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RADARSAT Constellation Mission (RCM): 6 Years of Operations

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Abstract

The RADARSAT Constellation Mission (RCM) was launched in June 2019. It is Canada's Earth observation flagship mission with the three identical satellites equipped with both SAR and AIS payloads working together to bring solutions to key challenges for Canadians. It provides effective maritime surveillance, disaster management and ecosystem monitoring. With their rapid revisit capability, the satellites can capture the exact same view of the exact same location on the Earth's surface once every four days.

The Canada-wide operational infrastructure for RCM is complex and diversified. The overall system availability has exceeded 97% since launch. This paper will present a highlight of key operations special activities conducted since launch and discuss some of the operational improvements added over the years to increase imaging capabilities and spacecraft performance.

Forest fires in the northern part of Canada were quite extensive during 2023 leading to difficulties of accessing ground stations such as Inuvik located in the north. Reconfiguration of the ground segment and downlink planning was performed leading to little/no net loss of data for users.

With the significant increase of space objects launched, assessing the risk of collision remains an important duty for the operations team. Given the requirement to maintain all three satellites within a certain "orbital tube", a space debris avoidance manoeuvre on one satellite impacts the other two satellite and corrections are required after in cases where the manoeuvre would bring the satellite outside the "orbital tube". The paper will discuss the main operational issues faced on the topic over the last year or so.

During this time of high solar activities, the drag coefficient estimation remains key to properly plan orbit maintenance maneuvers. There are sometimes large variations of the key coefficients used for planning maneuver leading to operational challenges.

Finally, improvements on the ground segment were conducted to improve the automation of telemetry monitoring to simplify the operator's workload, reduce human errors and reduce the reaction time in case of anomalies.

Keywords: RCM, Operational Issues, Data, Ground Segment, Space Debris

1. Background

The Canadian Space Agency (CSA) launched RADARSAT-1 in 1995 to fulfil the needs of the Synthetic Aperture Radar (SAR) community. The RADARSAT-1 mission was owned and operated by the Government of Canada and it demonstrated the operational use of a SAR satellite. RADARSAT-2 was then developed through a partnership between CSA and Macdonald Detwiler and Associates (MDA). It was launched in 2007 and provided data continuity to RADARSAT-1 users with the addition of new beam modes to improve the resolution from 8m to 3m and add the multi-polarization capability. RADARSAT-2 is a commercial program which is owned and operated by MDA.

In response to an increased number of mandates within the Government of Canada (GC), future observational needs and requirements were outlined in a Mission Requirements Document. This document initiated the design and development of the RADARSAT Constellation Mission (RCM), a Government of Canada-owned project. To meet the growing demand for Synthetic Aperture Radar (SAR), particularly in terms of coverage and revisit frequency, a constellation of three SAR spacecraft was deemed necessary. Launched on June 12, 2019, RCM represents

Canada's latest generation of earth observation satellites, designed to address the evolving needs of the Canadian Government.

2. RADARSAT Constellation Mission

RCM was developed to meet the needs of the Canadian government departments and ensure the continuity and utilization of operational SAR imagery. The main uses of RCM SAR data are for Maritime Surveillance, Disaster Management, and Ecosystem Monitoring, which are summarized as shown below,

- Daily coverage of Canada's territorial and adjacent waters for maritime surveillance, including ship detection and monitoring of ice, marine wind, and oil pollution; and,
- Monitoring of all of Canada for disaster mitigation on a regular basis (monthly to twice-weekly) to assess risks and damage-prone areas; and,
- Regular coverage of Canada's land mass and inland waters, up to several times weekly in critical periods, for resource and ecosystem monitoring.

CSA led the development of critical technologies for the next generation of SAR Instruments in partnership with Canadian industries. The SmallSat SAR concept was chosen to provide a cost reduction by using a small satellite platform, which was launched using a low-cost launcher.

RCM is the Government of Canada's leading Earth Observation mission, delivering all-weather, day and night imagery in support of Canadian priorities for environmental monitoring, natural resources management, Northern development, sovereignty and security.

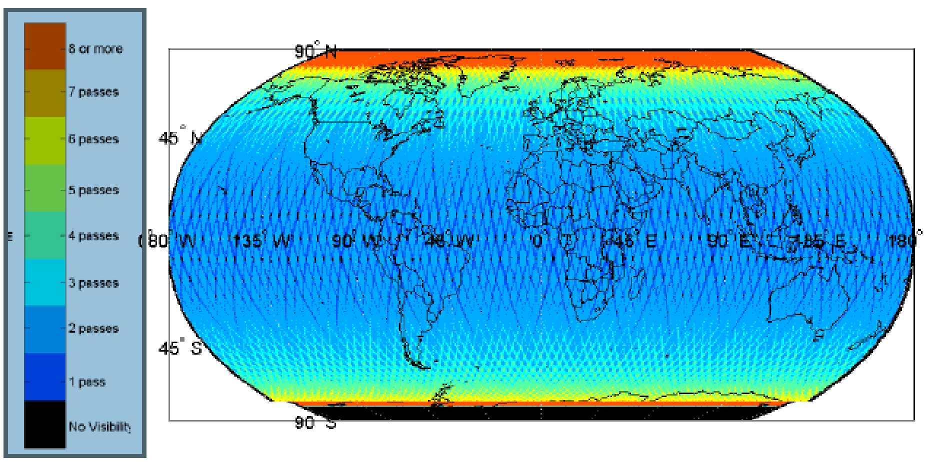

FIGURE 1. RADARSAT CONSTELLATION MISSION (RCM) AVERAGE 500KM GLOBAL ACCESS (12 day Repeat Cycle) (Credit: Canadian Space Agency)

The constellation allows for daily revisit of Canada and its surrounding waters. RCM provides global coverage daily with an accessible swath of about 1500 km. For a three-satellite system, if each satellite has a 500 km accessible swath, then any point on the globe except the South Pole may be imaged daily, as shown in the diagram above. Together, the three RCM satellites also provide a four-day revisit, allowing high revisit coherent change detection. Many Government users require daily re-look and an exact revisit once to twice weekly for interferometric change detection applications. Increased revisit capacity improves the likelihood of timely repeat coverages for applications such as operational disaster management, and land deformation.

RCM is composed of the Space Segment and the Ground Segment. The space segment consists of three small spacecraft each weighing 1,400kg and flying at an altitude of approximately 600kms (evenly spaced at 120° on the same orbit) in a sun-synchronous polar orbit. Each spacecraft consists of a bus module and two payloads: a SAR payload and an Automated Identification System (AIS) payload for ship detection. The bus module provides telemetry, payload commands, attitude and orbit control, power generation and storage, thermal control and the primary support structure. The SAR payload performs all imaging operations and stores the data. The radar data is then encrypted and downloaded for processing and distribution.

The AIS is used to exchange information between ships for navigation control and collision avoidance. The ships using AIS can identify themselves and provide their position and course. RCM carries a combined AIS antenna and receiver that collects and digitizes identification messages transmitted from ships over the area covered by the SAR signal. Ships detected by radar that do not correspond to AIS reports will be flagged as targets of interest by maritime surveillance authorities and may be subject to further investigation.

On-board AIS enhances Canada's ability to identify and monitor maritime traffic and provides awareness of vessels approaching and operating in Canadian waters. The International Maritime Organization (IMO) requires that all ships beyond 300 tons (Class A) transmit their identification, location, bearing and velocity with an AIS transponder. Incorporating AIS messages with RCM imagery provides a greatly enhanced product for maritime surveillance. The AIS payload enables the detection of illegal vessels in Canadian waters and up to about 1,000 nautical miles from the shore. Having SAR and AIS payloads on the same satellite provides near "real time" maritime surveillance, leading to an effective surveillance solution compared to the fusion of separate AIS and SAR data streams. The key advantage in combining the AIS and SAR technologies is that RCM can detect ships that deliberately turn off the AIS transmitter to avoid being identified or ships that do not have a functional AIS signal.

3. Ground Segment Activities

RCM relies on a robust network of ground stations to meet its low-latency requirements from tasking to data delivery. In collaboration with Natural Resources Canada's (NRCan) Canada Centre for Mapping and Earth Observation (CCMEO), the mission uses three primary Canadian ground stations located in Inuvik (NT), Prince Albert (SK), and Gatineau (QC). These stations handle both data reception and Telemetry, Tracking, and Command (TT&C) services, covering 10 to 11 out of 14 daily RCM orbits. Furthermore, through the Polar Epsilon 2 (PE2) project, the Department of National Defence (DND) provides additional reception stations located in Masstown (NS) and Aldergrove (BC). To extend coverage and improve resilience, RCM also utilizes the Northern Ground Terminal (NGT) at the Swedish Space Corporation's Esrange site in Kiruna, Sweden, which provides visibility for orbits not visible from the Canadian ground stations. This international collaboration ensures full orbit coverage and offers a valuable redundancy in case of unavailability at Canadian sites.

Meeting the mission's low-latency data delivery goals requires optimal use of the ground segment. CSA's antenna reservation and pass planning system accounts for both scheduled and unscheduled maintenance, enabling fast turnaround for re-planning. In cases of station outages, the system allows manual overrides to reassign downlinks while maintaining service continuity. Over the past year, several unplanned maintenance events were successfully mitigated through this approach, with minimal user impact.

Despite a strong performance, the ground segment still faced challenges. A key risk stems from reliance on the telecommunications infrastructure, particularly the 1,154-kilometre Mackenzie Valley Fibre Link (MVFL)—the sole fiber route to the Inuvik station. In the summer of 2023, Canada experienced its worst wildfire season to date, burning over 15 million hectares. Fires in the Northwest Territories damaged the MVFL infrastructure, rendering the Inuvik Station unavailable for nearly a month and disrupting real-time services.

To address the non-redundant fiber route to the Inuvik station, the 778-kilometre Dempster Fibre Line is being deployed along the Dempster Highway, connecting Dawson City (Yukon) to Inuvik. Once operational later this year, it will complete a 4,000-kilometres fibre ring, dramatically improving redundancy and resiliency for northern operations. In the meantime, the "Inuvik Lost" contingency strategy was activated, redirecting scheduled contacts to other stations, including Kiruna. While effective, this cannot fully replace near real-time access within the Inuvik mask.

Each Canadian ground station currently operates with a single major S/X-band antenna (13 m at Gatineau and Inuvik), which must be taken offline for maintenance. This limits redundancy and introduces planned service interruptions. These challenges were compounded during the COVID-19 pandemic, which restricted site access—especially to Inuvik—and delayed critical servicing.

To increase capacity and mitigate future risks, several upgrades are planned:

- A new S/X/Ka 7.3 m antenna at Gatineau (summer 2025)
- S-band capability added to Prince Albert's 13 m X-band antenna (summer 2025)
- Two new S/X/Ka 7.3 m antennas at (2026) Inuvik to support upcoming missions like WildfireSat

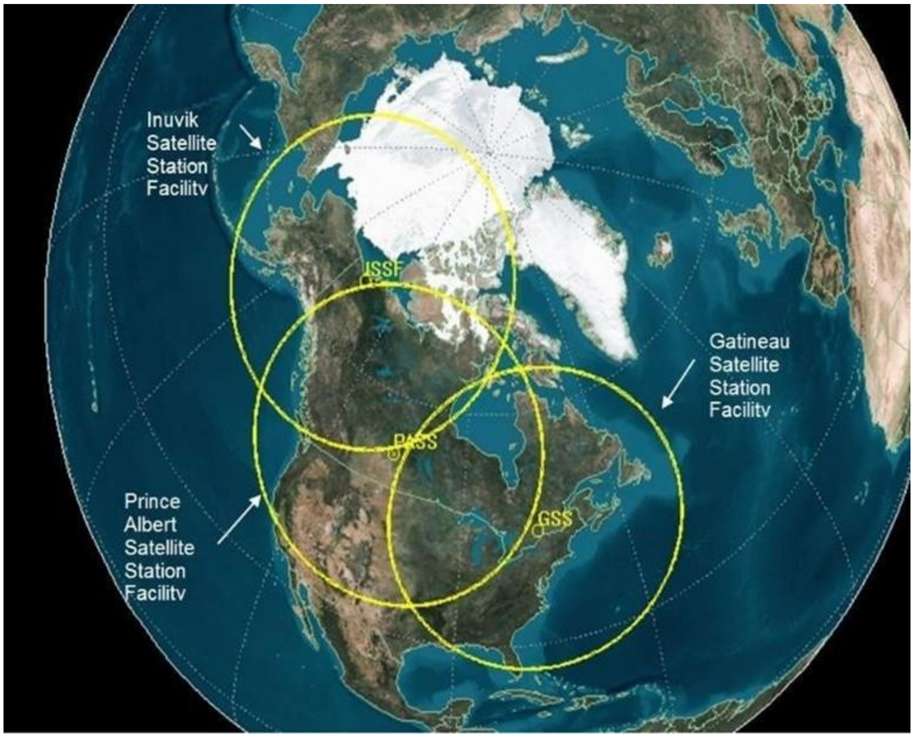

FIGURE 2. CCMEO Ground Station Network (Credit: Canadian Space Agency)

4. Special Operations Activities

The Radarsat Constellation Mission has been a key milestone in Canada's contributions to Earth observation and satellite technology. Over the past six years, the mission has significantly advanced our understanding of global environmental changes, improved disaster response capabilities, and contributed to both scientific research and operational needs in various sectors, such as agriculture, forestry, and climate monitoring.

While the mission has seen tremendous success and delivered valuable data, like any complex spacecraft operation, it has also experienced some anomalies and challenges over the years. These anomalies are important to track and address to ensure continued mission success and the longevity of the spacecraft. The following section will highlight the key spacecraft anomalies or operational challenges encountered by the Radarsat Constellation Mission during the last six years of operation and discuss some of the operational improvements added over the years to increase imaging capabilities and spacecraft performance.

Thermal Fatigue Estimator for Critical Payload Units:

The Payload Electronics Unit (PEU) on RCM is the key component at the heart of the SAR payload. The payload is also equipped with redundant elements to ensure mission longevity. The Payload Electronics Unit (PEU) is the radar transceiver for the RCM synthetic aperture radar. It generates the required modulated low power chirp pulses to drive the antenna assembly and collects and digitizes the return echo from the ground. The digital representation of the echo is formatted and sent to the Mass Memory Unit (MMU). Two physical Payload Electronics Unit (PEU) units, a prime and a cold-redundant unit, form part of the RCM Payload. The Payload Control Unit (PLCU) acts as the operational coordinator for the radar operations, programming the various hardware elements of the radar to perform the required imaging scenario. The PLCU responds to a set of activity requests to manage the state of the other payload equipment. The PLCU unit is internally redundant with two separate controllers inside the same chassis. There are several interfaces between the PLCU and the Payload Electronics Unit (PEU) unit.

One of the most important elements that could affect the durability of the Payload Electronics Unit (PEU) is the thermal fatigue of the unit as the Payload Electronics Unit (PEU) is solicited for on and off cycles of the payload. The duration of imagery per orbit (SAR on time) also contributes to the fatigue. In order the closely monitor this aspect a thermal fatigue tool has been developed. It was initially "conservatively" configured based on initial testing results. Over the course of the recent years of operations it has been updated with flight data allowing more margin.

The thermal-fatigue conditions for an imaging SAR system in LEO is a key life-limiting factor that has been extensively evaluated during the design phase with some imaging scenario design cases. Mission profile changes have led to the need to evaluate new dynamic payload usage profiles. Furthermore, the need to preserve constellation life for mission extension, led to the need of a Thermal-Fatigue (TF) life estimator driven by flight telemetry. The estimation model uses all the relevant information about the on-off cycles, on-time, off-time, unit temperature. It calculates the thermal fatigue damage caused by each cycle and compares to the TF design margins for the driving unit components. Generally, the internal payload electronic units are well isolated from the external thermal variations, therefore they are neglected in the thermal fatigue calculations.

Since the effect is a long-term cumulative effect, the model is run monthly giving feedback to the flight operations and mission team with respect to payload usage. This is also used for yearly Satellite health assessment evaluations and mission update reviews. Although the telemetry-based provides a precise estimation of the TF damage cumulated, a simplified model has also been introduced at the planning stages to assess up-front the impact of mid-long term acquisition plans for the main mission and background missions. This is useful to avoid implementing and committing to over taxing coverage plans.

The pictures below present the limit (dotted red line) and the usual thermal fatigue assessment. Part of the day-to-day telemetry review includes ensuring that the trending of the thermal fatigue remains inside the boundary limits.

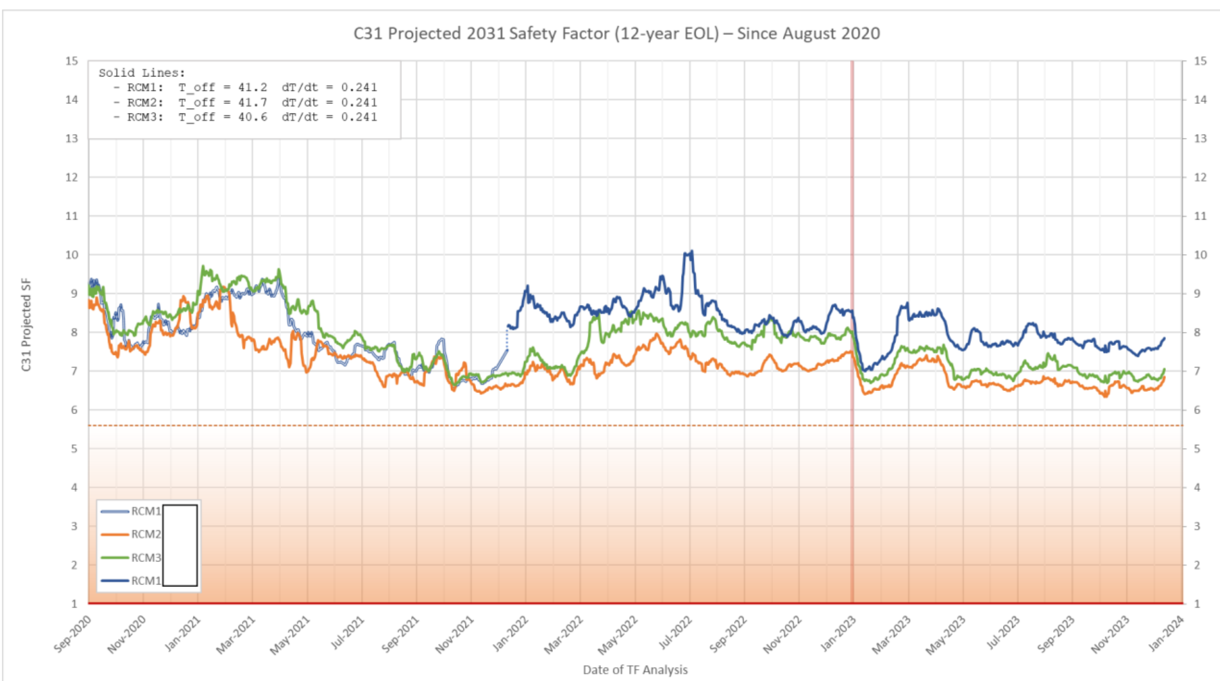

FIGURE 3. Thermal Fatigue Assessment Graph (Credit: Canadian Space Agency)

Spacecraft anomalies, such as the central electronics issue on RCM, are an expected part of space operations, especially given the complexity of managing multiple systems in orbit. The RCM mission team continues to carefully monitor the spacecraft's health and performance to identify potential issues before they lead to more serious disruptions. As part of ongoing operations, engineers and mission controllers apply lessons learned from these anomalies to improve the reliability of future spacecraft missions, as well as to adjust mission parameters and operational protocols as necessary.

Eclipse Battery Management:
Spacecraft often undergo battery discharge tests during eclipse seasons to ensure their power systems can handle extended periods without solar input. Battery deep discharge tests during the eclipse season are aimed to evaluate the rate of battery discharge and compare it with predictions from battery models. The results provided valuable data for understanding battery performance under eclipse conditions.

To meet the power consumption requirements late in the mission, two calibration methods are used: the Battery Capacity Fade Tuning and the Battery Resistance Calibration. The results obtained from these calibration tests can be used early in the mission to improve operations of the RCM mission.

The Battery Capacity Fade Tuning activity is required to verify the drift of the on-board capacity estimator. The State of Charge (SOC) and accurate battery capacity estimation is required to prevent unplanned outages from the power sub-system. The variation of the capacity as a function of the number of power cycles requires tuning. This will decay from its initial value of 116Ah to nearly 90Ah at End of Life (EOL), based on the battery cycling requirements.

The Battery Resistance Calibration method is an integral part of the estimate of battery V_{EMF} that is used in most of the state of charge algorithms and eventually used for load sheds. Th objective of this calibration is to estimate the very long term expected increase in ohmic resistance. RCM batteries use 18650HC Li-Ion cells, with an internal resistance that can be modified by two-time dependent components being the quasi-static ohmic resistance, and a short time-constant chemical diffusion resistance.

Both estimations require battery voltage and current measurement data from a long and steady discharge, which does not occur during nominal operations and therefore a test is required. During the last few years, different approaches were used to attempt to create suitable discharge conditions required for the battery discharge test,

1) Catbed heaters were turned on during an eclipse for five minutes.
2) Special SAR acquisitions were scheduled just before and after the eclipse events

For both tests, the discharge profile was relatively stable, but the additional power draw was low and did not provide a suitable discharge for the test. A solution was then proposed in 2024 to obtain a steeper discharge by using a calibration SAR acquisition with a known power draw. The main objective was to create a larger discharge during the eclipse, without exceeding the different power limitations of the spacecraft. The three power constraints that were taken into consideration were the overall power balance, battery maximum continuous discharge rate, and the payload Distribution Unit minimum voltage supply. Following an analysis of the constraints, the power balance and the battery discharge rates were determined as not being a concern, but the PDU minimum voltage could become a limitation if starting from a low SoC and discharging for a long time.

It was determined that a five-minute test with a 1000W total load would be desirable to produce ideal conditions for the battery discharge test, while maintaining comfortable safety margins. Two calibration acquisitions were executed to measure the total load on the power systems outside of eclipses, which showed a very stable power draw with averages in the range of a 1000W with an estimated battery current in the range of 25A to 30 A.

MMU Application Software (MAS)

The MMU's main functions are to receive science data from the Central Electronics (CE), store the science data as image files in memory and format the stored files into transfer frames. These frames are then sent to the Encryption Unit and subsequently to the X-Band transmitter for transmission to the Ground Station via the X-Band downlink. The MMU application software implements the capability of recording incoming science data originating from the payload CE to a file. Simultaneously, the MAS will support the playback of the contents of up to two files to the external encryption unit.

RCM offers the capability to perform multi-segment downlinks and or split downlinks. This feature allows to take advantage of Canada's ground stations located in strategic geographical locations. This feature allows large downlinks to occur by using 2 ground stations with overlapping masks, offering more than 15 mins of consecutive downlink. An anomaly occurred when the RCM spacecraft was not able to perform multi-segment downlinks due to a bug in the MMU Application Software (MAS).

To identify the root cause of the anomaly, a flight equivalent setup was required to reproduce the anomaly and the flight software development setup to isolate the root-cause in the software. Furthermore, to provide an integrated flight software validation setup it was decided to interconnect the Bus Flatsat to the Payload electrical model (PEM). This provided the ops team a full flight equivalent to validate the delivered FSW and all related operations. An updated software version was delivered by the contractor and testing on the Spacecraft FlatSat system was successfully completed. The MMU Application Software (MAS) was updated on all three spacecraft between October and December 2022 to fix the software bug that prevented the payload from performing split downlinks.

<u>GPS Reset Investigation:</u>
Since the beginning of the mission, there have been random occurrences of GPS resets on all three spacecraft. As confirmed by Airbus/Atrium, the GPS receivers are susceptible to "Spontaneous Reboots" and is expected every three months on each spacecraft. There are various sources for these reboots such as GPS Hot Restart, GPS Cold Restart, GPS Reset due to PVT Timeout Error, and GPS Checksum Verification Failed. After several investigations, there was no clear indication of a root cause for these GPS resets.

The latest analysis shows that there was an increase in the number of GPS spurious resets during last quarter of 2024, particularly on one of the three spacecrafts. This recent increase in GPS spurious resets drove the overall average above the expected value of one reset every three months. An investigation was carried out aiming at quantifying and understanding the phenomenon. Several potential causes were identified and examined as shown below,

- There was no noticeable relationship between the GPS reset occurrences and the geographical location.
- Only a slight seasonality with more frequent occurrences from September to March (Fall/Winter period)
- Weak correlation with the long-term solar activity (Similar to what was observed by Astrium)
- No unit deterioration was discovered from current and temperature trends.

The cumulative number of GPS anomalies shows that rate of increase in the number of GPS Resets for the constellation has stabilized to reach values closer to the expected rate of 1 event every 3 months. The rate of increase on one spacecraft has remained relatively constant since last year, while on another spacecraft it has seen a slight increase at the beginning of 2025. However, none of these trends are of concern for the moment and no further investigation is recommended.

<u>Orbit Maintenance Maneuvers</u>:
The RCM mission must ensure cohesion between the three satellites to maintain a certain position within an orbital tube. This constraint aims to meet a planned ground track to ensure image planning and image acquisition match within a certain level of uncertainty. At the beginning of the mission, the 11-year solar activity was near minimum in terms of its measured outputs at the 10.7cm radio band. In October 2024, the start of solar maximum for the current cycle was announced and the activity seems to have peaked in late summer of 2024. The solar activity was predicted to peak during 2025, therefore it is likely to see the overall activity increase and cause a second peak or continue to plateau. When solar activity increases, it causes the upper atmosphere to become noticeably denser thereby significantly increasing the drag force experienced by the spacecraft. This lowers the semi-major axis, reducing the orbit period and causing the ground track to drift further away from its nominal value. This increase in the solar activity leads to an increased need for ground track burns and increased fuel usage

During this time of high solar activities, the drag coefficient estimation remains key to properly plan orbit maintenance maneuvers. There are sometimes large variations of the key coefficients used for planning maneuver leading to operational challenges. The high solar activity not only increases the drag but also its variability. These 2 elements lead to more frequent orbit maintenance activities but also variation in the amount of delta-v required to remain inside the orbital tube. The RCM flight dynamics system has the capability to automatically plan orbit maintenance delta-v, but the variability of the current solar activity required additional operational processes and skills to modify control parameters related to burn planning to guard against excursions from the nominal orbital tube

Collision Avoidance Maneuvers: With the significant increase of space objects launched, assessing the risk of collision remains an important duty for the operations team. With a constellation of three satellites flying in a narrow orbital tube, any space debris threat affecting one satellite and requiring an avoidance manoeuvre will typically also require a second manoeuvre to ensure that the orbital tube constraint and ground track requirement are met. CSA's conjunction risk analysis and mitigation system (CRAMS) continuously monitors and processes conjunction data messages affecting RCM. CRAMS computes possible avoidance maneuvers based on possible times when to execute the manoeuvre

There have been 14 collision avoidance (COLA) maneuvers with associated recovery maneuvers performed so far in the mission. The most amount of fuel used for COLA and recovery maneuvers was for the RCM-2 spacecraft in 2024, due to the spacecraft encountering two actionable close approaches during the year. A total of 0.25m/s of DV was used for these events. It is difficult to forecast how much fuel should be budgeted for COLA maneuvers over the rest of the mission, but a very conservative value of 0.5 m/s per year is used.

Conclusion

The RADARSAT Constellation Mission (RCM) has been operational essentially flawlessly for nearly six years since its launch on June 12, 2019. The system availability is over 97% and thereby exceeding the baseline requirement of 90%. RCM is providing daily Earth observation data to support various applications across Canada and the Arctic. In March 2023, the RCM captured its one millionth image of Earth, highlighting its significant contribution to Earth observation. The RCM system is continuously being improved while facing the challenges of ground segment outages, space debris, and orbit maintenance activities. The Government of Canada is exploring options to ensure continuous access to satellite radar Earth observation imagery beyond the RCM's lifetime, including potential collaborations and the development of new technologies.

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