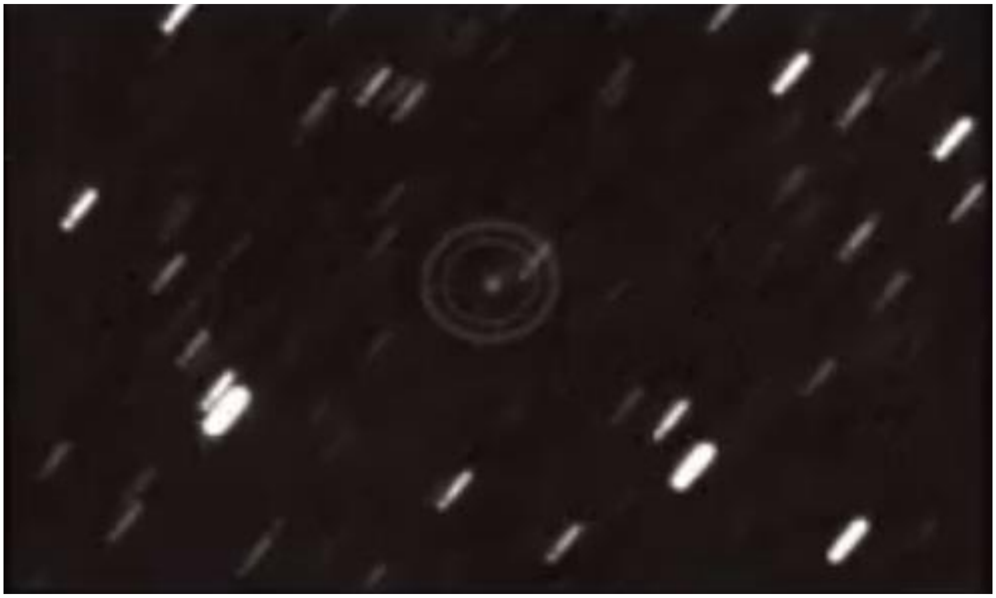


Fig. 9 Interstellar comet 2I/Borisov as seen from NEOSSat (Credit: DAO/NRC & CSA)

NEOSSat was also quick on the scene to image the potentially hazardous near-Earth asteroid Didymos (65803) within minutes of the kinetic impact from NASA’s Double Asteroid Redirection Test (DART) planetary defence demonstration mission on Sept 26, 2022. NEOSSat obtained images starting 14 minutes post-impact, since NEOSSat was on the wrong side of Earth at the time of impact). A series of images is shown in Figure 7, starting at 23:28 UTC (14 minutes post-impact) and every 2 minutes thereafter (top-left to lower right). Each stamp is 15 x 15 minutes of arc. The red bar shows a span of 4000 km at the distance (0.076 AU = 11,324,000 km) of the asteroid. The data shows the human-made debris cloud that dissipates quickly with time. Astrometric observations before and after impact are able to confirm the trajectory change imparted due to the kinetic strike.

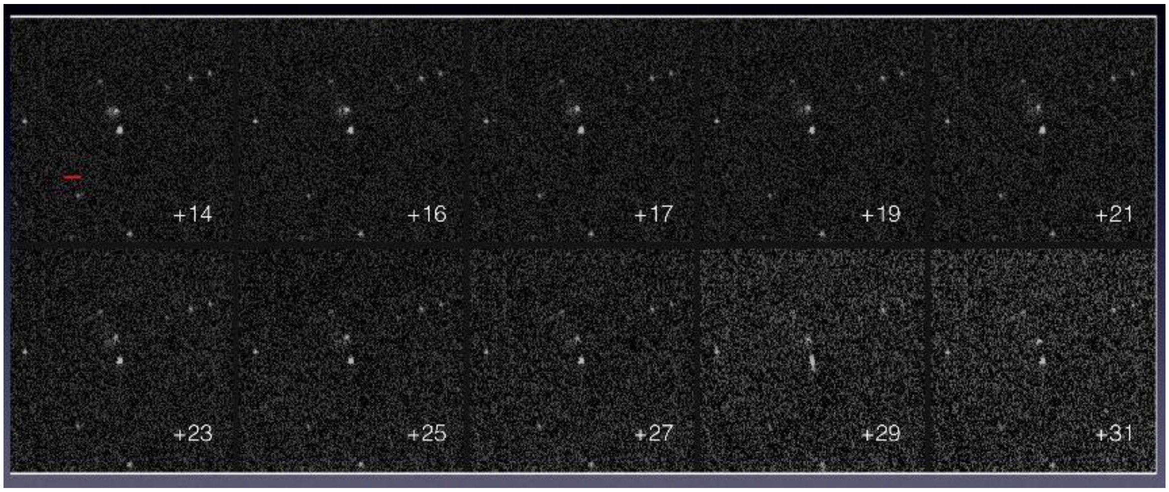


Fig. 10. NEOSSat images of asteroid Didymos starting at 14 minutes post-impact and every 2 minutes thereafter (top-left to lower right). (Credit: DAO/NRC & CSA)

### *6.2 Exoplanet transit photometry*

As the Guest Observer program was being launched, experiments were underway to assess the potential to assess the photometric precision of NEOSSat with a view towards new scientific applications based on long-duration photometry, such as exoplanet transit follow-up and confirmation and other variable star phenomena. Early results showed good photometric precision from NEOSSat observations [17]. Applying modern image processing and photometric techniques, NEOSSat is now participating in exoplanet research, by imaging stars with known/candidate transiting exoplanets and demonstrating an ability to detect exoplanet transits. Today, a large portion of the NEOSSat 50% space astronomy tasking is used for photometric applications, something that was never envisioned as the mission was being developed.

The technique for non-differential photometry using NEOSSat is shown in Fig. 11. In this example, we see 1-sigma poisson errors of the flux from the star WASP-33 in blue and from a nearby comparison star in pink. An expected exoplanet transit model is shown in red to demonstrate the expected signal. The transit of the exoplanet WASP-33b, shown by the dip in flux, is easily detected by NEOSSat. The science team is now routinely scheduling NEOSSat to follow up on exoplanet candidates from NASA's Transit Exoplanet Survey Satellite (TESS) mission and Kepler K2 missions, both of which performed surveys but have limited ability to follow-up.

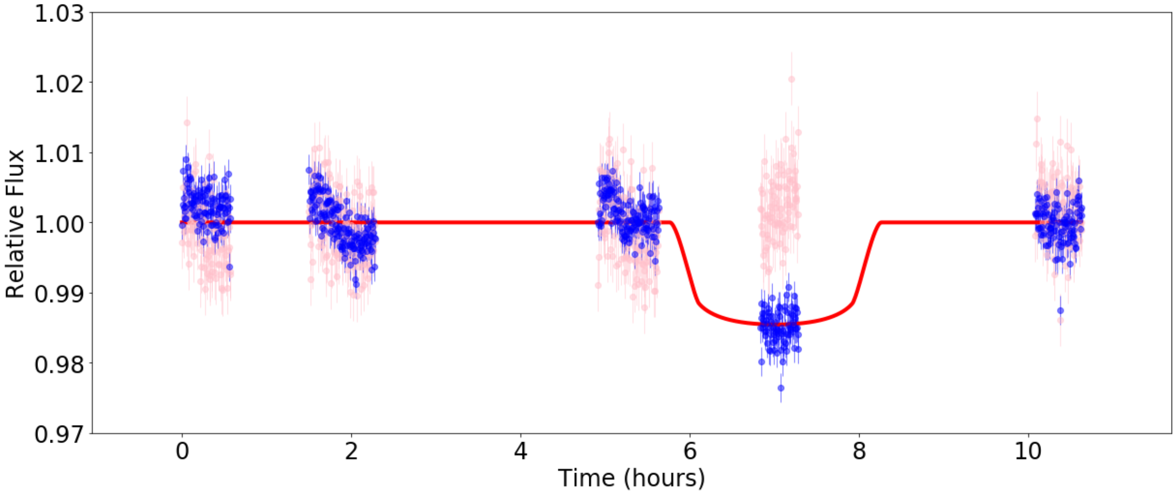


Fig. 11 WASP-33b exoplanet transit detection using NEOSSat photometry (Credit: J. Rowe/Bishops via [12])

Applying similar techniques to the study of near-Earth objects and Earth-orbiting resident space objects, photometry from NEOSSat contribute to improved near-Earth asteroid and comet characterization, in addition to exoplanet research and other applications.

## 7. Space Surveillance / Space Situational Awareness with NEOSSat

NEOSSat has become an important tool for SSA research in Canada. DRDC's original NEOSSat space surveillance mission, High Earth Orbit Space Surveillance (HEOSS), focussed on tracking of objects in geosynchronous orbits (GEO). Since then, improvements to NEOSSat's attitude control system's slew acceleration and rates expanded its orbital observation remit to both LEO, and recently, Cislunar altitudes.

Since 2016, NEOSSat has observed LEO space objects in orbits like its own. LEO-to-LEO observations are challenging due to high relative velocities, angular accelerations and stressing Earth limb background illumination which complicates the imaging process. Observing windows on LEO objects are generally 2-4 minutes in duration and begin at ranges up to 4000 km, down to ~50-100 km. NEOSSat can now track LEO satellites in dissimilar orbits and observe objects which conjunct with NEOSSat itself. An example of this LEO capability is NEOSSat's photometric characterization of Starlink satellites during a space-based campaign in 2020. While these megaconstellation objects can be easily viewed, sometimes to the dismay of ground-based astronomers, NEOSSat's space-based vantage point adds additional geometric perspective on these satellites' brightness. NEOSSat's high altitude orbit enables dayside observations of Starlink which is generally unobservable by ground-based observers. Figure 7 shows a single track of NEOSSat imagery on a Starlink satellite observed at ranges of ~2000 km. Figure 8 shows an aggregated light curve of multiple Starlink satellite tracks showing Starlink's unique chevon-shaped brightness signature (light curve) when viewed from orbit. A key finding from this campaign was that darkening treatments added to Starlink satellites by SpaceX helping dim the satellites, to the benefit of ground-based astronomers, has no effect on Starlink brightness characteristics when viewed from space [18].

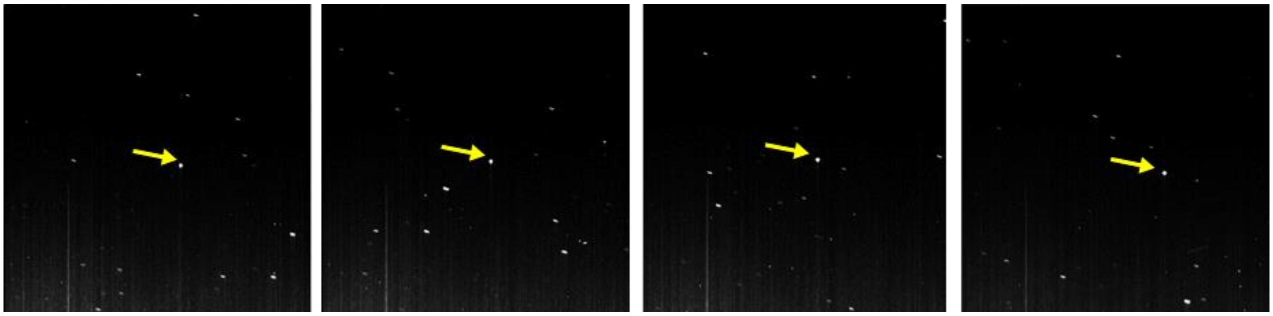


Fig. 12 Single NEOSSat track of a Starlink satellite (marked) (Credit: DRDC)

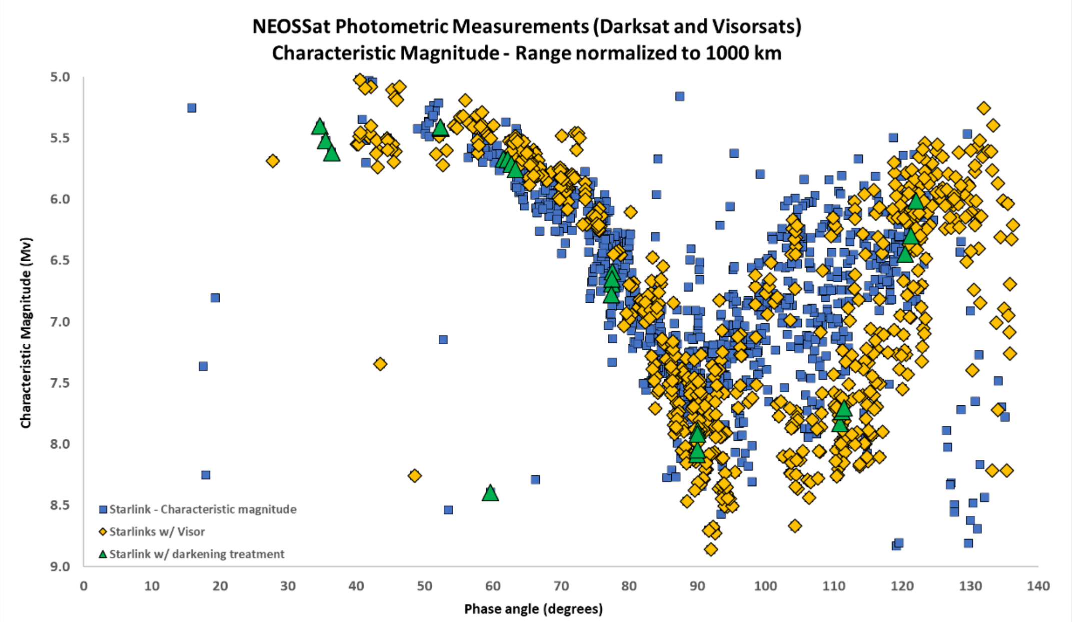
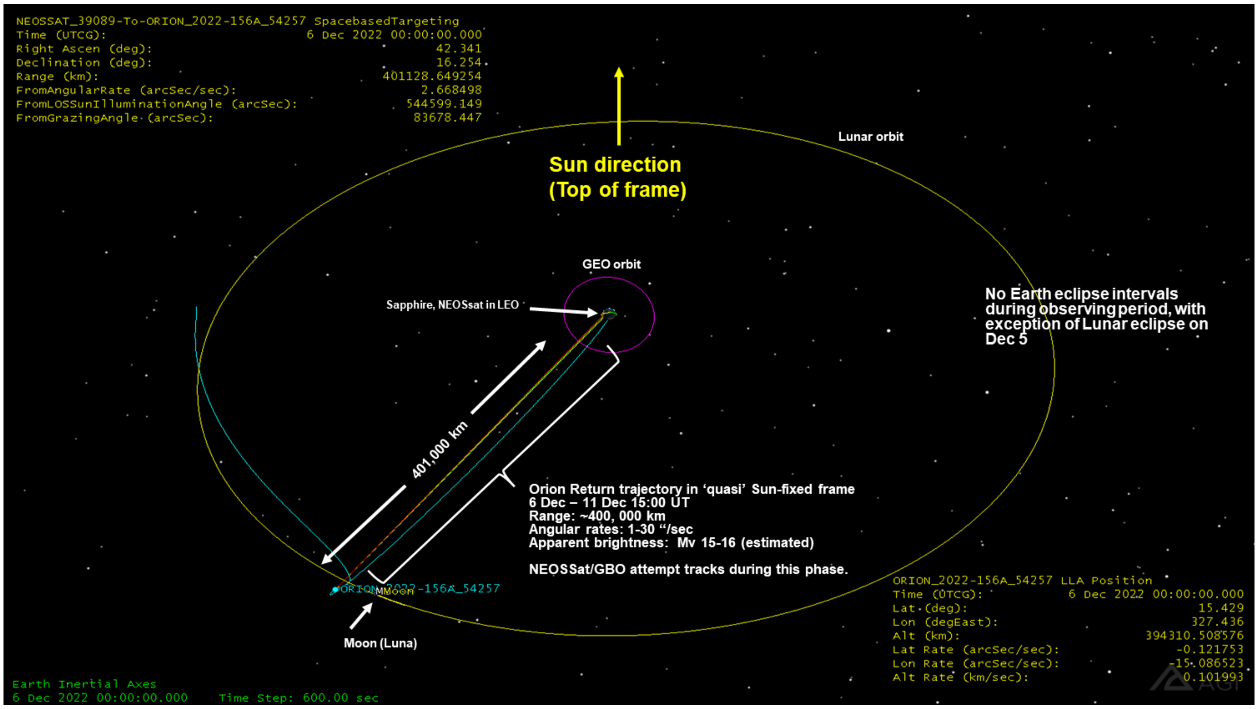


Fig. 13 Aggregated light curve of Starlink satellites. Blue points show measurements on Starlinks without darkening treatments. Orange, green points show satelites with visors or darkened finishes [18]. (Credit: DRDC)

Cislunar observations are possible with NEOSSat provided the targeted object is large, relatively reflective, and does not sit on the direct Earth-moon axis near the Lagrange points. The NASA Artemis-1 Orion uncrewed vehicle was tracked by NEOSSat during its return stages of its mission. This mission return trajectory had favourable illumination geometry (see figure 14) and the Orion vehicle was large (>10 m$^2$) and reflective placing it within NEOSSat's sensitivity range for space object tracking (< *Mv* 16). NEOSSat began observations on Orion when it was at 390,000 km altitude just after its commanded deorbit burn. NEOSSat continued its observations throughout Orion's Earth return trajectory (see figure 15) collecting both astrometric (position) and photometric (brightness) measurements (see figure 16).


```
NEOSSAT_39089-To-ORION_2022-156A_54257 SpacebasedTargeting
Time (UTCG):                              6 Dec 2022 00:00:00.000
Right Ascen (deg):                                         42.341
Declination (deg):                                         16.254
Range (km):                                         401128.649254
FromAngularRate (arcSec/sec):                            2.668498
FromLOSSunIlluminationAngle (arcSec):                  544599.149
FromGrazingAngle (arcSec):                              83678.447
```

No Earth eclipse intervals during observing period, with exception of Lunar eclipse on Dec 5

Orion Return trajectory in ‘quasi’ Sun-fixed frame
6 Dec – 11 Dec 15:00 UT
Range: ~400, 000 km
Angular rates: 1-30 “/sec
Apparent brightness: Mv 15-16 (estimated)

NEOSSat/GBO attempt tracks during this phase.

```
ORION_2022-156A_54257 LLA Position
Time (UTCG):               6 Dec 2022 00:00:00.000
Lat (deg):                                  15.429
Lon (degEast):                             327.436
Alt (km):                            394310.508576
Lat Rate (arcSec/sec):                   -0.121753
Lon Rate (arcSec/sec):                  -15.086523
Alt Rate (km/sec):                        0.101993
```

```
Earth Inertial Axes
6 Dec 2022 00:00:00.000     Time Step: 600.00 sec
```

Fig. 14 Orion Earth return trajectory. GEO orbit shown in purple near the centre of the image (Credit: DRDC)

Figure 15. Orion uncrewed vehicle (centre point) as detected by NEOSSat. Orion was relatively bright despite initially being detected at ranges of 390,000 km. Streaks are stars trailed at the angular rate of NEOSSat's fine tracking slew on Orion's ephemeris. (Credit: DRDC)

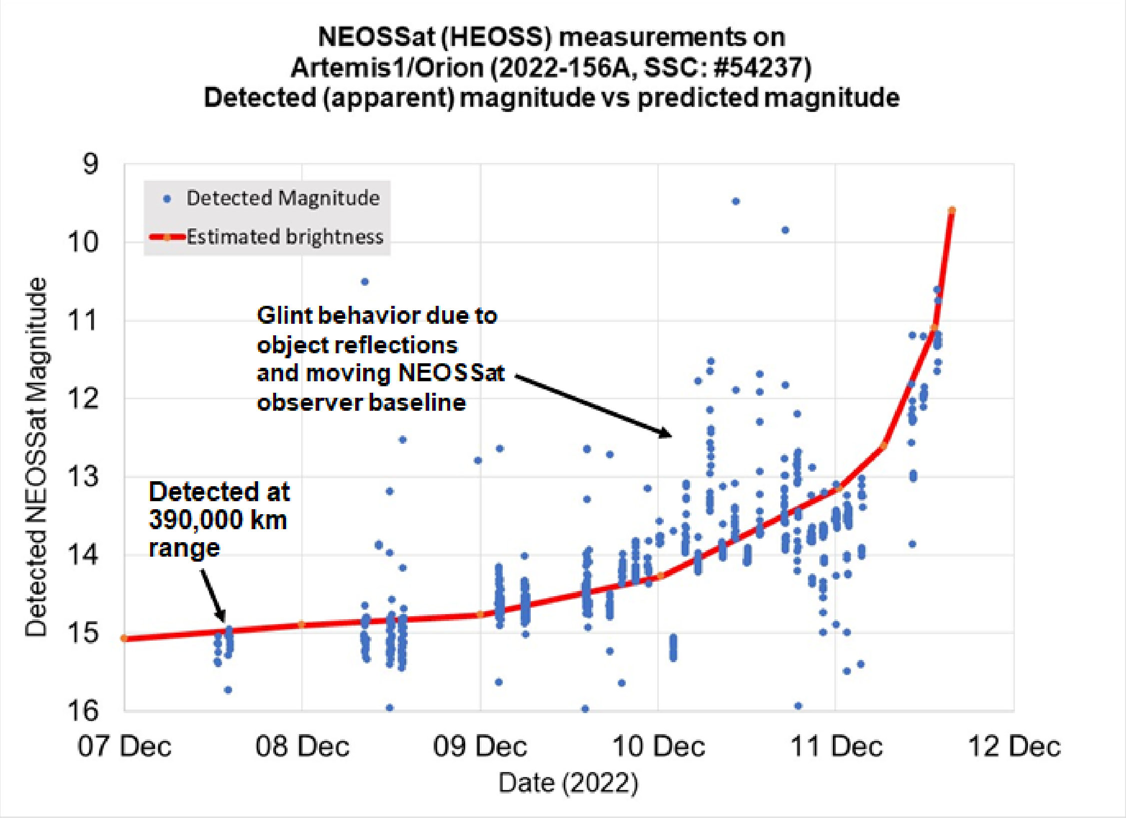


Figure 16. NEOSSat brightness measurements of the NASA Artemis-1 Orion uncrewed vehicle return. The red line is the estimated brightness of Orion. (Credit: DRDC)

## 8. Conclusions

The NEOSSat mission offers many lessons in resilience through innovation through its first ten years of operations. Innovation in the attitude control system flight software has enabled the successful recovery from three critical hardware failures that could have ended the mission. The operations team demonstrated resilience to maintain the system safety during the difficult periods while new flight software workarounds were being devised. The NEOSSat team then developed an innovative new GPS-based coarse attitude sensor to replace the failed magnetometer and developed a new desaturation technique to manage the loss of onboard torque rod controller. These novel techniques restored NEOSSat's capabilities, enabling a return to science operations.

The recoveries, alongside ground segment improvements, enabled a return and expansion of NEOSSat-based science. The team has also innovated in the types of science that can be achieved from a small microsatellite-based space telescope, expanding the research in both space astronomy and space situational awareness. The launch of a Guest Observer program for NEOSSat and the decision to serve all astronomy images through Open Data platforms has brought about new users and new applications for NEOSSat, as well as improved ground processing software pipelines. The Guest Observer program, now in Cycle 5, has executed 33 proposals and delivered hundreds of thousands of images so far. For space astronomy, a platform initially designed for astrometry on near-Earth asteroids and comets is now routinely supporting photometry for numerous applications, including confirmation of exoplanet transits, and performing critical follow-up on near-Earth objects. On space situational awareness, a platform initially designed to observe resident space objects in high-Earth orbit is now routinely being used for observations from LEO to Cislunar orbit. NEOSSat has been witness to some of humanity's great innovations in space, including the human-made coma around the asteroid Didymos following the kinetic strike from NASA's Double Asteroid Redirection Test (DART) and the return of NASA's Orion vehicle, imaged from lunar distances through to Earth re-entry.

Over time, additional software enhancements in both the space segment and ground segment are expected to further expand capabilities. With its open data model, expanding user base and expanded capabilities, it is expected that NEOSSat will remain at the forefront of advanced space-based observation services delivered from an innovative, agile and resilient microsatellite platform.

## Acknowledgements

The authors would like to acknowledge the continued efforts of Microsat Systems Canada Inc (MSCI), prime contractor for NEOSSat microsatellite and ongoing flight software development support, as well as Calian Advanced Technologies in their support of NEOSSat flight operations within CSA's Satellite Operations Centre. Furthermore the NEOSSat team would like to acknowledge the support of its partners in Canada's National Research Council (NRC) and Bishop's University, which developed the automation and image processing pipeline increasing NEOSSat data visibility and access through the CADC portal.

## References

[1] Laurin, D., Hildebrand, A., Cardinal, R., Harvey, W., & Tafazoli, S., "NEOSSat: A Canadian small space telescope for near Earth asteroid detection," *Proceedings of SPIE Astronomical Telescopes and Instrumentation*, Marseille, France, July 2008.
[2] Scott. R. L., Wallace, B., Sale, M., Levesque, M., & Thorsteinson, S., "Toward Microsatellite Based Space Situational Awareness," *Proceedings of the 14th Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS)*, Maui, Hawaii, Sept. 2013
[3] Rucinski, S., Carroll, K., Kuschnig, R., Matthews, & J., Stibrany, P., "MOST (Microvariability & Oscillations of STars) Canadian astronomical micro-satellite," *Advances in Space Research*, Vol. 31, Issue 2, 2003, pp 371-373
[4] Wallace, B., Scott R., Sale, M., Hildebrand, A. & Cardinal, R., "The Near Earth Object Surveillance Satellite: Mission status and CCD evolution after 18 months on orbit". *Proceedings of the 15th Advanced Maui Optical & Space Surveillance (AMOS) Technologies Conference*, Maui, Hawaii, 2014.
[5] Axelrad, P. and Behre, C., "Satellite Attitude Determination Based on GPS Signal-to-Noise Ratio", *Proceedings of the IEEE*, vol. 87, no. 1, 1999.
[6] Wang, C., "Single-antenna attitude determination for Fedsat with improved antenna gain patterns", *Proceedings of the 6th International Symposium on Satellite Navigation Technology*, paper 25, 2003.

[7] Eagleson, S., Abbasi, V., Jackson, N., Scott, R., Thorsteinson, S. & Wessels, R. "Single GPS Antenna Attitude Vector Pair – NEOSSat Recovery" *32nd AIAA/USU Conference on Small Satellites*, Logan, Utah, 2018

[8] Abbasi, V., Jackson, N., Doyon, M., Wessels, R., Sekhavat, P., Cannata, M., Gillett, R., & Eagleson, S. "NEOSSat Recovery Following Magnetometer and Torque Rod Failure", *15th International Conference on Space Operations (SpaceOps 2018)*, Marseilles, France, May 2018

[9] Carroll, K., Hildebrand, A., Balam, D., & Matthews, J (2000). "NESS: Using a Microsatellite to Search For and Track Satellites and Asteroids", *14th AIAA/USU Conference on Small Satellites*, Logan, Utah, 2000

[10] CSA Open Data Portal, https://www.asc-csa.gc.ca/eng/open-data/access-the-data.asp (accessed 30.01.23)

[11] Canadian Astronomy Data Centre (CADC) Near-Earth Object Surveillance Satellite (NEOSSat) https://www.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/en/neossat (accessed 10.04.21)

[12] NEOSSat Science Guest Observation Cycle 5, https://www.asc-csa.gc.ca/eng/funding-programs/funding-opportunities/ao/2022-neossat-science-guest-observation-program-cycle-5.asp (accessed 30.01.23)

[13] International Astronomical Union (IAU) Minor Planet Center (MPC) https://minorplanetcenter.net (accessed 30.01.23)

[14] National Research Council Canada / Dominion Astrophysical Observatory https://nrc.canada.ca/en/research-development/nrc-facilities/dominion-astrophysical-observatory-research-facility (accessed 30.01.23)

[15] International Comets Quarterly (ICQ) http://www.icq.eps.harvard.edu/ or the ICQ Comet Observations Facebook page at https://www.facebook.com/groups/227002358661288/ (accessed 30.01.23)

[16] Gladman, B., Boley, A., Balam, D. "The inbound light curve of 2I/Borisov". *Research Notes of the AAS*. 3 (12): 187. Dec. 2019

[17] Fox, Chris, and Paul Wiegert. "NEOSSat observations of three transiting hot Jupiters." *Monthly Notices of the Royal Astronomical Society* 516.4, 2022

[18] Johnson, C., Scott R.L., Thorsteinson S.E.., "Comparing photometric behaviour of LEO Constellations to SpaceX Starlink using a space-based optical sensor". *22nd Advanced Maui Optical & Space Surveillance (AMOS) Technologies Conference*, Maui, Hawaii, 2021