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Advancing Space Sustainability through Canada's Conjunction Analysis and Space Situational Awareness Services

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Abstract

The Canadian Space Agency (CSA) Multi-Mission Satellite Operation Centre, located at CSA headquarters in Longueuil, Quebec, has been operational since the 1995 launch of Canada's first domestic Earth observation satellite, RADARSAT-1. Low-Earth Orbit was a very different place back then, with little thought towards potential collisions or close approaches in space. It wasn't until 2002 that CSA received its first close approach alert for RADARSAT-1, which contained limited information about the event or its associated uncertainty, leading to considerable manual analyses to determine the risk. Another alert came a few years later, again with its risk assessment burden. Over time, alerts became more frequent and by 2011, CSA Satellite Operations had developed the first operational version of its Conjunction Risk Assessment and Mitigation System (CRAMS), an automated system that processes conjunction data messages (CDMs) from conjunction data providers, such as the United States 18th Space Defense Squadron (18SDS), and delivers user-friendly reports containing advanced analysis and mitigation options to facilitate rapid decision-making in response to a conjunction situation.

As the space domain becomes increasingly popular, congested and complex, tracking agencies have increased their data sharing policies in order to minimize the risk of collisions. This increase in data availability has led to new features in CRAMS, such as CDM validation and better support for repeating conjunctions. As large volumes of data files are hard for operators to manage and quickly integrate into decision-making, CRAMS allows satellite operators to maintain their space situational awareness (SSA) through easy-to-use reports with value-added data that facilitates decision making about collision avoidance maneuvers.

Over the years, the CRAMS service has improved and now supports conjunction analysis services for a large variety of satellite operators, in industry, academia and government. Today, over 100 satellites in different orbital regimes are supported by the CRAMS service, with each addition allowing CRAMS to see more real-world situations and become robust to edge cases, complex conjunction situations and data quality issues. The 2019 launch of Canada's flagship RADARSAT Constellation Mission (RCM), with its tight orbit control requirements necessitating frequent maneuvers, presented new challenges for space situational awareness. This led to new features and operational procedures to ensure spaceflight safety while maintaining RCM's operational service at the required performance level. New features have just been added to allow screening of maneuvers based on available CDMs.

This paper will discuss the evolution of Canada's conjunction analysis and space situational awareness (SSA) services, and observations on space sustainability based on real-world experience with complex conjunctions, problematic conjunction data messages, and statistics on the evolution of the on-orbit conjunction risks, as seen by CRAMS. Best practices, lessons learned and future research and development directions will also be presented.

Keywords: conjunction analysis, space sustainability, conjunction data message, CRAMS, maneuver screening

Acronyms/Abbreviations

18SDS - 18th Space Defense Squadron
19SDS – 19th Space Defense Squadron
CDM - Conjunction Data Message
CDMe – Ephemeris-based Conjunction Message
CRAMS – Conjunction Risk Assessment and Mitigation System
CSM – Conjunction Summary Message

HAC – 18SDS High Accuracy Catalog
HBR – Hard Body Radius
JSpOC – Joint Space Operations Center
OEM – Orbital Ephemeris Message
OPM – Orbital Parameter Message
NEOSSat – Near-Earth Orbit Surveillance Satellite
RCM – RADARSAT Constellation Mission

1. Introduction

The Canadian Space Agency (CSA) operates a fleet of satellites for the Government of Canada from its Multi-Mission Satellite Operations Centre, located at CSA headquarters in Longueuil, Quebec. First established with the Canada's first synthetic aperture radar (SAR) satellite, RADARSAT-1 [1], launched in 1995, the centre now hosts the follow-up RADARSAT-2 (launched 2007 under a public-private partnership [2]), two scientific missions (SCISAT, launched 2003 for atmospheric chemistry and climate change science [3], and NEOSSat launched 2013 for space surveillance and space astronomy [4]) and its flagship operational mission, the RADARSAT Constellation Mission (RCM), serving Canada's Earth observation needs in many domains [5]. All of these satellites operate in low-Earth orbit, at different altitudes. While the RADARSAT fleet has onboard propulsion to maintain the desired ground track, the scientific satellites, SCISAT and NEOSSat, were designed and launched before space debris had become the concern it is now and lack propulsive capabilities. As the low-Earth orbit space environments evolved to become increasingly congested, contested and complex, CSA has increased in its capabilities in space situational awareness in order to better understand and mitigate the risks to its fleet of satellites. Today, Canada has over twenty-five (25) years of experience in satellite operations and associated space situational awareness capabilities. Its space situational awareness services are offered to operators around the world, contributing to best practices in space sustainability. The history and evolution of these capabilities and services are discussed in this paper.

2. History of Conjunction Analysis in Canada

During the early years of RADARSAT-1 operations, launch in 1995 and operating at an 800km altitude sun-synchronous orbit, low-Earth orbit was a very different regime, with little thought towards potential collisions or close approaches in space. CSA received its first close approach alert for RADARSAT-1 in 2002 and it contained very limited information about the event compared to what operators are accustomed to these days in Conjunction Data Messages (CDMs) [6]. At the time, there were no data sharing standards for close approaches, although some entities, such as the United States Joint Space Operations Center (JSpOC) – later known as the 18th Space Control Squadron (18SDS), maintained a catalog of space objects. In 2002, it alerted the CSA via email about a potential close approach with RADARSAT-1, and the only information provided was a time of closest approach and the relative separation of the two objects. CSA used open-source information and literature review to develop a risk assessment methodology in the absence of detailed information. Ultimately, to err on the side of caution, a collision avoidance maneuver was performed and this was the first collision avoidance maneuver made by a CSA satellite. Other operators were also dealing with similar alerts and exercising operational decisions based on the limited information available.

Two events led to a marked increase in the data quality shared with the operators: the 2007 Fengyun-1C kinetic impact that created a fragmentation debris cloud at 800km sun-synchronous orbit, and especially the 2009 accidental collision between defunct satellite Cosmos-2251 and operational Iridium-33 at 790km. Both events generated clouds of debris that continue to menace satellites in low-Earth orbit to this day. The 2009 event in particular was a source of concern due to the fact that Iridium-33 was operational and capable of maneuvering, yet its operator did not receive high-quality information to properly assess the risk and perform a collision avoidance maneuver. According to some sources [6], the close approach between Cosmos-2251 and Iridium-33 was not even a Top Ten risk event prior to the collision, clearly highlighting a gap in data quality and data sharing at the time. The ensuing debris clouds became (and continue to be) a significant contributor to the space debris environment.

Following these two debris-creating fragmentation events, satellite operators and tracking agencies collectively realized that better information sharing was necessary to prevent further collisions in space and degradation of the space environment. Tracking agencies increased information shared on secondary objects tracking and operators started sharing ephemeris to be screened [7]. JSpOC defined a more formal data format, known at the time as the Orbital Conjunction Message (OCM), and entered into agreements with satellite operators, including CSA, to issue an

OCM for any event where a secondary object approached within a specified miss distance of the primary, based on the following conditions: *Overall miss < 1000m and Radial miss < 200m*. Based on this new criterion, CSA started to receive more conjunction alerts and a more formal, consistent data format, which enabled further automation.

Early OCMs still contained limited information, featuring only the relative miss distance and the errors of the radial components for the two objects. In order to characterize the severity of these events, the CSA Satellite Operations team would estimate the combined in-track errors of the two objects using available radial errors through a simple approximation: *in-track errors = 10*radial errors*. A “serious” event would be one where the in-track separation of the two objects both resided within the combined errors. Subsequently, a collision avoidance maneuver could be sized based on increasing the overall separation such that the miss distance would be outside the error margin.

Later, based on continued collaboration with operators and policy shift towards prioritizing space sustainability, JSpOC further upgraded from the redacted OCM format to a more complete Conjunction Summary Message (CSM) format, which provided full state vectors for both primary and secondary objects at the time of closest approach along with errors for both objects in all three coordinates. With this new, improved data format, CSA could further improve its calculations using the expanded CSM and supplemental data sources. The approach chosen by CSA was to model the geometry of the event and its errors, creating a “close approach box” based on the transformation of the secondary object’s errors into the primary object’s frame. Once a “close approach box” was established, collision avoidance maneuver could be sized to ensure that the separation of the two objects was greater than the size of the close approach box. Not long after, JSpOC again upgraded the published CSMs to provide more complete covariance matrices along with state vectors. This allowed for calculation of the probability of collision, using methods established by Chan [8] and others [9, 10], establishing the basis for modern conjunction assessment. CSA’s implementation was validated with other space agencies and satellite operators and then replaced the “close approach box” previously established.

The final and most recent evolution of data quality improvement from tracking agencies came with the 2013 transition to the Conjunction Data Message (CDM) [11], formalized by Consultative Committee for Space Data Systems (CCSDS) and implemented by tracking agencies to replace the CSM. The new format generally included all the same information as the latest CSM format, but further standardized the field names and other conventions. It remains the standard used to this day by 18SDS, other tracking agencies, and satellite operators worldwide. The standard format facilitates communication between tracking entities and operators and now includes essential covariance information, which was considered sensitive early on, allowing operators to better characterize the risks and make appropriate decisions regarding collision avoidance maneuvers.

3. Conjunction Analysis Service via CSA’s Conjunction Risk Assessment and Mitigation System (CRAMS)

Once it became apparent that space debris conjunction alerts were going to continue to be a routine part of satellite operations, the CSA developed its own software to assess and manage conjunction alerts, automating processes that had previously been manual. As the CSM and CDM evolved with more data, CSA evolved its automated analysis software to quickly perform the necessary calculations for risk assessment and mitigation. This software became known as the Conjunction Risk Assessment and Mitigation System (CRAMS), an automated system that initially processed CSMs, and later conjunction data messages (CDMs), from JSpOC (later 18SDS), CRAMS performs data quality and other assessments and delivers user-friendly reports containing advanced analysis and mitigation options to facilitate rapid and correct decision-making in response to a conjunction situation. Initially put into service in 2011 to support only CSA’s fleet, the CRAMS system has since evolved into a service that now supports conjunction analysis for a large variety of satellite operators in industry, academia and government. By supporting many satellites over a variety of orbital regimes, CRAMS sees more real-world situations, allowing it to evolve and become more robust to edge cases, complex conjunction situations and data quality issues. It also provides greater situational awareness on the evolution of the near-Earth space environment and the risks presented to satellite operators.

CRAMS’ primary data source for conjunction data messages (CDMs) is the United States 18SDS’s *Space-Track.org* platform, which serves a central repository for CDMs produced from the US Space Surveillance Network (SSN). When new conjunction data messages are made available on Space-Track.org, a notification email is sent to the applicable mission team. For satellites that are “CRAMS service subscribers”, the CRAMS account on Space-Track.org is given permission to access that operator’s CDMs and CRAMS’ email account is added to the list of email addresses that receives these notification emails. Once this setup is configured, CRAMS triggers its operations based on the notification emails it receives indicating the availability of the new CDMs.

As soon as a CDM availability email is received, CRAMS logs into Space-Track.org, downloads the applicable set of CDMs, and starts its processing. There are many steps in this processing, as follows:

1. Login to Space-Track.org
2. Retrieve the applicable CDMs
3. Organize CDMs into events, noting multiple-encounter events where a given primary and secondary object have close approaches across multiple orbits on the same day, resulting in a set of CDMs that should be considered as a set
4. Perform an initial sorting to determine whether a CDM is reportable or not, according to mission-specific criteria, such that the most urgent CDMs are processed and deliver their results first
5. Establish a hard-body radius for primary, based on configuration parameters provided by the operator
6. Establish a hard-body radius for the secondary object, based on the size or radar cross section data in the CDM and a heuristic to scale objects
7. Evaluate the covariance matrices in the CDM to ensure they are well-formed and credible
8. Evaluate whether the event data allows for 2D probability of collision calculations based on the assumption of rectilinear motion at the time of closest approach
9. Perform probability of collision calculations, using numerical and analytical approaches
10. Perform sensitivity calculations of the probability of collision, assessing impact of specific changeable parameters, notably the errors on the primary and secondary object (which are expected to change with new measurement data) and the hard-body radius assumptions (which have a level of inherent uncertainty and conservatism and also can be impacted by the conjunction geometry), then create associated plots
11. Perform maneuver tradespace calculations, showing the impact of potential collision avoidance maneuvers (Delta-V at different times) on the miss distance and probability of collision, then create associated plots
12. Evaluate maneuver tradespaces to validate that collision avoidance maneuvers meet the operator-defined target threshold, to ensure that CRAMS report provides options
13. Build a recommendation based on operator-configurable risk thresholds, including all the rationale for the recommendation into the text
14. Build graphics to visualize the encounter, including covariance geometry at time of closest approach
15. Compile all the information into an Excel spreadsheet and a summary text file
16. Email the Excel spreadsheet and summary text file to the relevant operational team.

As indicated through the steps above, many items are configurable on a mission-specific basis. Consequently, the process of onboarding a new satellite in CRAMS does involve providing a Satellite Configuration Form, with applicable mission-specific details. Table 1 below summarizes the configuration parameters requested from operators to onboard their satellites to the CRAMS service, along with the default proposed values. Italicized values are mandatory, while remaining parameters are optional, with default configuration values being applied if unspecified by an operator. The configuration categories are as follows:

- Satellite and point of contact details, specifying required details about the satellite itself and its operators
- Maneuver trade space configuration parameters, specifying the range of Delta-Vs to analyze when producing maneuver trade spaces. These parameters are configured based on the mission-specific maneuvering capabilities, with the “nominal range” typically corresponding to the size of routine orbit maintenance maneuvers, allowing the operator to assess the impact of routine orbit maintenance maneuvers on close approaches
- Actionable criteria configuration parameters are used to develop the “CRAMS recommendation” embedded in CRAMS reports, and also to configure the “reportable” criteria to specify the cases where a CRAMS report should be delivered to the mission team. The “reportable” criteria provides a kind of “filter” to allow operators to avoid receiving too many low priority reports, which increases the risk of missing more important reports.
- Finally, the “ephemeris provision” parameter drives how CDMs produced from operator ephemeris should be handled. When operators provide routine ephemeris to Space-Track, the resulting CDMs are treated like any other CDMs, but marked as “ephemeris-based CDMs”, and applicable report distribution criteria are applied. Whereas, if an operator doesn’t normally provide ephemeris, or only provides ephemeris in response to high priority conjunction alerts, then CRAMS ensures that special “Ephemeris-Response” CRAMS reports are delivered to operators, containing all CDMs produced from a given ephemeris. This special report allow an operator to assess whether their proposed ephemeris is safe or not.

Table 1. CRAMS Satellite Configuration Form for onboarding new satellites, including default configuration values

Parameter	Explanation	LEO	GEO
Satellite & Point of Contact identification			
Common Name	Common Name typically provided on Space-Track and in CDMs	-	-
SSN Catalog ID	Satellite Unique ID, used when name is unavailable	-	-
SpaceTrack constellation	Constellation, as indicated on SpaceTrack	-	-
Email Address	CRAMS products get emailed to this (or these) addresses	-	-
Operator Name / Tel.	Additional contact information for the mission	-	-
Hard Body Radius (m)	Hard Body Radius (HBR), as exposed in the Cross-Track direction	10	30
In-Track Hard Body Radius (m)	HBR exposed In-Track. Used to potentially shorten HBR based on conjunction geometry; if not provided, same HBR is used InTrack & X-Track	same as HBR	same as HBR
Maneuver Trade Space (Only applicable for maneuverable satellites, i.e., those with thrusters)			
DeltaV Nominal Range [-X, +X] (m/s)	Initial range of ΔV to analyze when producing the tradespace	[-0.02, +0.02]	[-0.02, +0.02]
DeltaV Total Range [-X, +X] (m/s)	Maximum range of ΔV to analyze for the tradespace	[-0.05, +0.05]	[-0.1, +0.1]
DeltaV Expand Range Increment [-X, +X] (m/s)	Amount by which to expand the ΔV range when necessary to achieve the targeted probability	[-0.01, +0.01]	[-0.01, +0.01]
Probability to Achieve	Probability to achieve to declare that a useful tradespace	1e-9	1e-9
Actionable Criteria			
Actionable Time (hrs)	Hours before TCA before which event is not considered actionable	72 hrs	336 hrs (14 days)
Actionable Probability	Probability threshold above which event is considered actionable	1e-6	1e-6
Actionable Miss Dist. (m)	Miss Distance below which the event is considered actionable	200	10,000
Non-Actionable Miss Dist.	Miss Distance above which the event is always considered non-actionable	1500	40,000
RSS Error Limit (m)	Limit of the size of the RSS errors accepted to be considered "good data"	1700	9000
CRAMS Report Distribution Criteria	ALL of the selected conditions must be met. Available options for filter conditions, based on the CDM only, are: [Radial Miss Distance, In-Track Miss Distance, Cross-Track Miss Distance, Overall Miss Distance, Time-to-TCA].	Radial < 200m Overall Miss < 1km Time-to-TCA < 72hrs	Overall Miss < 15km
Reportable Probability	Probability that will force CRAMS report distribution, regardless of other criteria	1e-4	1e-4
Default Covariance	Covariance to use when no covariance is available in CDM or from operator ephemeris. This avoids using zero-covariance in calculations	[300, 0, 0 0, 30000, 0 0, 0, 300]	[1e+4, 0, 0 0, 2.5e+5, 0 0, 0, 1+4]
Ephemeris Provision	Do you provide ephemeris to Space-Track.org (a) routinely, (b) only to assess station keeping maneuvers, (c) only to assess potential avoidance maneuvers?	(c)	(a)

Examples of the CRAMS conjunction analysis reports are provided in Figure 1. The left graphic shows the summary sheet showing the history of the event, while the middle and right graphics shows a typical CDM sheet, reproducing all the original CDM data (middle, top of sheet) and providing value-added plots (right, bottom of sheet) for more detailed assessment and decision-making support. The intention is to deliver reports that are easy to understand for non-technical personnel who need to understand risk and useful for technical personnel in the operations team responsible to take the appropriate actions to mitigate any risks.



Fig. 1. Example CRAMS report, containing analysis summary sheet (left) and CDM details sheet (middle & right)

More detailed examples of the value-added maneuver trade space plots from CRAMS are provided in Figure 2 and examples of the probability sensitivity plots are provided in Figure 3. These plots are designed to facilitate operator decision-making on maneuvers. Additional details about CRAMS CDM processing algorithms are available in [12], which details the algorithms implemented for data quality assessment, the rectilinear motion test to ensure applicability of probability calculations and approaches taken to reduce excessive reporting from CRAMS as the number of CDMs increased.

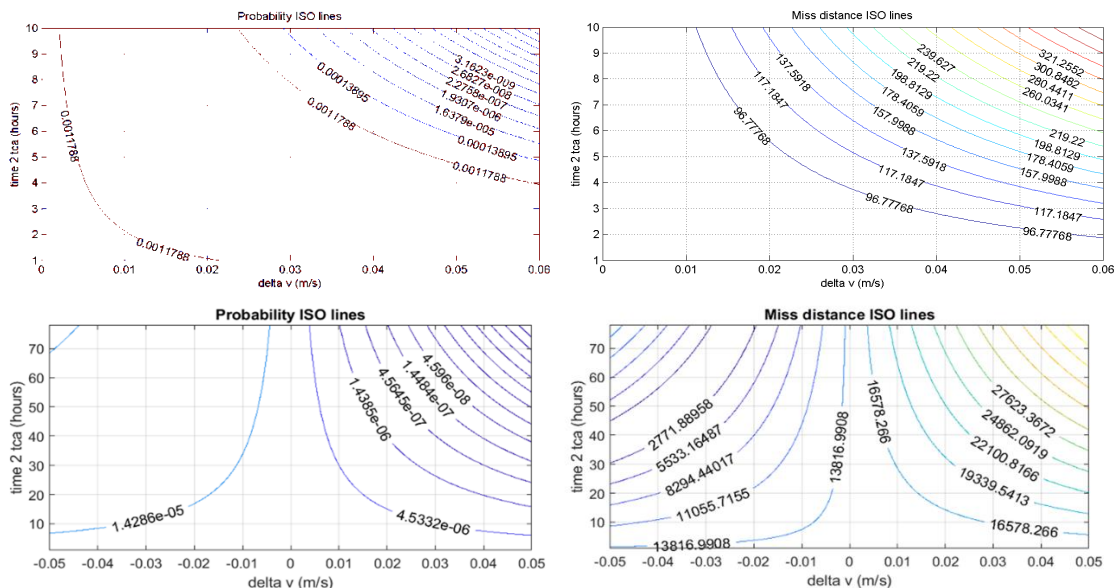


Fig. 2. CRAMS Maneuver Tradespace plots to assess time-varying Delta-V impacts on Probability of Collision (left) and Miss Distance (right)

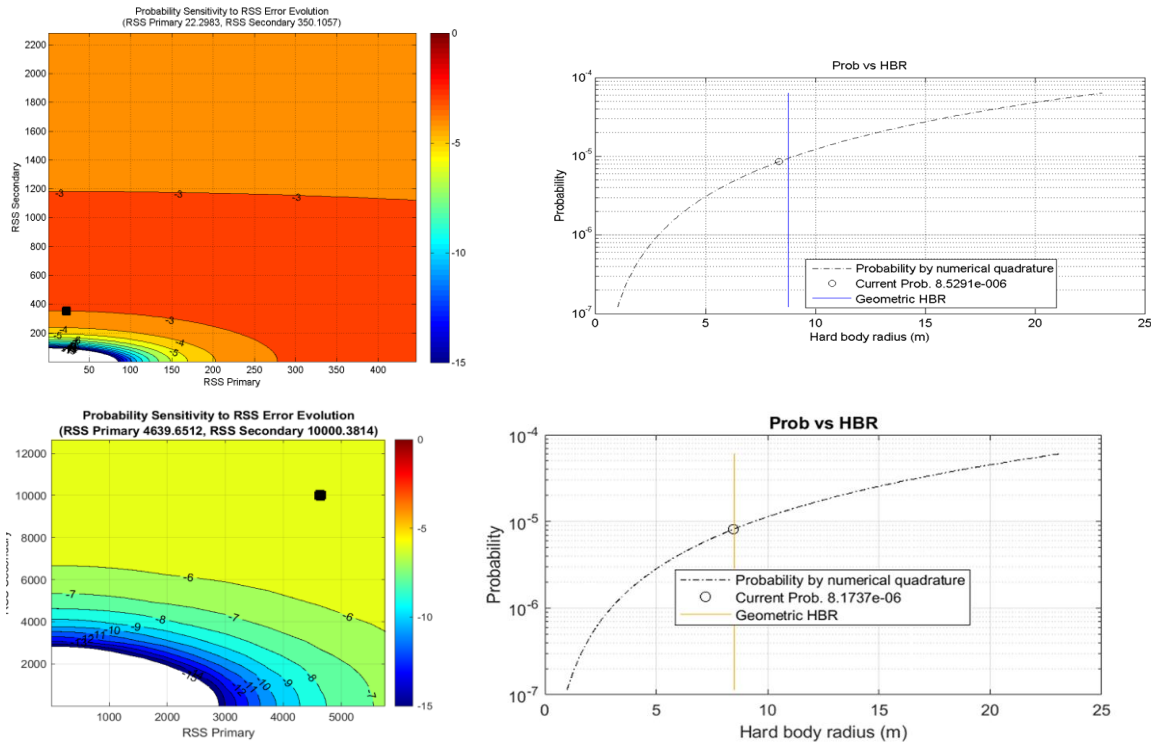


Fig. 3. Two of the six CRAMS Probability Sensitivity plots, one to assess impact of data quality evolution (left) and the other to assess impact of changing hard body radius assumptions (right)

In order to ensure a robust, 24/7 service for its subscribers (including CSA’s own fleet), CSA operates CRAMS on multiple servers in a high-availability, prime and backup configuration, with external, independent monitoring. The service helps Canada to ensure it is robustly monitoring its space assets, contributing to space sustainability and space situational awareness.

4. Ephemeris Management Service with CRAMS

Initially, the CRAMS service simply focused on CDM processing and this was suitable for satellites that maneuvered infrequently or didn’t maneuver at all, since the high accuracy catalogue maintained by the US-SSN tracking service generally produced high quality state vectors and CDMs suitable for understanding and mitigating collision risks. However, the launch of Canada’s flagship RADARSAT Constellation Mission (RCM) in 2019 drove the development of important new capabilities for ephemeris management. Each of the three RCM satellites needed to perform frequent routine orbit maintenance maneuvers to maintain strict orbit control requirements and, as a result, it was difficult for the US-SSN tracking to produce accurate state vectors in the CDMs that represented the expected flight path for the three RCM satellites. Catalogue-based CDMs often had unrealistic or non-existent covariance matrices and consequently, these CDMs were not suitable to fully understand the collision risks and plan appropriate collision avoidance maneuvers. To address this issue, CSA developed new capabilities in CRAMS to support ephemeris screening, using the service provided by 18SDS whereby operators would upload their appropriately-formatted ephemeris to Space-Track.org and 18SDS would produce “ephemeris-based” CDMs, using the uploaded ephemeris (rather the US-SSN catalogue) as the data source for the primary object. Prior to RCM, maneuvers were generally rare for the CSA fleet and the quality of the US-SSN catalogue data was comparable to the data quality of the mission flight dynamics system, and thus CSA operators would generally produce ephemeris for upload to Space-Track.org only when they wanted to screen a collision avoidance maneuver embedded within the ephemeris. However, these assumptions didn’t remain true with RCM, as the frequent maneuvers led to a degradation of the US-SSN’s ability to track the RCM satellites. The RCM flight dynamics system would produce daily ephemeris in support of orbit maintenance, including covariance data, but not in the formats supported by Space-Track.org. RCM mission data management systems were updated to push RCM mission-specific ephemeris products to a drop-box where CRAMS would be able to retrieve then. Then, the CRAMS team created features to autonomously download the ephemeris, perform data validation, apply required frame transformations, and convert the RCM data into the Orbital Ephemeris

Message (OEM) ephemeris-format expected by Space-Track.org, detailed in [13]. This automated new feature allowed 18SDS to produce ephemeris-based CDMs for RCM on a daily basis, ensuring that higher quality conjunction screening data was available for RCM mission operators. Once this feature was implemented, the CRAMS report for a given event would include many more CDMs to follow the evolution of the event, as CDMs would be produced from both the regular US-SSN high accuracy catalogue (HAC) screenings and from the operator ephemeris screenings. Although both CDM types are in all reports, only CDMs based on operator ephemeris are considered useable for spaceflight safety, which is also observed to be a common practice for operators with satellites in geostationary orbits to mitigate the large uncertainties associated with geostationary satellite tracking from the US-SSN.

Once the CRAMS ephemeris management service was established for RCM, CSA decided to apply it for other CSA satellites, specifically NEOSat. The NEOSat flight dynamics system was updated to produce high-precision ephemeris files with covariance data, then the CRAMS ephemeris management functions were adapted to process the NEOSat's ephemeris format into the OEM ephemeris format for Space-Track.org. In NEOSat's case, ephemeris files are produced once a week, and, in addition to uploading predicted ephemeris to Space-Track.org, both predicted and definitive ephemerides are also published on CSA's Open Data portal [14], in order to allow researchers to study orbit prediction/evolution as a function of atmospheric drag, solar radiation pressure, space weather and other factors.

For RCM and its need for frequent maneuvering, the baseline implementation is that CRAMS schedules nominal ephemeris processing and Space-Track.org uploads three times a day for each satellite, with each ephemeris marked as "Operational", meaning that ephemeris including its maneuvers are planned operationally. Sometimes, however, the operations team needs an assessment of candidate collision avoidance maneuvers (which may or may not be planned, depending on the response) and these resulting CDMs from a "special" ephemeris screening are needed faster than the standard response time due to an active high risk conjunction event. For these situations, 18SDS via the Space-Track.org interface supports both "operational" and "special" ephemeris screening options, with further details about 18SDS handling of "Operational" vs "Special" ephemeris available in [13]. To support both types of ephemeris screening service in a straightforward manner for its operations, the CRAMS team implemented another feature of the CRAMS ephemeris management service to allow authorized operators to send a specially formatted email to CRAMS that would trigger additional ephemeris retrievals from the mission's drop-box and allow operators to specify that the new ephemeris should be uploaded to *Space-Track.org* as a "special" ephemeris. This feature has allowed RCM operators to be more responsive to high-risk conjunction events by uploading candidate maneuvers as "special" ephemeris and quickly obtaining new CDMs to evaluate potential collision avoidance actions. The process of interacting with CRAMS is simple and robust, and can be executed from any location at any time. The primary delay in this process is waiting for resulting CDMs in order to make final decision based on an ephemeris being "all clear" relative to all potential conjunction events.

5. Maneuver Evaluation Service with CRAMS

The aforementioned CRAMS ephemeris management service allowed RCM operators to receive CDMs and maintain situational awareness in the context of RCM's unique maneuvering requirements, through the regular or on-demand upload of both "operational" and "special" ephemeris. Both routine orbit maintenance and collision avoidance maneuvers could be included in ephemeris uploaded to Space-Track.org and resulting CRAMS reports would include ephemeris-based CDMs that are timely and relevant in light of the dynamic orbital environment. While this service has been necessary and essential for RCM operations safety, it does rely on screening from 18SDS, which guarantees a response (i.e., resulting ephemeris-based CDMs) within a prescribed timeframe (defined in [13]). This response time is in the order of magnitude of hours, depending on the service standards for a given orbital regime and operator agreement. If the operations team has several candidate maneuvers (Delta-V at a particular time), then it would be more convenient to be able to evaluate them immediately, rather than converting all the options into ephemeris candidates, uploading all of the candidate ephemerides to Space-Track.org and waiting for the CDMs resulting from the 18SDS screenings. The latest CRAMS feature for maneuver evaluation service provides this capability to allow maneuver screening using only CRAMS historical CDMs, without integrating those maneuvers into full ephemerides.

The newly implemented CRAMS maneuver evaluation service relies on the CRAMS archive of CDMs collected through routine CRAMS operations. Recognizing that every active conjunction event is updated with new CDMs on a regular basis, and that those CDMs contain state vectors at the time of closest for all conjuncting primary and secondary objects, it becomes possible to apply a particular maneuver (i.e., Delta-V at a particular time) in all the latest applicable CDMs, i.e., all known CDMs with a time of closest approach after the proposed maneuver. This is

essentially taking one option in a particular maneuver tradespace and evaluating it against the latest CDM of applicable conjunction events in the CRAMS archive.

To use this feature, the authorized satellite operator submits the maneuver details to CRAMS (by email or internal means) using the Orbital Parameter Message (OPM) format for maneuver notification. This format is also used by 18SDS and *Space-Track.org* as detailed in [13] and was selected to allow CRAMS to also potentially upload the OPM to *Space-Track.org* if such a need arises in the future. To complete CRAMS-based maneuver evaluation processing, the supplied maneuver notification file requires details on the primary object, the complete maneuver time in UTC and the components of the Delta-V. In addition, the operator may specify additional optional parameters that control processing details. Figure 4 shows an example of a maneuver notification field, including required and optional fields.

Once CRAMS receives a properly-formatted maneuver file from the satellite operator, CRAMS will identify all the applicable conjunction events and the latest associated CDMs, and produce a special “ManeuverEvaluation” report, showing how all the known events are impacted by the maneuver. The maneuver evaluation report contains information from the original CDM, including the time of closest approach, secondary object and original miss distances (per axis and overall) and probability of collision, along with new miss distances (per axis and overall) and new probability of collision, after implementing the maneuver. This allows an operator to quickly see, within a single report, whether the maneuver is “all clear” or not, from a screening that is entirely local to CRAMS and thus can be provided within minutes, rather than hours. Figure 5 provides an example of CRAMS Maneuver Evaluation report.

```
CCSDS_OPM_VERS = 2.0
CREATION_DATE   = 2025-04-28T16:00:00
ORIGINATOR      = CSA
USER_DEFINED_RELEASABILITY = PRIVATE
USER_DEFINED_CLASSIFICATION = unclassified

COMMENT CDM_DAYS_AHEAD = 15
COMMENT USER_DEFINED_MAN_ID = 12348
COMMENT USER_DEFINED_DISTRIBUTION_LIST = RCM_INFO
COMMENT RESCREEN_AT_NEXT_CDM_UPDATE = 0
OBJECT_NAME     = RCM-2
OBJECT_ID       = 2019-033C
USER_DEFINED_NORAD_CAT_ID = 44324
CENTER_NAME     = EARTH
TIME_SYSTEM    = UTC

MAN_EPOCH_IGNITION = 2025-04-29T03:11:16.000Z
MAN_DURATION       = 0.00000000 [s]
MAN_REF_FRAME     = RTN
MAN_DV_1          = 0.00000000 [km/s]
MAN_DV_2          = 0.00000185 [km/s]
MAN_DV_3          = 0.00000000 [km/s]
USER_DEFINED_MAN_PURPOSE = COLA
USER_DEFINED_TCA   = 2025-05-02T18:29:38.000Z
USER_DEFINED_MAN_STATUS = PREDICTED
```

Fig. 4. Maneuver notification in OPM format, providing details about a maneuver to be screened

CRAMS		4.3		Configurable Parameters		Thresholds of Concern:	
Primary Object		RCM-2		Error scaling: 1 1		Depth of Intrusion: 1	
Maneuver Evaluation Run at:		2025-04-28T17:47:08		RSS Errors limit: 1700		Probability of Collision: 1.00E-04	
Maneuver Plan File Name:		man2025-04-29T03-11-16-0.00000185-12348 (20250428-17-45-51-304)					
Maneuver Time:		2025-04-29T03:11:16					
Delta-V (km/s):		0.00000000,0.00000185,0.00000000					

TCAs (UTC)	Ref #	Data Type	Miss distance before -> after Maneuver (m)				Original PoC	PoC after Maneuver	Secondary Object (m)			Original Recommendation	Post-Maneuver Recommendation
			Radial	In-track	Cross-track	Overall			Name-SSN	RSS Errors	HBR		
2025-04-29T00:39:51	1	CDMe	1536 -> -1536	7408 -> 7408	-12689 -> -12689	14772 -> 14772	0.00E+00	0.00E+00		858.77	1.00	No Action Required (N)	No Action Required (PoC>1e-05, Miss>1500m, Good data)
2025-04-29T13:29:09	2	CDMe	1169 -> -1168	4852 -> 4895	9086 -> 9173	10366 -> 10462	0.00E+00	0.00E+00		850.17	1.00	No Action Required (N)	No Action Required (PoC>1e-05, Miss>1500m, Good data)
2025-04-29T18:15:33	3	CDMe	1651 -> -1651	750 -> 776	2445 -> 2530	3044 -> 3119	0.00E+00	0.00E+00		931.72	1.00	No Action Required (N)	No Action Required (PoC>1e-05, Miss>1500m, Good data)
2025-04-29T18:42:23	4	CDMe	1968 -> 1968	2173 -> 2174	-22608 -> -22637	22797 -> 22826	2.18E-126	0.00E+00		42786.43	1.00	No Action Required (N)	No Action Required (PoC>1e-05, Miss>1500m, Bad data)
2025-04-29T19:09:34	5	CDMe	994 -> -995	14828 -> 15038	-10710 -> -10861	18318 -> 18577	0.00E+00	0.00E+00		725.65	3.61	No Action Required (N)	No Action Required (PoC>1e-05, Miss>1500m, Good data)
2025-04-29T20:04:18	6	CDMe	1432 -> -1432	3172 -> 3195	11552 -> 11638	12064 -> 12154	1.64E-41	9.36E-49		10409.73	1.00	No Action Required (N)	No Action Required (PoC>1e-05, Miss>1500m, Bad data)
2025-04-29T21:36:01	7	CDM	166 -> -166	-206 -> -193	-1220 -> -1161	1248 -> 1188	3.30E-181	1.64E-173		1279.75	13.47	No Action Required (C)	No Action Required (Good data)
2025-04-29T22:31:21	8	CDMe	724 -> 723	14716 -> 14874	-17607 -> -17798	22958 -> 23206	0.00E+00	0.00E+00		785.16	1.00	No Action Required (N)	No Action Required (PoC>1e-05, Miss>1500m, Good data)
2025-04-29T23:12:23	9	CDMe	164 -> -164	1962 -> 1975	11711 -> 11776	11875 -> 11941	0.00E+00	0.00E+00		794.76	13.47	No Action Required (N)	No Action Required (PoC>1e-05, Miss>1500m, Good data)
2025-04-30T00:48:54	10	CDM	-200 -> -200	4084 -> 4099	24207 -> 24278	24550 -> 24622	0.00E+00	0.00E+00		1490.56	13.47	No Action Required (N)	No Action Required (PoC>1e-05, Miss>1500m, Good data)
2025-04-30T00:48:54	11	CDMe	-207 -> -207	4139 -> 4148	24499 -> 24570	24846 -> 24919	0.00E+00	0.00E+00		868.34	13.47	No Action Required (N)	No Action Required (PoC>1e-05, Miss>1500m, Good data)
2025-04-30T06:37:08	12	CDMe	575 -> 575	-1502 -> -1496	-15570 -> -15518	15653 -> 15601	9.38E-74	1.23E-25		17137.00	1.00	No Action Required (N)	No Action Required (PoC>1e-05, Miss>1500m, Bad data)
2025-04-30T15:51:11	13	CDMe	666 -> 666	-6221 -> -5533	-1574 -> -1399	6451 -> 5746	8.65E-09	3.46E-12		17948.15	1.00	No Action Required (N)	No Action Required (PoC>1e-05, Miss>1500m, Bad data)
2025-04-30T17:22:09	14	CDM	396 -> -395	5496 -> 6126	2526 -> 2816	6061 -> 6753	6.41E-141	3.51E-137		6052.93	3.48	No Action Required (N)	No Action Required (PoC>1e-05, Miss>1500m, Bad data)
2025-04-30T17:22:09	15	CDMe	447 -> -447	4796 -> 5425	2203 -> 2494	5296 -> 5988	3.12E-154	8.36E-150		2545.63	3.48	No Action Required (N)	No Action Required (PoC>1e-05, Miss>1500m, Bad data)
2025-05-01T05:45:34	16	CDMe	1382 -> -1382	-8214 -> -7309	-2811 -> -2502	8790 -> 7848	1.16E-10	5.49E-17		63529.89	1.00	No Action Required (N)	No Action Required (PoC>1e-05, Miss>1500m, Bad data)
2025-05-01T06:45:20	17	CDMe	-951 -> -945	2280 -> 2286	24965 -> 25058	25086 -> 25180	8.86E-170	3.65E-244		31870.48	1.00	No Action Required (N)	No Action Required (PoC>1e-05, Miss>1500m, Bad data)
2025-05-01T07:57:00	18	CDM	-262 -> -266	88 -> 89	21290 -> 21294	21291 -> 21296	0.00E+00	0.00E+00		2657.21	1.28	No Action Required (N)	No Action Required (PoC>1e-05, Miss>1500m, Bad data)
2025-05-01T07:57:00	19	CDMe	-257 -> -262	88 -> 89	21286 -> 21291	21288 -> 21293	0.00E+00	0.00E+00		1657.19	1.28	No Action Required (N)	No Action Required (PoC>1e-05, Miss>1500m, Good data)
2025-05-01T09:34:01	20	CDMe	1883 -> 1878	17 -> 13	6328 -> 6331	6601 -> 6604	0.00E+00	0.00E+00		1734.30	1.28	No Action Required (N)	No Action Required (PoC>1e-05, Miss>1500m, Bad data)

Fig. 5. CRAMS maneuver evaluation report, showing impact of maneuver on applicable conjunction events (Secondary objects redacted)

Using the new CRAMS maneuver evaluation, authorized satellite operators have more features to evaluate maneuvers before integrating them into their operational planning system and uploading them to *Space-Track.org*. This helps to ensure spaceflight safety, while reducing the burden on 18SDS to process “candidate maneuvers” that are ultimately not selected by an operator. RCM operators will continue to use CRAMS ephemeris management features to upload ephemeris regularly for screening and this remains essential to maximize the generation of high quality CDMs by 18SDS on *Space-Track.org*. The new CRAMS maneuver evaluation also still relies entirely on the availability of high quality CDMs, so production of ephemeris-based CDMs remains critically important. However, this new CRAMS maneuver evaluation feature allows a faster turnaround time and a level of independence to do “self-screening” that previously was not possible.

6. Summary and Forward Work

Overall, CSA’s conjunction analysis capabilities and services have matured considerably in the 14 years since CRAMS first became operational. Following initial support for “collision avoidance box” methods that later evolved to modern probability-based assessment approaches, recent advancements for ephemeris management and self-screening maneuver evaluation have been introduced. All updates are initially built based on CSA’s operational needs but implemented in a generic way to facilitate onboarding of new missions/operators and sharing of best practices. Inspired by and in collaboration with responsible satellite operators, CSA aims to keep advancing CRAMS in support of space situational awareness and space sustainability.

While CRAMS remains a centrepiece of Canada’s activity in space sustainability, connecting CSA with many other satellite operators and tracking entities worldwide, it is not the only important component of Canada’s contributions to space sustainability. Canadian satellites SAPHIRE and NEOSSat, launched together in February 2013, are space telescopes that serve as space-based sensors collecting in-space observations of resident space objects orbiting the Earth and beyond. SAPHIRE, managed by Canada’s Department of National Defence (DND), is a contributing sensor to the US-SSN, while NEOSSat, a partnership between CSA and Defence Research and Development Canada (DRDC) commits at least 50% of its observing time to research and development on resident space object space surveillance, (with the other 50% committed to space astronomy, including near-Earth asteroids/comets, another important aspect of space sustainability). Initially designed for high-Earth orbit observation, NEOSSat has proven to be agile enough to observe objects from cis-lunar orbits to low-Earth orbit, including conjunctions in low-Earth orbit. The NEOSSat team receives CRAMS reports (for NEOSSat and other objects) and often requests NEOSSat to observe secondary objects based on CRAMS reports to help reduce the uncertainty and thus probability of collision for a given event. This innovative capability integrating CRAMS and NEOSSat is further detailed in [15]. In the future, tighter integration between CRAMS and NEOSSat may be envisioned, such as NEOSSat tasking requests being included in CRAMS reports and the ability for CRAMS to make use of NEOSSat observations within its reports. Such features will be discussed and prioritized alongside other feature requests for future release of CRAMS and NEOSSat ground segment software.

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