NEOSSat Canadian Satellite Tasking List: Maintaining Sovereign Object Orbit Custody with a Single Space-Based Sensor

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ABSTRACT

This paper summarizes results from a two-year campaign of repeated imaging of the Canadian Satellite Tracking List (CSTL), a collection of Canadian-attributed resident space objects. It investigates an experiment into the feasibility of maintaining long-term custody of many objects with a single space-based sensor. The Near-Earth Orbit Surveillance Satellite (NEOSSat) is a research micro-satellite space telescope performing Space Domain Awareness (SDA) experimentation for Defence Research and Development Canada (DRDC). At the experiment start, fall 2020, CSTL objects were tracked consistently by NEOSSat, with revisit periods varying from daily to several weeks. The CSTL contains inactive and active Canadian space objects, of which 27 are at or near Geosynchronous (GEO) orbit and 4 in Low Earth Orbit (LEO), satisfying NEOSSat's visibility and tracking capabilities.

This paper focuses on the exploitation of metric observations of both well and infrequently-tracked objects. Photometric results from NEOSSat's optical observations were employed to refine tasking opportunities on difficult-to-track objects. CSTL object orbit determination results from repeated measurements are presented – on well-sampled functioning and derelict GEO objects and infrequently spaced LEO to LEO measurements. As a space-based sensor, NEOSSat relies on ground station contact to uplink taskings and downlink imagery, leading to multi-day delays between tasking requests and observation creation. Given NEOSSat's narrow 0.85-degree field of view, tasking requests require decent a-priori orbital estimates. A summary of results maintaining orbit custody and re-imaging CSTL objects long term is presented, using single sensor-derived element sets.

In the final phase, batch least squares orbit estimation was employed to generate orbits from 2023 observations. NEOSSat was tasked with using these updated orbits to evaluate the accuracy of our orbit determination methods and the overall pipeline. This process was repeated twice following the initial observation. Ultimately, 20 out of 27 satellites were successfully re-observed on the second revisit with in-house orbits. The results of this experiment demonstrate that a single sensor can maintain long-term custody of Canadian objects and that, with the current state of Canadian-owned objects in space, a national catalogue is well within reach of its operational community.

1. BACKGROUND

Earth orbit is becoming increasingly congested, making space surveillance and space situational awareness (SSA) ever more critical for ensuring the safety and functionality of these assets. Among these satellites, 27 Canadian-owned geostationary satellites are in orbit. However, at the time of this report, the Canadian government does not maintain an independent monitoring catalogue of these objects. Instead, it relies on the United States Space Surveillance Network (SSN) as its primary source for satellite orbital data.

The primary objective of this experiment is to assess the feasibility of using a single space-based sensor, specifically NEOSSat, to maintain long-term orbital custody of Canadian-owned satellites, focusing on those in the Geosynchronous orbital regime. This research builds upon a 2021 experiment that conducted photometric characterization of Canadian GEO satellites under similar observational conditions [1]. This study aims to demonstrate the potential of establishing a small-scale satellite tracking operation with just one sensor, comparing the metric accuracy of precision ephemerides acquired from the SSN against the orbits generated by the observations taken during the experiment.

The benchmark for the success of this experiment is the propagation of orbits with sufficient metric accuracy to enable subsequent tasking of NEOSSat for future observations. Accurate orbit determination entails a range of modelling and simulation techniques to account for Earth's effects. To precisely model a satellite's orbit, obtaining consistent and accurate observations over an extended period is crucial. Depending on the satellite's orbital regime, factors such as atmospheric conditions, solar radiation, and Earth's oblateness must be considered. Continuously updating orbit predictions based on new observations is essential to maintain accuracy, as outdated information can rapidly diminish precision. Events like satellite maneuvers or tumbling can also impact orbit predictions.

Currently, Canada operates two space-based sensors: Sapphire and NEOSSat. The DRDC-owned Near-Earth Orbit Surveillance Satellite (NEOSSat) is a research microsatellite telescope designed for SSA experimentation and asteroid astronomy. Jointly operated by DRDC and the Canadian Space Agency, NEOSSat shares satellite time on a rotating schedule between the two organizations, limiting observation frequency and duration. The Resident Space Objects (RSOs) observed by NEOSSat vary by experiment, and currently, NEOSSat does not maintain any orbital catalogues or long-term custody of objects. NEOSSat is mainly scheduled on publicly available TLEs produced by the SSN.

Orbiting at an altitude of 785km, NEOSSat is equipped with a 15-cm optical telescope, an E2V 47-20 science CCD, and is capable of imaging objects to within 45 degrees solar elongation of the Sun. RSOs are primarily imaged using Track Rate Mode (TRM), a satellite imaging method in which NEOSSat's camera slews at the angular rate of the satellite. This technique detects objects as points rather than streaks moving across the frame. Sequences of these images are then stacked to reject random energetic particle radiation signatures and enhance the RSO signal-to-noise ratio. This approach also provides a limiting visual magnitude of 16 when stacking NEOSSat imagery during image processing [2].

2. EXPERIMENT STRATEGY

2.1 Observation Methodology

In this experiment, we comprehensively analyzed NEOSSat's capabilities for maintaining long-term custody of Canadian-owned satellites, particularly in the geosynchronous orbital regime. The study was divided into three phases: observation, photometric characterization, and orbital metric analysis. From October 2020 to the present, NEOSSat periodically tracked 32 Canadian space objects. This paper focuses on the orbit determination aspect of our experiment, which aims to demonstrate the feasibility of establishing a small-scale satellite tracking operation using a single space-based sensor and testing whether we can consistently observe our satellite list through the refeeding of custom orbits.

The CSTL is a specialized collection of Canadian satellites divided into two primary categories based on their orbits: Geosynchronous Orbit (GEO) and Low Earth Orbit (LEO). The total number of tracked satellites comprises 28 GEO satellites and 4 LEO satellites. Throughout the 2022 observation period, NEOSSat successfully captured 11,387 observations. The frequency of these observations varied from satellite to satellite due to factors such as orbit type, satellite visibility, and operational conditions. A breakdown of observations per satellite and their revisit frequency is provided in Table 1.

The NEOSSat microsatellite was tasked using an automated scheduler developed in-house in Python. The scheduler takes TLE input of RSOs and the desired number of tracking periods as inputs to optimize our observation plan. Its algorithm seeks to find the optimal path to visit each satellite to maximize the number of successful taskings per night.

NEOSSat has several viewing constraints that must be considered when planning tasking schedules, including a solar exclusion angle of no less than 45 degrees. The RSO must be in direct sunlight outside the Earth's shadow. Furthermore, the angular rate of the RSO relative to NEOSSat, which is the rate at which the position of the RSO changes from NEOSSat's perspective, was required to be under 220 arc-seconds per second. These constraints are naturally achievable to all GEOs from NEOSSat but greatly limit the observable time available to LEOs, which are at a much closer range. Fig. 1 shows the viewing geometry possible from NEOSSat to the GEO belt. Another constraint was the grazing angle of the RSO above the Earth's limb, which should be greater than 10 degrees. Lastly, lunar and planetary exclusion angles were required to be greater than 4 degrees to avoid interference from bright celestial bodies. A complete list of NEOSSat's viewing constraints can be found in [3].

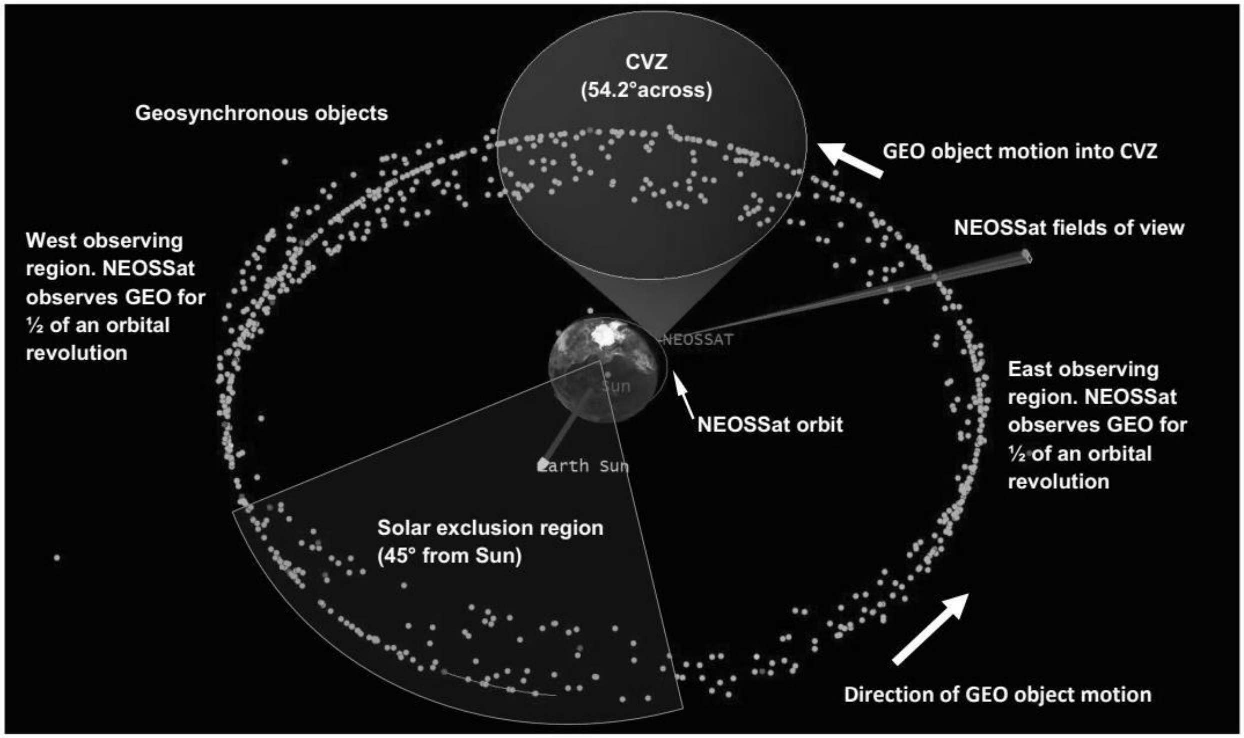

Fig 1. NEOSSat Geostationary object observing geometry with viewing regions [3]

The scheduled track of each Geosynchronous Orbit (GEO) object was structured as a series of five images, with a 30-second interval between each image capture. The exposure duration was variable and largely dependent on the angular velocity of the target object, with the majority of exposures ranging between 2 and 5 seconds. Our experiment aimed to capture between 2 to 5 tracks for each of the 27 GEO objects during each observation day. However, due to various constraints, including hardware limitations, accessibility of the observation windows, and the logistical challenges associated with shared time allotments of NEOSSat, it was occasionally not feasible to image every satellite within every observation window, especially the LEO satellites.

Additionally, a significant variation exists between successful image capture and successful observation. Successful observation is when an object is detected and correlated within the image post-processing. If the satellite was successfully imaged but had issues with the image quality that prevented correlation, the image was discarded and not considered a successful observation.

The diversity of these factors from satellite to satellite led to a considerable variation in the number of successful observations per object, as outlined in Table 1. These limitations underscored the pressing need to optimize the observation schedule to maximize data collection within the limited observation time. The optimization strategies developed during this experiment to address the challenges associated with space-based imaging and observation of GEO objects will likely inform the methods taken in future experiments.

2.2 Data Processing

The received imagery is processed via an internal image processor named SQUID3 (Semi-Quick Detection, 3rd iteration). Constructed on MATLAB, SQUID3 processes the image set by filtering out background effects and artifacts, such as cosmic rays and noise spikes, common corruptive artifacts in space-based imaging. This step ensures the isolation of star streaks and satellites in the images, allowing for more accurate and consistent object detection. Detailed investigation of the image processing and streak detection algorithms is beyond the scope of this paper, and further reading can be found in [4].

The processed observations consist of angles-only data, specifically the SSN ID, timestamp, right ascension, and declination of the RSO in J2000 coordinates, corrected for all aberrations. Also included are the precise coordinates of NEOSSat for each observation derived from its onboard GPS navigation solution. The observation data serves as input to Orbit Determination Tool Kit (ODTK) software [5], which uses this data to compute orbits for each satellite.

Table 1: NEOSSat CSTL Observation Summary 2022 – GEO

Object Name	**Object SSN #**	**Status**	**# Of Successful Observations**	**Mean Time Between Tracks (Days)**
ANIK A1	6278	Defunct	84	9.3
ANIK A2	6437	Defunct	126	7.1
ANIK A3	7790	Defunct	156	5.9
CTS	8585	Defunct	174	5.1
ANIK B1	11153	Defunct	235	3.5
ANIK D1	13431	Defunct	583	1.7
ANIK C3	13652	Defunct	587	1.7
ANIK E2	21222	Defunct	428	2.4
ANIK E1	21726	Defunct	483	2.1
ANIK F1R	28868	Active	767	1.3
ANIK F1	26624	Active	429	2.4
ANIK F2	28378	Active	406	2.5
ANIK F3	31102	Active	524	2.0
ANIK G1	39127	Active	838	1.2
TELSTAR 18V	43611	Active	825	1.2
CIEL-2	33453	Active	579	1.7
NIMIQ-1	25740	Active	673	1.5
NIMIQ-4	33373	Active	550	1.9
NIMIQ-5	35873	Active	454	2.2
NIMIQ-6	38342	Active	420	2.4
TELSTAR 11N	34111	Active	495	2.1
TELSTAR 12V	41036	Active	666	1.5
TELSTAR 14R	37602	Active	437	2.4
TELSTAR 19V	43562	Active	468	2.3
Total Obs - 2022			11,387	Mean revisit time: 2.8

Table 2: NEOSSat CSTL Observation Summary 2022 - LEO

Object Name	**Object SSN #**	**Status**	**# Of Successful Observations**
ALOUETTE 1	424	Defunct	36
ALOUETTE 2	1804	Defunct	81
ISIS 1	3669	Defunct	44
ISIS 2	5104	Defunct	112

3. OBSERVATIONS

Table 1 shows the GEO satellites observed as part of the CSTL experiment over 2022. As can be seen in the table, smaller objects (e.g. Anik A series) produce much fewer observations than larger objects. Furthermore, some of the most observed objects were observed in clusters with other objects on the list, resulting in multiple unintended observations (e.g. ANIK F1R/G1).

As can be seen in Table 2, access to LEO satellites was considerably less frequent due to their lower altitude and, consequently, higher orbital velocity, which presented unique challenges for imaging. The infrequent revisit windows prevented long-duration orbit determination on these objects.

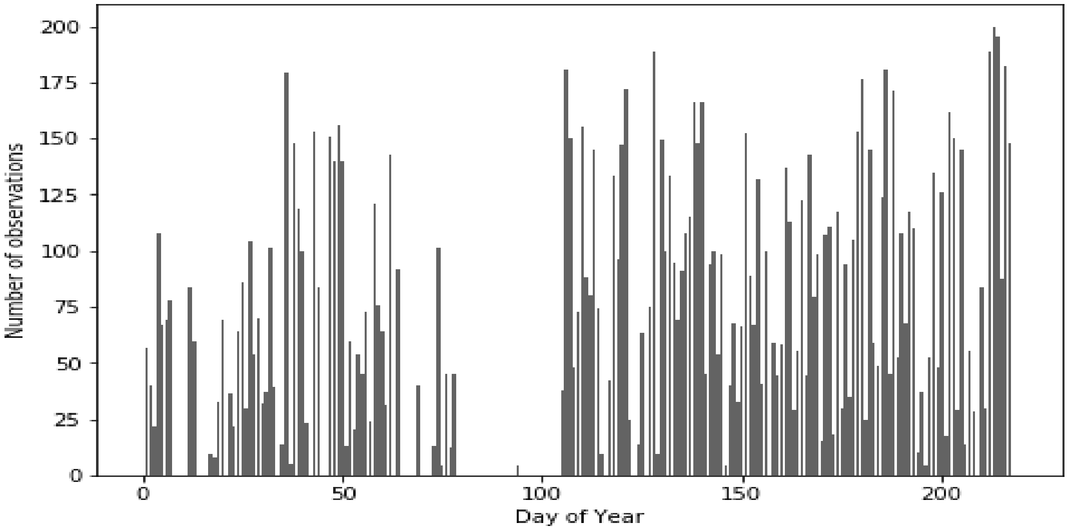

Fig. 2. CSTL Observations by Day of Year (2022)

Fig. 2 shows the number of NEOSSat observations on CSTL objects collected daily for the 2022 calendar year. Longer gaps indicate an absence of NEOSSat time for this experiment, and during most days when the CSTL experiment ran, the CSTL observations were interspersed with competing experiments. In Fig. 3, revisit histograms can be found for select objects throughout the 2022 tracking year.

4. ORBIT DETERMINATION

Orbit Determination (OD) was performed on CSTL data via two methods – post-acquisition in bulk over long durations using a Kalman filter and via rapid tasking orbits produced by batch least squares to produce a TLE in order to re-schedule NEOSSat on the same object in an attempt to re-acquire it and maintain its orbit independently.

The orbit determination steps utilize AGI's Orbit Determination ToolKit (ODTK), automated to process NEOSSat observations via custom Python routines. The CSTL object orbits were initiated via ODTK's initial state tool. This step establishes an initial guess of each satellite's state (position and velocity) for us to estimate outward using our observations. Following the initialization, the orbits are propagated forward in time, producing a time-series estimation of the satellite's predicted positions and velocities.

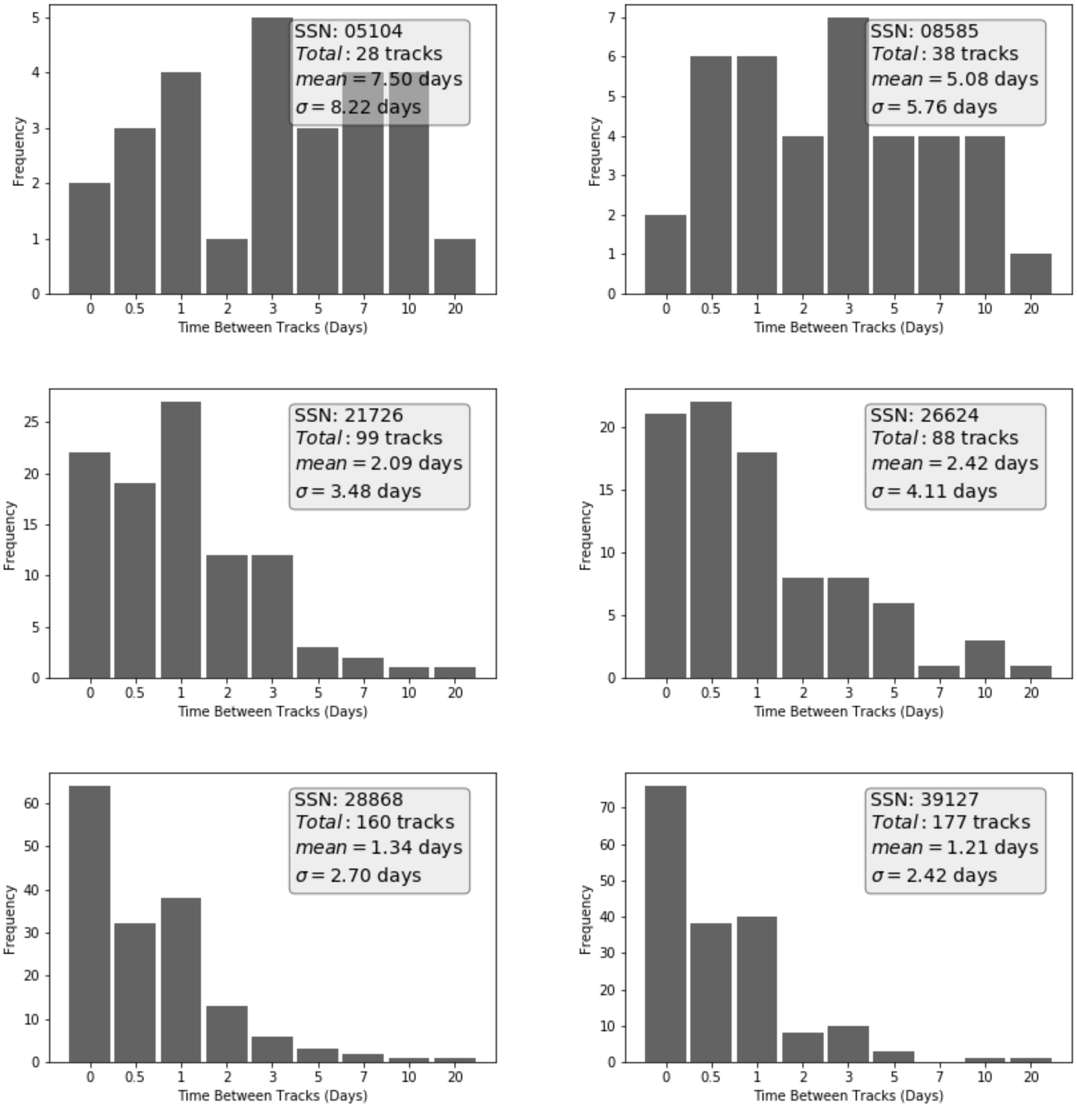

Fig. 3. Frequency of time between tracks for select CSTL objects (2022)

4.1 Long Term Orbit Residuals

For each object in the CSTL list, a long-duration orbit determination process was done using ODTK's Kalman filter. These fits were done post the entire collection period, and the Kalman filter settings (mainly dynamic sigma editing) were chosen to attempt to maintain custody on objects throughout some of the longer gaps seen in the CSTL observations. Fig. 4 shows the measurement residuals on one object throughout this process. The object is ANIK-E1, chosen because it is non-functioning and not subject to station-keeping maneuvers. The filter had a decent amount of success maintaining custody of the object when observations were dense. However, after several days of no data, the filter would accept observations with significant residuals.

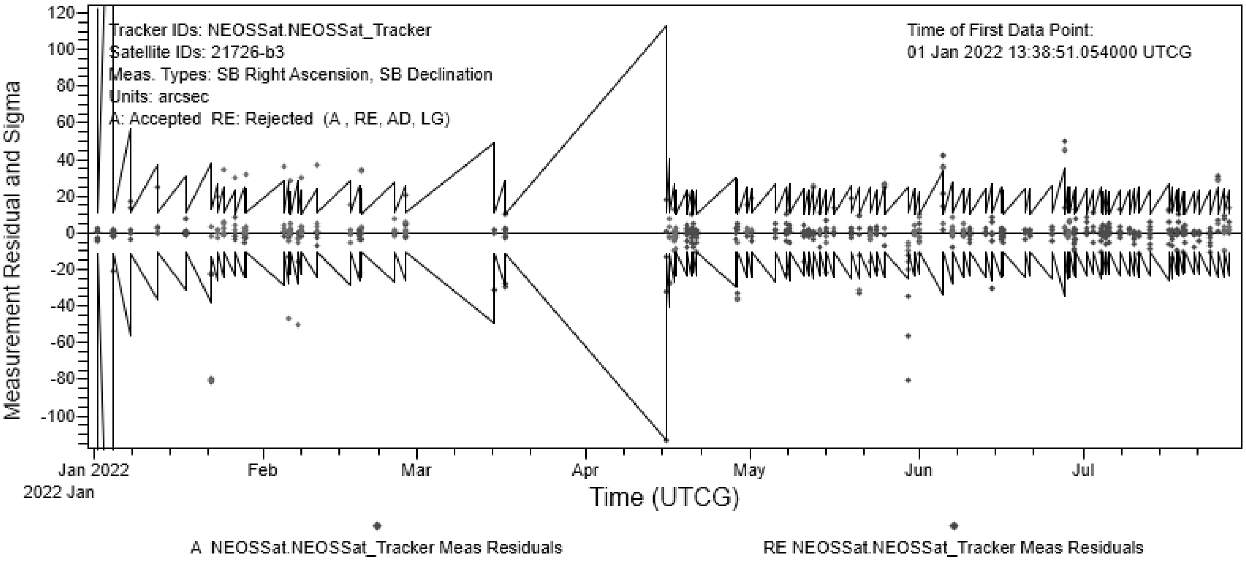

Fig. 4. 2022 Post-Fit measurement residuals of ANIK-E1 (21726)

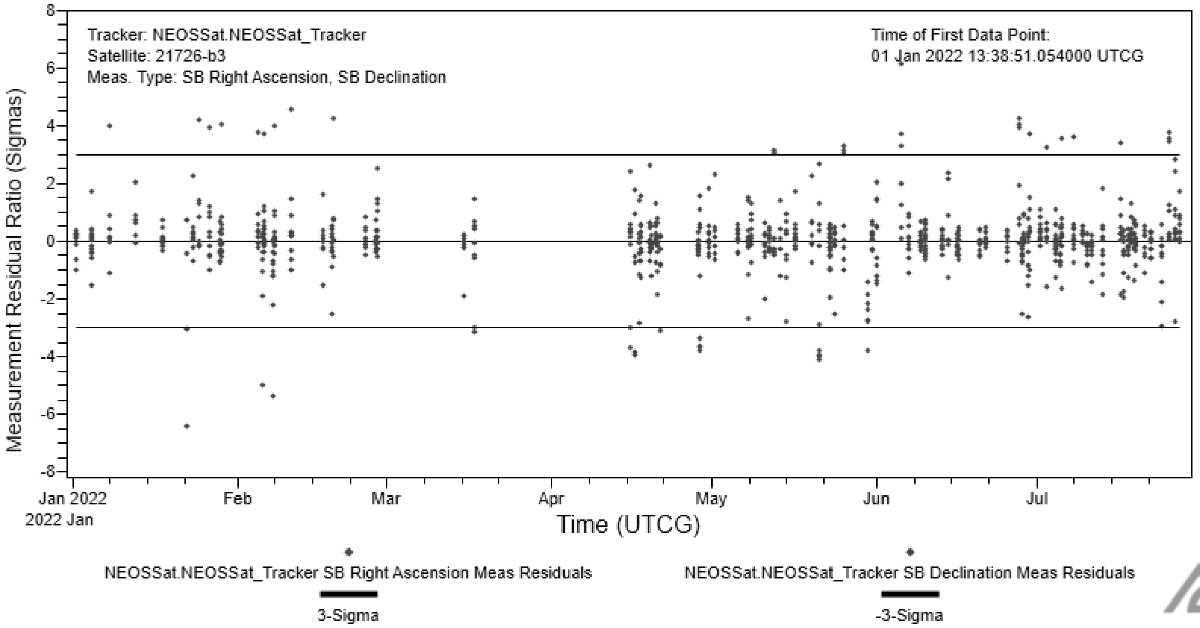

Fig. 5. 2022 Post-Fit measurement residual ratios of Anik-E1 (21726)

Fig. 5 shows the residual ratio graph for this process, with NEOSSat's 1-sigma white noise error statistics set to 2.6 arc seconds. The data falls decently within a 3-sigma limit. Fig. 6 below shows the position uncertainty of the object throughout 2022. The initial high uncertainty was from a significant covariance estimate associated with the initial state vector. Despite long gaps in the tracking data, including one of almost a month, the position uncertainty remained under 10 km in each axis, much lower when tracking data was dense.

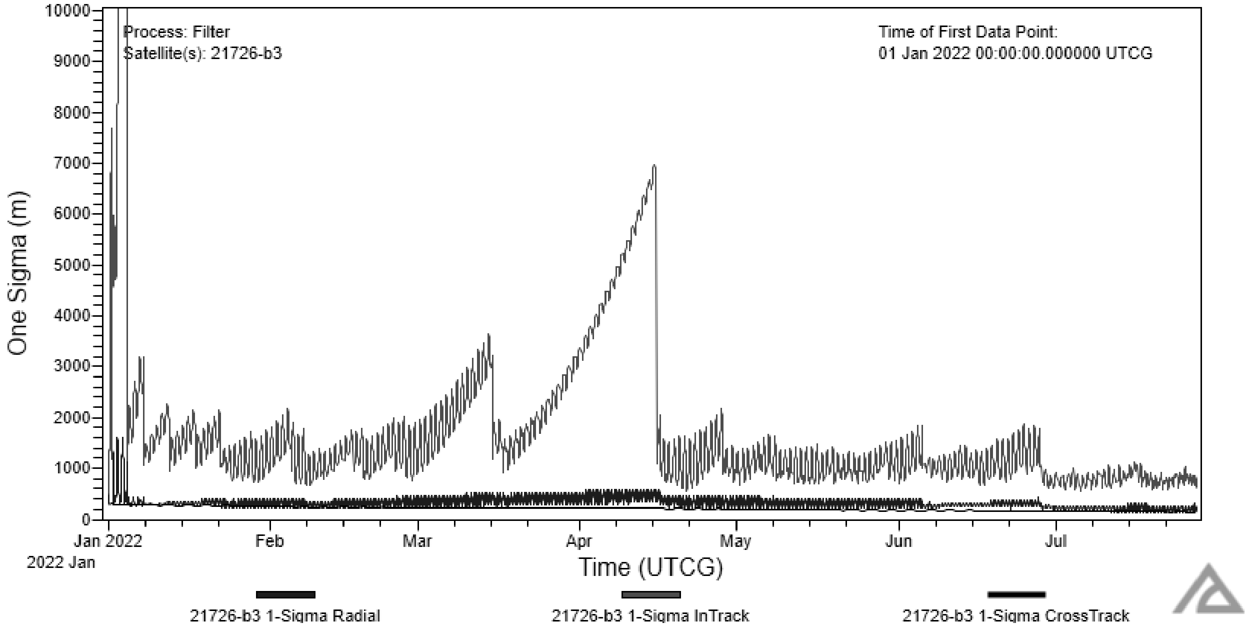

Fig. 6. 2022 Post-Fit 1-sigma position uncertainty Anik-E1 (21726)

Finally, Fig. 7 shows a final smoothed orbit product for the entire year, with orbit uncertainty maintained at the kilometer level.

4.2 Rapid Orbit Determination and Re-Acquisition

In June 2023, the CSTL object list was observed over the period of one week in an attempt to re-acquire all objects on its GEO list in a rapid fashion after the OD process, using TLEs produced by NEOSSat observations to seed NEOSSat's scheduler and determine if limited custody could be self-maintained.

While ODTK's Kalman filter is useful for long-term orbit propagation, ODTK's Least-Squares (LS) method was chosen for short-arc orbit updates during this phase of the experiment as it provided an easy method of pass/fail by scrutinizing the least square residuals and TLE convergence, due to the fact that a lower accuracy TLE was needed as output to go back into NEOSSat's scheduler rather than an optimal sequentially filtered state vector.

The experiment ran with two days of NEOSSat data on all CSTL GEOs, after which a batch LS run was done, and a new TLE was produced. If the TLE converged successfully, NEOSSat was re-tasked on the object with it. Otherwise, another re-task was done with a TLE from the SSN. This process was repeated over five days, continually with a 24-48 hour turnaround time between image collection and TLE generation and the next imaging attempt. This lag represents the cadence of downloading the imagery to ground-stations, performing image processing, orbit determination and re-scheduling, and finally waiting for station upload time to commence a new schedule.

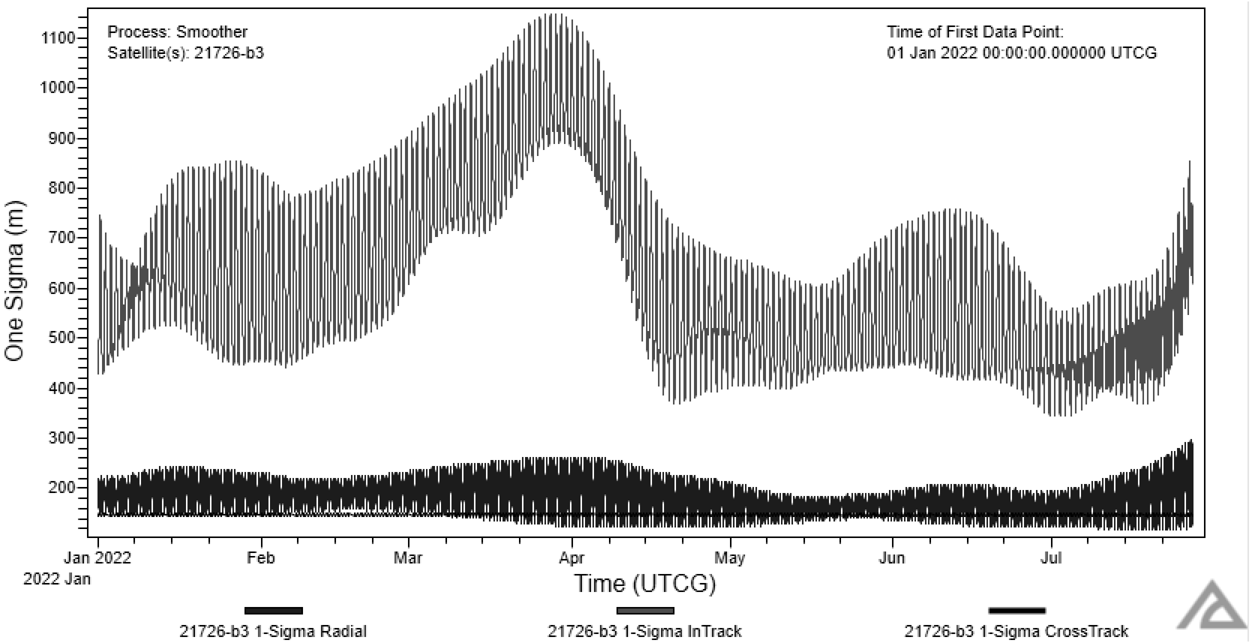

Fig. 7. 2022 Smoothed 1-sigma position uncertainty Anik-E1 (21726)

Table 4 shows the TLE generation and revisit success over this period. The much smaller Anik-A class satellites, as usual, proved difficult to track (SSN # 6278-8585), but on larger objects, the experiment proved a success, with NEOSSat about to successfully re-observe and generate a new TLE, seeded with one it made from the previous observations. Additionally, some objects experienced a failure to revisit. NEOSat's field of view in this setup was approximately half a square degree. However, overall, TLE generation was of sufficient quality for re-tasking and custody maintenance.

Table 4: NEOSSat CSTL OD Fits June 2023

Object SSN	# Of Successful TLE generations	#Of revisit attempts	#Of successful revisits
6278	1	2	0
6437	0	0	0
7790	1	2	0
8585	0	0	0
11153	2	2	2
13431	2	2	2
13652	2	2	2
21222	3	3	2
21726	3	2	2
25740	2	2	2
26624	3	3	2
28378	3	2	2
28868	3	2	2
31102	3	2	2
33373	3	2	2
33453	2	2	2
34111	2	2	1
35873	2	3	1
37602	4	3	3

38342	2	2	2
39127	3	2	2
41036	3	3	3
43562	4	3	3
43611	3	3	2

4.3.1 Sample Results: Active GEO 26624

Fig. 8 shows the history of the 4 TLEs produced by the CSTL-OD process for object 26624 compared to well-tracked TLE data from Space-Track.org [6]. Despite promising data from the first TLE, the second TLE produced at an epoch on June 19th shows some divergence, up to 200 km mostly in the radial component, but were within improving agreement afterwards. The TLE from June 19th, 2023, was used to successfully re-acquire the object (SSN #26624) on two separate occasions several days after TLE generation, just within NEOSSat's imagery edges. These results were typical of this initial trial.

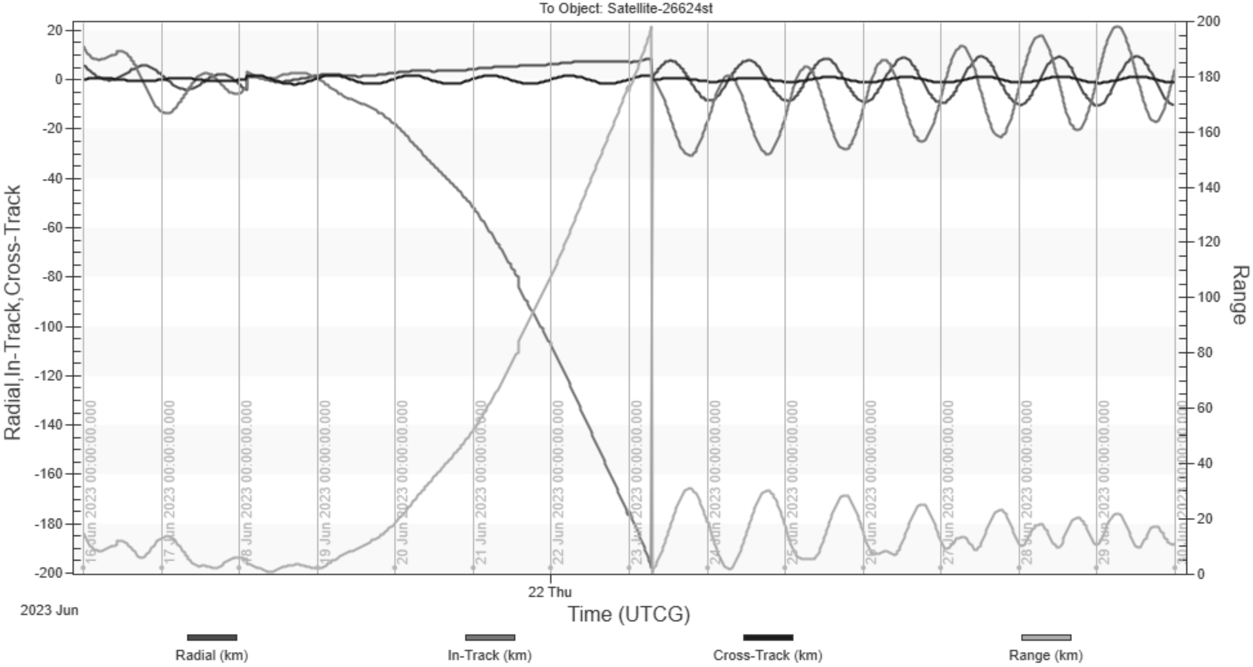

Fig. 8. Radial, In-Track, Cross-Track and total Range difference between CSTL produced TLE and TLE history from Space-Track.org.

5. CONCLUSION

Several long-term outcomes have been achieved as a result of this experiment. We have presented the tracking summary of the Canadian Satellite Tasking List from NEOSSat throughout the year 2022, with observation quality commensurate with the accuracy of the detector and a brief, rapid orbit determination experiment where NEOSSat successfully re-acquired objects when queued on TLEs produced via its own observations. Some longer revisit experimentation is required to refine the TLE convergence acceptance criteria and acceptable periods between observations. This system can be enhanced to include further sensors and tracking objects for long-duration tracking and independent orbit maintenance.

Additionally, since the CSTL dataset itself holds experimental value to future researchers, all of its observations from 2020 onwards can be found and accessed within the Unified Data Library [7] upon request. The dataset itself (>10,000 images and observations) is undergoing preparation and transformation into a training set for machine learning algorithms to perform RSO detection on NEOSSat and future space-based imagery systems, the methods of which will be the subject of future publications.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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