NEOSSat: Operational and Scientific Evolution of Canada's Resilient Space Telescope

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ABSTRACT

Canada's Near-Earth Object Surveillance Satellite (NEOSSat) is a joint mission operated by the Canadian Space Agency (CSA) and Defence Research & Development Canada (DRDC). Over nearly 10 years on orbit the mission has overcome multiple permanent hardware failures affecting the attitude determination and control subsystem. While overcoming these setbacks the mission has evolved in the type of science carried out both in Space Situational Awareness (SSA) as well as in the domain of astronomical observations. The space telescope routinely performs follow-up observations on recently discovered near-Earth objects (NEOs) as well as observations of those found at low solar elongations not possible from ground-based observatories. NEOSSat has been adapted to collect observations on Low-Earth Orbit (LEO) satellites representing an expansion of NEOSSat's original SSA mission, which was solely dedicated to observation of deep space objects. The mission has also improved in its data sharing capabilities with all astronomy data being made openly available through CSA's Open Data portal as well as the Canadian Astronomy Data Centre and some SSA observations being made available to limited partners through the Unified Data Library (UDL).

1 MISSION BACKGROUND

1.1 Spacecraft Characteristics

The NEOSSat mission was originally conceived nearly twenty years ago in 2004 as a joint project between CSA and DRDC. The mission was the first space-based sensor dedicated to observing both artificial and natural objects. The design was based on the architecture of an earlier Canadian astronomical satellite, MOST. This design would evolve into a generic multi-mission microsatellite bus intended to be easily adapted to new missions.

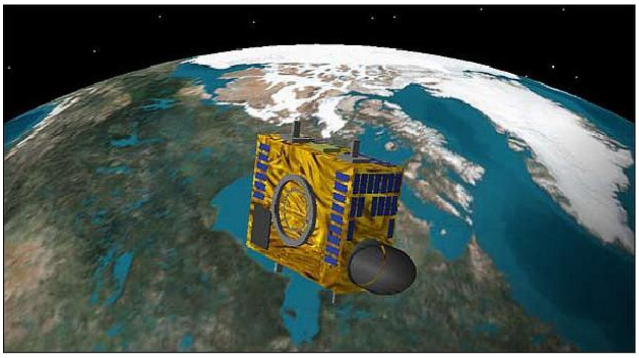

Figure 1. NEOSSat artistic depiction

After some unfortunate delays, the mission was launched in 2013 into a sun-synchronous orbit at approximately 780km altitude. The spacecraft has a mass of 75 kg and dimensions of 1.4m x 0.8m x 0.4m.

The payload consists of a 15-cm Maksutov telescope with a 0.85 degree field of view and 3 arcsec/pixel on two charge coupled devices (CCDs). The CCDs are identically sized 1024x1024 arrays each with an associated read-out electronics (ROE). One CCD and ROE string is used for science imaging with the second being used for the star tracker with both systems sharing the same optical boresight and field of view. Image cadence is based on the size of the image being taken with full-framed images typically having a cycle time of 50 seconds in between successive images. If the exposure duration is longer than the cycle time then the cadence simply becomes the length of the exposure. The telescope contains a large baffle helping prevent stray light for near-sun observations and more recently assisting in preventing stray light from the Earth for certain observations of LEO objects. The payload contains no active thermal control. A passive thermal approach is used through the attitude of the spacecraft. The telescope is currently capable of observing astronomical objects up to an apparent magnitude of 19.5, depending on lighting conditions.

The spacecraft has a fully redundant communications chain and power is provided via body-mounted solar panels, which also double as the spacecraft's coarse sun sensors.

NEOSSat's batteries have just recently began to show some signs of aging with additional constraints being placed on the spacecraft during the recent two eclipse periods in the winters of 2021 and 2022. The spacecraft timing and position knowledge is supplied via two GPS receivers. The spacecraft bus has suffered multiple attitude component hardware failures which will be further detailed in Section 2.2.

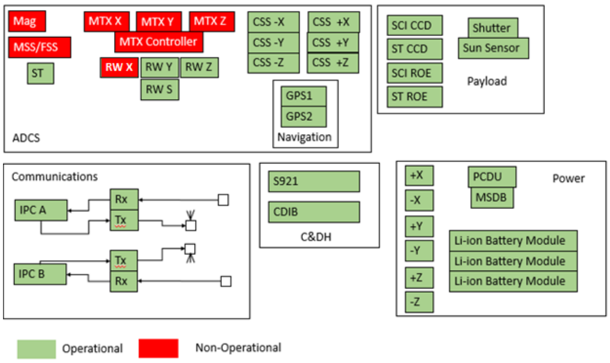

Figure 2. NEOSSat subsystem layout

1.2 Payload Tasking

The spacecraft is tasked with 24 hour schedules each day with time being shared equally between DRDC and CSA. Time-sharing is typically split into half days for each planning session, but if either team has priorities or observations that require additional time then time is allocated accordingly. Both teams have planning tools developed in-house that take into account the constraints placed on the mission in order to create valid spacecraft schedules.

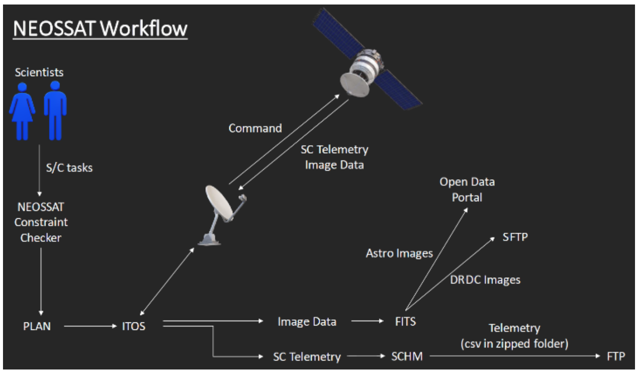

Figure 3. Workflow of NEOSSat data and products

The primary constraint since the failure of the torque rods is the need to enter a dedicated attitude mode to desaturate the momentum wheels as mentioned in section 2.2. This results in a necessary payload outage and also requires the star tracker to reacquire from a lost-in-space position once the desaturation period has finished. The need for star tracker re-acquisition can sometimes result in images not being taken in "Fine Point" while the platform is stable and locked onto a star tracker solution. Given the star trackers narrow field of view (required for precise tracking and pointing), re-acquisition can be more challenging at some targets depending on available guide stars, background illumination and other factors. Improved coarse sensor performance and target selection are continual objectives of the operations team with on-board software updates on the coarse sun sensors and GPS sensors being carried out with the latest FSW release. Additional outages are put in place when passing through the South Atlantic Anomaly (SAA) as the increased radiation activity negatively affects the ROE device, both the imager but also the star tracker.

2 ROAD TO 'NOMINAL' OPERATIONS

2.1 Commissioning Period

Facing a compressed schedule, NEOSSat was launched with a minimal flight software (FSW) suite especially with respect to its ADCS software. Initial work on orbit was dedicated to refining the algorithms, coarse sensors and star tracker software in order to allow the satellite to enter the accurate attitude modes required for astronomical or SSA observations. While the ADCS subsystem was a primary concern additional payload specific challenges were also present. Primary among them was significant read-out noise that had not been present during ground testing. This noise ended up being due to interference from the switching power supply, which was isolated during the first eclipse season. A workaround was achieved, but required the ROE to read each pixel twice and average the result, in effect doubling the time required to take an image [1]. A longer framing time between images can impact certain observation metrics, but a subsequent software update was able to reduce this time and thus reduce the impact. Image quality was further impacted by defocus present due to thermal variation. As NEOSSat contains no active thermal control an optimal thermal point is attempted via attitude control, but this form of control is still limited based on target and other thermal limits.

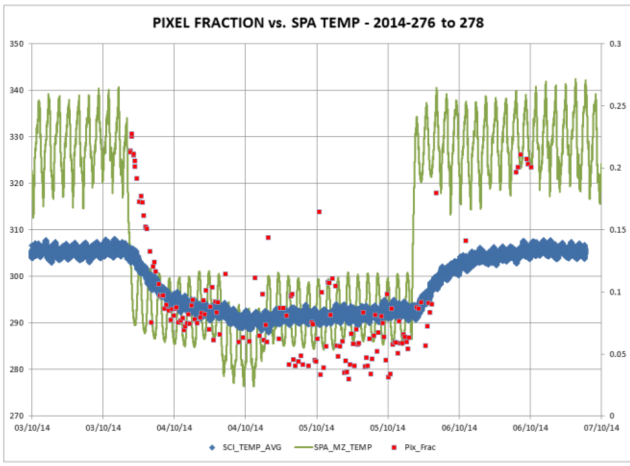

Figure 4. Relation between pixel fraction and temperature

Following a slightly longer commissioning period containing twenty-five FSW updates and multiple adjustments to the ground segment, the NEOSSat mission was ready to carry out its mission.

2.2 Attitude Control Anomalies & Recovery

After a rocky commissioning period, NEOSSat has had the additional misfortune of three hardware failures affecting its attitude determination and control system. The first failure occurred in 2016 when the magnetometer on NEOSSat ceased functioning. Coupled with the sun sensor, the magnetometer acts as a critical input to allow the star tracker to lock and fine pointing to be achieved. The loss of this sensor not only prevented fine attitude pointing but also resulted in NEOSSat completely losing the ability to determine and control its attitude. Therefore, NEOSSat remained in a quasi-tumbling state. The most prudent path forward was to let momentum dissipate naturally while the engineering team explored novel ways to regain positive ADCS functionally onboard the satellite. Originally, the only regular active control commanded during this time was to the Y reaction wheel in order to induce a slow rate "rotisserie" spin to ensure thermal integrity of the satellite. Engineers then updated flight software to implement a new "Sun Point" mode that used only the coarse sun sensors and rate sensors. Once this was implemented and uploaded, NEOSSat was commanded regularly to the "Sun Point" mode which would minimize body rates and keep the spacecraft thermally safe. Due to lack of attitude determination at this time following the magnetometer failure, the satellite was prone to high levels of momentum accumulation because the torque rods did not have sufficient knowledge of the Earth's magnetic field. Momentum build up meant the satellite would only be able to stay in the "Sun Point" state for finite periods of time. A solution was found when it was discovered that a residual magnetic dipole was the primary disturbance contributor to the saturation. Since the orientation of the dipole was fixed and known in the body frame, an equal and opposite torque could be commanded from the torque rods, allowing the momentum to be desaturated. This allowed regular use of "Sun Point" mode. While this mode was not stable enough for science mission imaging, it did allow more reliable and autonomous thermal control and allowed some basic imaging that allowed the engineering to study new solutions to regain attitude determination and control.

Among the many unorthodox ideas considered by the engineering team, it ultimately decided to employ the on-board GPS unit as an attitude sensor in lieu of the failed magnetometer. The approach involved using the orientation knowledge of the GPS receiver antennas in the body and inertial frame, respectively, in order to estimate the look direction of the antennas when paired with reference data from GPS space vehicles [2]. This in effect, would create a new attitude sensor.

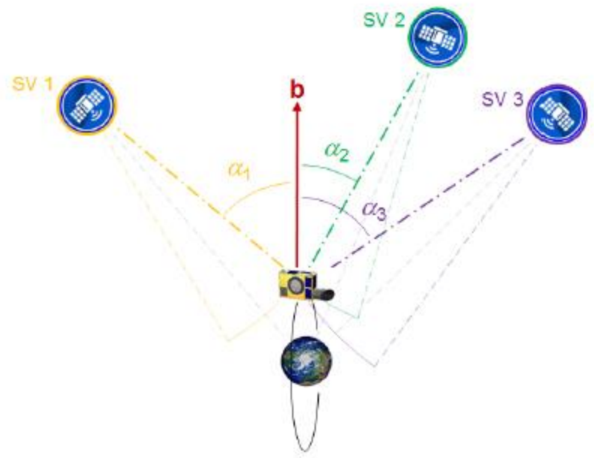

Figure 5. NEOSSat's GPS attitude sensor relies on the knowledge of SV position and their received signal strength [2].

The use of the onboard GPS as an attitude sensor would allow NEOSSat to be able to achieve both the pointing states required for resuming nominal science operations. Testing results from engineering model hardware on the ground confirmed this approach as a successful recovery from the state NEOSSat found itself in. However, before it could be implemented, another major anomaly occurred which threatened the life of the mission.

Later in 2016, another anomaly occurred, this time on the STM32 microcontroller for the torque rods, resulting in a permanent loss of communication with the torque rods. This nullified the desaturation technique previously used to control momentum levels in "Sun Point" state. Upon seeing a sharp increase in spacecraft momentum after the loss of the torque rods, the operations team reverted to idle desaturation, leaving, the wheels in an idle state, barring brief activation for a "flip" manoeuvre to accommodate thermal constraints, and using "Sun Point" sparingly, when momentum allowed. During this time, the engineering team once again worked on defining recovery operations, this time to regain desaturation capability on the satellite.

To solve this problem, the team developed an innovative new control mode called "Dipole Desaturation." In this 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 takes into account NEOSSat's attitude relative to the magnetic field of the earth. The satellite then points itself in such a manner that the disturbance torques from the residual dipole reduce the total spacecraft momentum.

Flight software updates were performed to implement both the GPS attitude sensor and dipole desaturation solutions [3]. The results were positive and the mission regained active control of the ADCS modes required for science operations while simultaneously being able to reduce momentum levels between observations via the desaturation mode. Science resumed in earnest under this new concept of operations and it would be several years before NEOSSat experienced another significant anomaly.

In the summer of 2021 NEOSSat's x-wheel experienced a significant failure. It is suspected that the failure was electrical in nature, as a slow ramp down of wheel speed was observed in the telemetry, rather than a seizure. The spacecraft was put into dipole desaturation mode while recovery operations were attempted. The wheel itself could be turned on, however commanding the wheel to any speed or torque setting, resulted in the wheel shutting itself off.

Another impact of this anomaly is that when the x-wheel was shut off, the rate sensor in the same direction also powers down. This resulted in not being able to use the ADCS sun-point mode without risking significant and rapid momentum accumulation, as it required inputs from no less than all four rate sensors. Therefore, the operations team has stopped using this ADCS mode in operations until a code change can be made to relieve the issue and use less than the four required rate sensors inputs.

To quickly recover to hard-won science operations, the team made the necessary flight software table modifications for a 3-wheel configuration for the spacecraft. It was fortunate in this case, that during assembly and integration, the skew wheel was mounted to be aligned mostly in the x-axis. Therefore, the skew wheel could absorb the majority of the required actuation in the x-axis, with the y and z wheels providing additional compensation.

After approximately two weeks, the new ADCS parameters were uploaded which included the revised matrices for a 3-wheel configuration. Nominal operations resumed and science operations began to be performed at the same as frequency before the wheel failure.

There is occasionally a slight negative effect in terms of performance and image quality after changing to the 3-wheel configuration. Of note, more images may have blurring in the fine pointing mode. The reason attributed to this is that the wheels cannot maintain a directional bias in a 3-wheel configuration as they can in a 4-wheel configuration. With no directional bias implemented, the satellite experiences far more "wheel crossings" when a wheel has to change its direction from positive to negative

2.3 Improved Automation

While much of NEOSSat's time spent during its first few years on orbit was spent on updates and fixes to get the satellite into an operational state. The recent few years have seen a relatively stable vehicle carrying out high-value science on a routine basis. In 2022, the satellite downloaded more than 200,000 images totalling approximately 230GB of astronomy and SSA image data. This stability and return to a new normal has allowed increased automation to be introduced which helps to increase mission up-time as well as lay the foundation for new features and capabilities.

One such change is the automation of the NEOSSat Constraint Checker (NCC). The NCC helps serve as a partial replacement for the Mission Planning System. Automation has been implemented through a script, which periodically checks an SFTP server where payload users dump their schedules whether astronomy or space situational awareness. At a configurable time or when both users have submitted a schedule for the next calendar day the wrapper script starts the merge process. During the merge process, any temporal conflicts are flagged so operators can be made aware. Once successfully merged the schedule passes through a program connected to STK using the API in order to ensure that the schedule does not break any of the spacecraft constraints. These include slew timings, baffle exclusions, desaturation limits, etc. The NCC also creates an STK scenario of the tasked schedule which can help operators in anomaly investigations by providing a 3D visualization of the spacecraft's attitude and orbital position. Finally, the NCC generates several files for use by downstream systems including ground station deconflict and image processing tools. The automation of this system is a major step towards automating the entire NEOSSat planning process which can increase NEOSSat's capabilities by reducing the lead time required for scheduling and permitting "fast-tasking" as routine. Reducing the lead-time is critical for allowing more high-impact observations including NEO follow-ups or potential on-orbit conjunctions whether in GEO or LEO.

Some additional key automation improvements have been made to the telemetry analysis tools in order to aid in anomaly diagnosis and speed up their recoveries. Each real-time contact consists of running a script for detecting a subset of known anomalies and then recovering from them. The biggest improvement from this real-time script is the improvement in time to recover from GPS anomalies. Because the GPS receiver also doubles as an attitude sensor the loss of one receiver while not critical from a timing or positioning perspective significantly reduces the accuracy of the coarse attitude solution thus making star tracker lock harder to acquire. The script allows GPS anomalies to be diagnosed and recovered on the first contact with the satellite after they occur. Additional anomaly detection has also been added with respect to the processing of science data. There are certain anomalies that affect imaging that have no signature provided through spacecraft telemetry and so go unrecognized by the real-time operating system. The initial diagnosis of these types of anomalies required end-users reporting to the operations centre that images were corrupted. Depending on when users were processing the image data this could result in days of images lost to corruption. After implementing a script analysing the meta-data present within FITS headers some versions of image corruption can be recognized as soon as corrupted images are received on the ground. Further work is in progress to capture the remaining edge cases relating to image corruption.

3 NEOSSAT NEAR-EARTH ASTRONOMY

NEOSSat astronomical science operates under a guest observer (GO) program. This allows any Canadian astronomer and their international partners to submit proposals for observations to be carried out by NEOSSat. To date ten different principal investigators have submitted proposals [4]. The majority of these proposals have targeted the field of exoplanet photometry, but the proposal that will be detailed in this section is *Morphology and Astrometry of Near-Sun Comets and Unusual Asteroids*. Observation of these objects is accomplished using a 'sensor bundle'. This bundle consists of the NEOSSat orbiting telescope (0.15-m Maksutov) , the 1.82-m Plaskett telescope at the Dominion Astrophysical Observatory (Herzberg Astronomy and Astrophysics, National Research Council of Canada) and the 0.76-m Baker-Nunn Schmidt telescope of the Rothney Astrophysical Observatory (University of Calgary). Each sensor has a specific strength: the Plaskett telescope has a relatively small field (22' x 11') but can reach (Sloan g' filter) magnitudes as faint as magnitude 22. The Baker-Nunn Schmidt has a very large (19.7 degrees squared) field of view and a limiting magnitude of approximately G(Gaia) 18.5. Observational results from the other two sensors are published elsewhere and the results from NEOSSat will be shared here. The results from program cycles 1 and 2 relating to NEOSSat, as well as a description of the associated image processing pipeline and astrometric reduction procedures have been described in an earlier conference paper [5]. In this paper, the results from GO cycles 3 - 5 will be presented. The current period covers more than 300 orbits of the spacecraft that were devoted to the observation of 63 cometary objects, resulting in the publication of more than 2200 astrometric positions in the publications of the International Astronomical Union (IAU)

3.1 Observational Methodology

NEOSSat was designed to survey the near-sun space from solar elongation 40 - 60 degrees, however, we have acquired useful astrometric data at much lower solar elongation using un-sharp masking techniques to minimize glare from the sun. The distribution of field 'visits' are shown in Figure 6 as a histogram of the solar elongation of 308 field centres. There are 25 successful visits to fields with solar elongation less than 40 degrees. Several of the more extreme values were reached during eclipse season, when it is possible to use the earth limb to occult the sun.

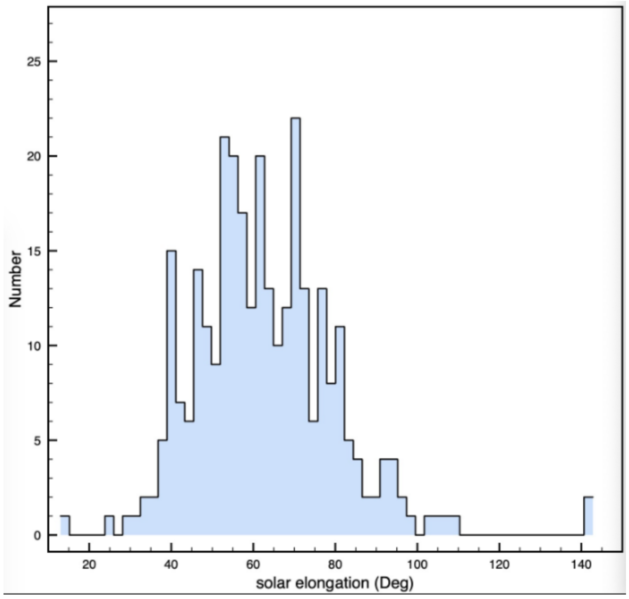

Figure 6. The distribution of 308 field centers as a function of solar elongation

Figure 7 shows the distribution of predicted total magnitudes of the complete sample of near-sun comets. Typically the spacecraft's limiting magnitude for long (motion-compensated) image stacks is around G(Gaia) = 18.5. There are several objects detected at magnitude 20 and these were new and active comets that were much brighter than predicted.

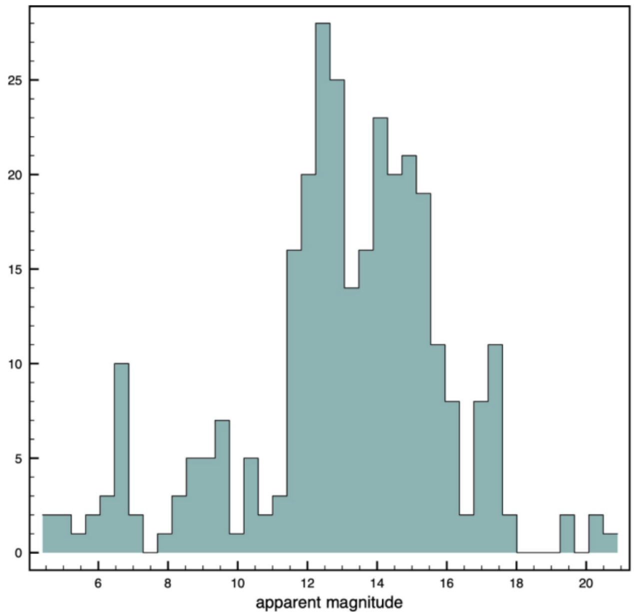

Figure 7. The published apparent magnitudes of 63 comets during 308 orbits

Approximately one third of each orbit is dedicated to the acquisition of a series of images with the exposure lengths calculated as a function of the plane-of-sky motion vector of the target object. Figure 8 is a histogram of the plane-of-sky motion rates of the sample of comets, as measured from 308 image stacks. Extreme rates were manifested by asteroids 2019 XS (1426 seconds of arc per hour) during its close earth encounter in February 2021 at seven times the lunar distance and Apollo asteroid 2016 AJ193 in August 2021 (840 seconds of arc per hours) during it encounter at 10 lunar distances.

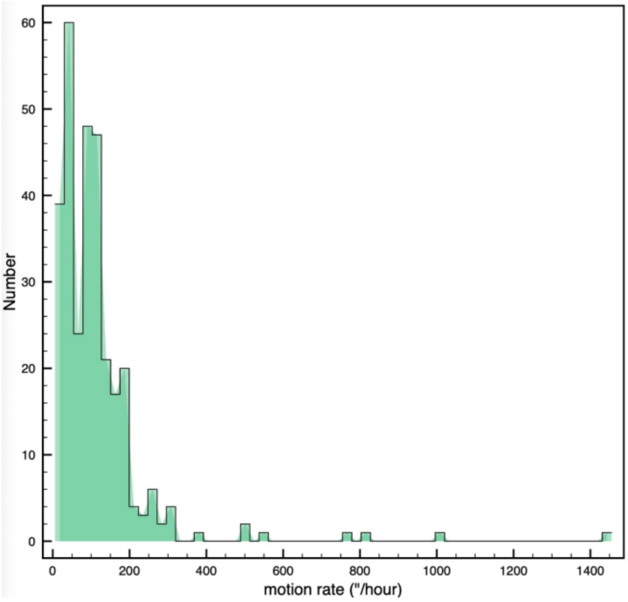

Figure 8. The measured motion rates of all target objects during 308 orbits

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 (i.e. 2MASS, PPM) . 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) 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 Figure 9 to illustrate the effects of parallax.

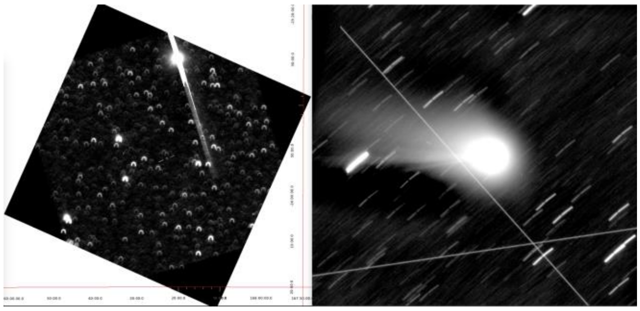

Figure 9. Hazardous asteroid (99942) Apophis (left) on UT 2021 Feb. 18 at a geocentric distance of 0.126 AU. The image stack is a co-addition of 32-66 second exposures. The parallactic effect of the spacecraft in its polar orbit is clearly seen. The long-period comet C/2020 F3 (right) on UT 2020 Aug. 01 at geocentric distance of 0.793 AU. The image stack is a co-addition of 26-28 second exposures.

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.

3.2 Near-Sun comet astrometry and morphology

NEOSSat has observed a variety of Near-Sun comets with the objective of better understanding the behaviour of their nuclei as well as their tails. The comets observed over the previous two Guest Observer cycles have been detailed in tables on the following pages. Hyperbolic or near hyperbolic orbits are listed in Table 1.

Table 1. Interstellar and Hyperbolic Comets

Object	q (AU)	e	M1
2I	2.007	3.356	13.7
C/2017 K2	1.800	1.001	9.1
C/2019 F1	3.590	1.004	9.9
C/2019 L3	3.554	1.001	5.6
C/2020 K5	1.536	1.002	15.1
C/2019 U5	3.623	1.001	6.2
C/2021 A1	0.615	1.001	12.4
C/2022 E3	1.112	1.000	9.8
C/2020 H6	4.703	1.001	6.5
C/2021 Y1	2.033	1.001	11.9
C/2020 S4	3.369	1.001	11.9
C/2022 A2	1.735	1.001	8.1
C/2018 F4	3.440	1.002	5.3
C/2019 J3	2.373	1.001	15.3
C/2020 F5	4.326	1.002	7.6

C/2020 J1	3.355	1.000	6.2
C/2020 K8	0.474	1.000	16.8
C/2020 P1	0.342	1.000	15.3
C/2020 V2	2.228	1.001	7.0
C/2021 E3	1.777	1.001	11.1
C/2021 O3	0.287	1.001	18.6

Notable among the hyperbolic comets in Table 1 is comet 2I/(Borisov). 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 period of 13 days was found from more than 6000 images obtained between September 2019 and February 2020 [6].

Long period comets are in Table 2 and short and intermediate period comets have been listed in Table 3

Table 2. Long-Period Comets

Object	q (AU)	e	M1
C/2021 A2	1.410	0.994	8.1
C/2019 N1	1.700	0.999	11.1
C/2021 A4	1.140	0.973	13.6
C/2020 R4	1.030	0.989	12.8
C/2021 A7	1.967	1.000	11.6
C/2019 T2	2.646	0.998	10.7
C/2019 T4	4.242	0.999	4.2
C/2020 T2	2.055	0.993	9.4
C/2021 F1	0.995	0.996	13.3
C/2020 Y2	3.132	0.997	10.5
C/2021 X1	3.234	0.999	6.2
C/2022 R2	0.633	0.998	16.6
C/2017 T2	1.615	0.999	10.2
C/2018 W1	1.360	0.937	14.0
C/2019 A9	1.426	0.963	10.3
C/2019 D1	1.577	0.988	11.9
C/2019 K5	2.035	0.986	11.2
C/2019 U6	0.914	0.998	13.2
C/2020 A2	0.978	0.999	15.1
C/2020 F3	0.295	0.999	12.1
C/2020 F8	0.430	0.999	11.6
C/2020 K1	3.074	1.000	7.4
C/2020 Q1	1.315	0.978	11.7
C/2020 S3	1.315	0.978	11.7
C/2021 S3	0.398	0.998	13.0
C/2021 P4	1.080	0.997	10.8

Table 3. Intermediate Period Comets

Object	q (AU)	e	M1
4P/(Faye)	1.619	0.577	11.1
10P/(Tempel 2)	1.412	0.538	14.3
15P/(Finlay)	0.992	0.717	15.0
19P/(Borrelly)	1.306	0.638	9.7
22P/(Kopff)	1.555	0.548	11.9
45P/(Honda-Mrkos-Pajdusakova)	0.532	0.824	13.7
46P/(Wirtanen)	1.055	0.658	16.5
67P/(Churyumov-Gerasimenko)	1.211	0.650	12.8
73P/(Schwassmann-Wachmann 3)	0.972	0.685	14.1
81P/(Wild 2)	1.597	0.537	8.6
106P/(Schuster)	1.529	0.594	11.2
116P/(Wild 4)	2.187	0.372	7.7
118P/(Shoemaker-Levy 4)	1.882	0.450	12.0
119P/(Parker-Hartley)	3.027	0.292	9.9
141P/(Machholz 2)	0.808	0.736	17.1
156P/(Russel-LINEAR)	1.330	0.615	12.7
169P/(NEAT)	0.607	0.767	16.9
252P/(LINEAR)	0.996	0.673	16.4
P/2016 J3	0.526	0.812	16.0
C/2021 K1	2.498	0.804	6.6
C/2021 Q5	1.234	0.624	15.7

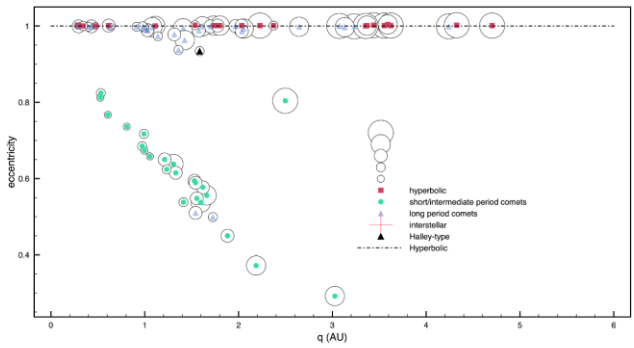

Figure 10. Perihelion distance (AU) versus orbital eccentricity for all observed comets. The size of the circles superposed on each data point are a function of the absolute magnitude of each object.

Figure 10 above details the orbital characteristics of the comets analysed. Objects that lie on or above the line at eccentricty of 1 are in near-hyperbolic orbits. There is one point missing from the plot, the interstellar comet 2I/(Borisov) with an eccentricity of 3.356.

Motion-compensated image stacks are ingested to a master database of comets in a standardized manner, for purposes of easy public access and for formal archiving via the International Comet Quarterly (a publication devoted to comets since 1978) and the Cometary Science Center (and Cometary Science Archive hosted on computers at the Earth and Planetary Sciences Department, Harvard University).

3.3 Near-Earth asteroid Observing Campaigns

NEOSSat was involved in five international asteroid campaigns: 2019 XS, Apollo (99942), Apophis [6]during its moderately-close encounter in March 2021 (0.126 AU) and Aten asteroid (66391) Moshup = 1999 KW4 during its earth encounter in May 2019. Although there was no direct CSA involvement in NASA's Double Asteroid Redirection Test (DART) kinetic experiment, NEOSSat did monitor the event both during the kinetic strike on September 26 and obtained follow-up observations afterwards on November 13 and December 15, 2022. NEOSSat was able to slew onto the asteroid system within 14 minutes of the event and every 4 minutes afterward (Figure 11). An expanding cloud of impact debris is seen extending for thousands of kilometres. Each stamp is 15x15 minutes of arc with east (left) and north (top). The red bar shows a span of 4000 km at the distance (0.076 AU = 11,324,000 km) of the asteroid.

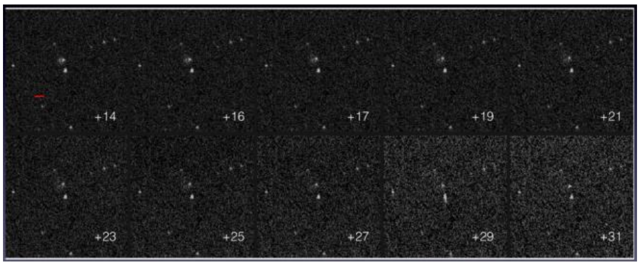

Figure 11. Near-Earth asteroid (65803) Didymos as seen during the kinetic strike starting on UT 2022 Sept. 26 at 23:28 (14 minutes post-impact) and every 2 minutes thereafter (top-left to lower right).

4 SSA EXPERIMENTS

NEOSSat continues to expand the science it is doing as a space based sensor dedicated to SSA, notably with respect to the LEO regime. With respect to its original mission dedicated to High Earth Orbit Space Surveillance (HEOSS), NEOSSat continues to track satellites in the geostationary regime on a regular basis. While routine observations are carried out there were also several dedicated exercises with DRDC partners where NEOSSat played varying roles of importance. These exercises included both fast-tasking of the vehicle, but also rapid processing and delivery of the resulting images in order to potentially re-task NEOSSat based on the observations. NEOSSat also began taking more observations of LEO constellations including the Starlink, OneWeb, and Flock constellations. While astronomers on the ground have raised concerns about the interference of Starlink satellites in optical telescopes, NEOSSat observed the satellites from an alternative vantage point and observed their photometric profile. The results of this experiment can be found in an earlier publication [8]. The most novel experiment perhaps carried out by NEOSSat in recent time was the tracking of the Orion Capsule during the Artemis I mission. Artemis I was the first integrated flight test of the Space Launch System (SLS) rocket and the Orion spacecraft. During the mission, the uncrewed Orion capsule completed multiple orbits and flybys of the moon. While Orion was at a lunar distance, NEOSSat began taking observations. The vehicle was detectable at these distances by NEOSSat (390,000 km) at a magnitude of approximately 15. Observations were continually carried out from December 7th through December 11th. Figure 12 showcases the final image taken shortly before capsule re-entry. NEOSSat was faced with a low grazing angle in order to achieve line of sight. In order to capture the image successfully NEOSSat slewed into the Earth limb immediately before imaging to maintain a stable attitude despite significant light pollution from the Earth.

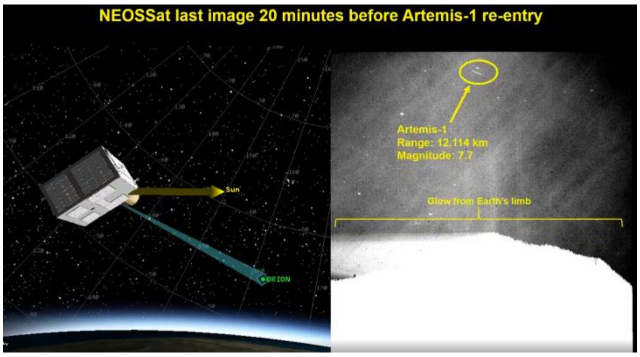

Figure 12. Geometry of NEOSSat compared to Orion and the Earth (left). NEOSSat image of Orion during reentry (right).

5 NEOSSAT DATA PIPELINE

5.1 Image Cleaning

While some NEOSSat users have developed their own pipeline for image cleaning, other users utilize some variation of the cleaning software developed by Bishop's University in support of exoplanet transit photometry [8]. It is this image cleaning pipeline that is currently being integrated into the NEOSSat operational environment to improve the image quality for all users. The details have been laid out in earlier papers [9], but this image cleaning pipeline involves overscan correction and dark subtraction in order to remove unwanted effects from the images. Increasing the signal to noise ratio of images and expanding the use cases of the platform into the realm of exoplanet transit photometry. This has allowed NEOSSat to contribute to exoplanet follow-up observations most notably those discovered by TESS including hot Jupiter's [10]. Image cleaning does result in additional data storage requirements. Not only are cleaned images larger, but some users as stated may have alternative methods of cleaning which means that raw FITS images still need to be stored. Finally the dark subtracted images are also generated which means each image will have three versions to be stored and archived. With the increased imaging activity upon resumption of nominal operations the original storage solution for NEOSSat images was already quickly approaching the limits of its viability. Astronomy images have recently been moved to CSA's new Open Data portal, a larger and faster cloud-based repository, enabling cleaned and dark corrected images to be stored and retrieved in a timely manner.

5.2 Data Sharing

The NEOSSat mission is a strong proponent of open data. All astronomy based images including all images of Near-Earth objects are published on the Government of Canada's Open Data portal immediately after being downloaded and processed. Astronomy images are also hosted by the Canadian Astronomy Data Centre. Both of these locations allow open and free access to thousands of quality astronomical images. As mentioned earlier, NEOSSat observations of recently discovered or interesting asteroids and comets are all submitted to public scientific bodies including the Minor Planet Center in order to assist with orbit determination and characterization of primarily near-sun objects. In another contribution to expanding the open and transparent data sharing policy of the mission more recently NEOSSat has taken to publishing its definitive and predicted ephemeris files on the CSA Open Data portal, a public facing website. This falls in line with UN-COPUOS guidelines for long-term sustainability of space [12], which encourage sharing orbital information. The ephemerides are published both in the STK .e format as well as in the CCSDS OEM format. These ephemeris products are generated during the weekly run of NEOSSat's orbit determination system. The definitive ephemerides cover a period of seven days, while the predicted ephemerides cover a period of ten days. For the moment, the ephemerides contain position and velocity information and position covariance. Velocity covariance will be added with the next update to the orbit determination system. After generating the predicted ephemerides they are automatically converted to OEM format and submitted to Space-Track in order to help improve any screening containing NEOSSat as a primary or secondary object. Accurate position knowledge of objects involved in conjunctions is critical to generating reliable data that can be confidently acted upon. Measurements of resident space objects are also submitted to the Unified Data Library when possible by DRDC. The Unified Data Library hosts space situational awareness from several different organizations including government, commercial, and academic organizations and helps collate data in the realm of space domain awareness. Debris detection and maintaining accurate orbit knowledge of objects benefits from an open approach when it comes to data, and the NEOSSat mission is a proud proponent of this philosophy.

6 NEXT STEPS

NEOSSat is a much different mission than it was when launched. The platform has continued to evolve both from a spacecraft perspective as well as a ground systems perspective. While NEOSSat has suffered several critical ADCS failures, work continues to be done with the ADCS system in order to refine and improve the new sensors and modes of operations in order to ensure the system performs as accurately as possible. Work is currently being carried out to perform additional troubleshooting on the failed X-wheel to determine if a recovery of the actuator is possible. Additional characterization of star tracker acquisition rates and areas of the sky where it performs best could also help increase the reliability of images being taken in the correct state as well as reduce the time currently dedicated in task planning for star tracker acquisition after exiting desaturation mode. Another enhancement under consideration is a "fine" desaturation mode which allows the spacecraft to enter a momentum negative mode while still maintaining a star tracker solution permitting the spacecraft to idle between tasking periods, but not require the additional period for star tracker re-acquisition. When dealing with an environment as changing as the near-Earth space speed and responsiveness are two critical factors. For this reason, reducing the headway required for nominal tasking and improving fast-tasking capabilities can also help improve the scientific capability of the observations that NEOSSat collects. Fast-tasking has been successfully demonstrated on several occasions but additional ground segment optimizations are being investigated to improve the process for fast tasking and image delivery for targets of opportunity that require short turn-around times. Introducing additional automation into the ground system will help with this as well as help recover from any anomalies more rapidly ensuring NEOSSat's uptime and time to recovery are optimized as much as possible.

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