

Evolution of Canadian Conjunction Analysis Capabilities and Services

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Abstract

As the space domain becomes increasingly congested, contested and complex, satellite and space system operators must continually enhance their space situational awareness (SSA) capabilities to ensure they can continue to safely operate and deliver their mission services. With over twenty-five (25) years of experience in satellite operations, the Canadian Space Agency (CSA) has taken a leadership role in Canada to maintain, advance and share best practices in operational orbital conjunction assessment, supporting its own fleet while also supporting other new operators in their processes and procedures. As mega-constellations take up an increasing share of the low-Earth orbital environment, these capabilities and services have been adapted in an effort to ensure operational safety sustainability.

One centrepiece of CSA's space situational awareness suite is the Conjunction Risk Assessment and Mitigation System (CRAMS), an automated system that processes conjunction data messages (CDMs) from SSA 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. Initially put into service in 2011 to support CSA's fleet, the CRAMS system has since evolved and now supports conjunction analysis services for a large variety of satellite operators, in industry, academia and government. By supporting many satellites over a variety of orbital regimes, CRAMS is able 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) presented new challenges in conjunction assessment due to frequent routine orbit maintenance maneuvers necessary to maintain the constellation's required orbital configuration. New features were added to better manage RCM's unique requirements, and ensure that conjunction reports remain timely and relevant in light of the evolving orbital environment.

Another emerging innovative capability for conjunction assessment is based on the imaging of conjunctions from Canada's orbiting space telescope, the Near-Earth Object Surveillance Satellite (NEOSSat). Launched in 2013 and orbiting at 775km, NEOSSat is jointly operated by CSA and Defence Research & Development Canada (DRDC) on a dual mission with equal time-sharing between space astronomy and space situational awareness research. Within its space situational awareness research activities, NEOSSat is now often tasked to observe space objects prior to a conjunction event. These observations could help to improve orbit estimates for conjuncting objects and thus reduce the uncertainty and probability of collision associated with a predicted conjunction event.

This paper will discuss the evolution of Canada's conjunction analysis and space situational awareness (SSA) capabilities and services, highlighting 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 and NEOSSat. Best practices, lessons learned and future research directions will also be summarized.

Keywords: conjunction analysis, space situational awareness, space surveillance, space debris, risk mitigation

Acronyms/Abbreviations

18SDS - 18th Space Defense Squadron
CDM - Conjunction Data Message
CDMe – Ephemeris-based Conjunction Data Message
CRAMS – Conjunction Risk Assessment and Mitigation System
CSA – Canadian Space Agency
DRDC – Defence Research & Development Canada
GEO – Geostationary Orbit
LEO – Low-Earth Orbit

NEOSSat – Near-Earth Orbit Surveillance Satellite
OEM – Orbital Ephemeris Message
RCM – RADARSAT Constellation Mission
RSS – Root Sum Square
SP – Special Perturbations catalog
SSA – Space Situational Awareness
SSN – Space Surveillance Network
TCA – Time of Closest Approach

1. Introduction

The Canadian Space Agency (CSA) has been operating satellites since 1995, following the launch of RADARSAT-1, Canada's first flagship synthetic aperture radar satellite for Earth observation [1]. The space environment in which satellite operations are conducted has transformed completely in the intervening years, as more nations and private actors launch more satellites, resulting in more objects and more space debris. On-orbit collision and fragmentation events, whether intentional or not, have increased the presence of space debris, especially in low-Earth orbit. Resident space object tracking services, such as those provided by the United States 18th Space Defense Squadron (18SDS) through the Space Surveillance Network (SSN), have matured their capabilities, now freely providing detailed information to operators to assess collision risks. A standard format has been agreed for conjunction data messages (CDMs), to facilitate communication between tracking entities and operators. Detailed covariance information, which was considered sensitive early on, is now being shared in CDMs in the interest of spaceflight safety, so satellite operators can better characterize the risks and perform collision avoidance maneuvers if necessary.

With over twenty-five (25) years of experience in satellite operations, the Canadian Space Agency (CSA) has taken a leadership role in Canada to maintain, advance and share best practices in operational orbital conjunction assessment, supporting its own fleet while also supporting other new operators in their processes and procedures. As mega-constellations take up an increasing share of the low-Earth orbital environment, these capabilities and services have been adapted in an effort to ensure operational safety sustainability. The evolution of these capabilities and services is discussed in this paper.

2. Conjunction Risk Assessment and Mitigation System (CRAMS)

2.1 Overview of CRAMS

One centrepiece of CSA's space situational awareness suite is the Conjunction Risk Assessment and Mitigation System (CRAMS), an automated system that processes conjunction data messages (CDMs) from SSA 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. Within minutes of the publication of Conjunction Data Messages (CDMs), CRAMS provides real-time operational collision avoidance support by autonomously processing CDMs and distributing value-added reports that provide probability-based risk assessment, relevant options for collision avoidance maneuvers and analytical features for sensitivity analysis. This enables operational teams to predict how the situation may unfold and to quickly make the best decision in light of reported close approach predictions. Initially put into service in 2011 to support CSA's fleet, the CRAMS system has since evolved and now supports conjunction analysis services for a large variety of satellite operators, in industry, academia and government. By supporting many satellites over a variety of orbital regimes, CRAMS is able to see more real-world situations and become robust to edge cases, complex conjunction situations and data quality issues.

CRAMS is designed with the satellite operator in mind. When new conjunction data messages are made available by 18SDS, a notification email is sent to the mission team. CRAMS receives this email and autonomously perform the following actions:

- Login to Space-Track.org to retrieve the CDMs
- Process the CDMs to determine probability of collision, to prepare the maneuver tradespace, and to build graphics visualizing the encounter
- Compile all the information into an Excel spreadsheet and a summary text file
- Email the Excel spreadsheet and summary text file to the relevant operational team.

The Excel spreadsheet has one sheet per CDM and a summary sheet, allowing operators to see the history and evolution of the event. An example of the summary sheet is shown in Figure 1. The CDM-specific sheets include all the information available in the CDM, plus the value-added analysis and graphs to visualize the maneuver trade space and to perform sensitivity analysis on the probability. An example of the data and plots delivered with the CRAMS Excel output is shown in Figure 2.

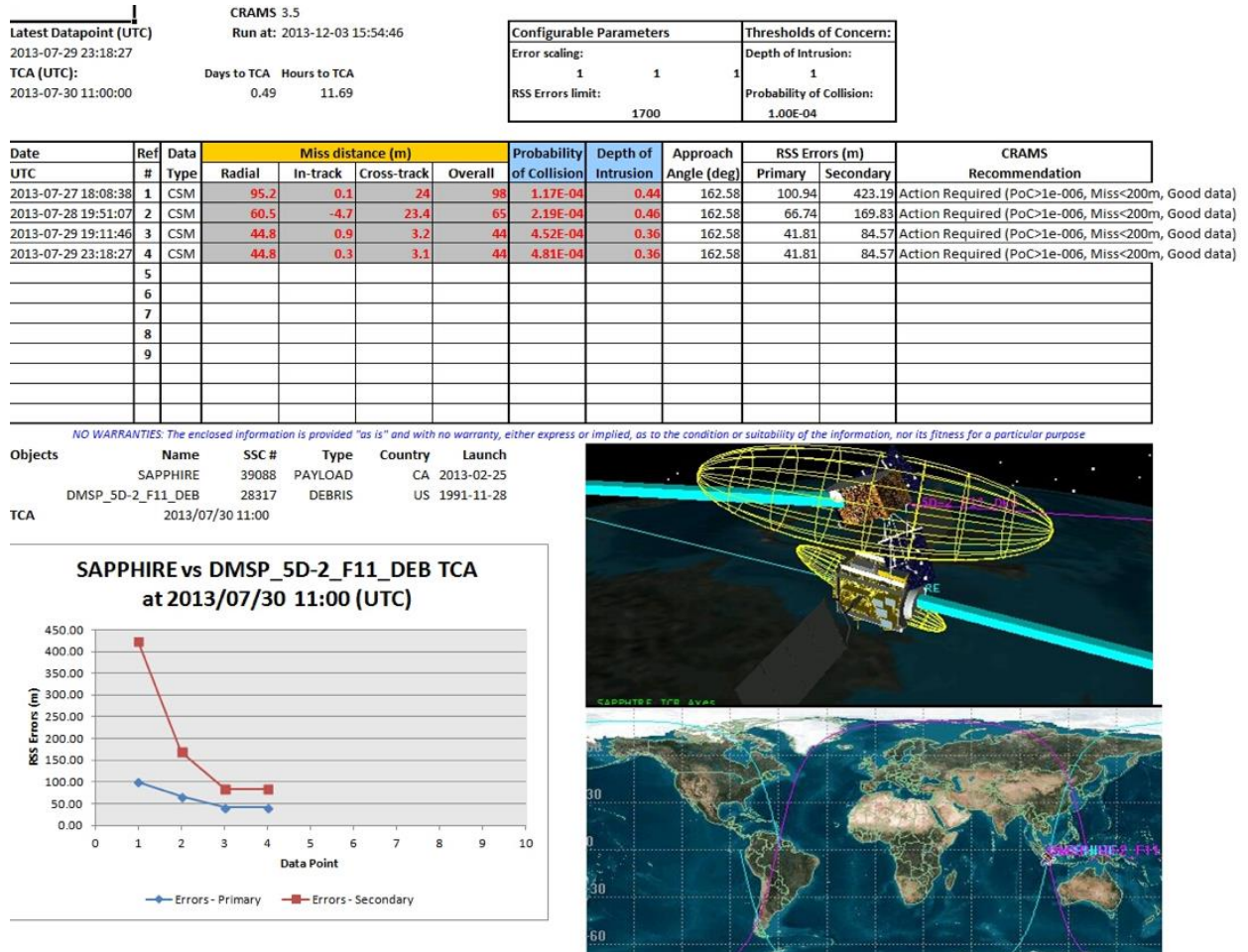


Fig. 1. CRAMS summary sheet, showing history of an event and visualisation

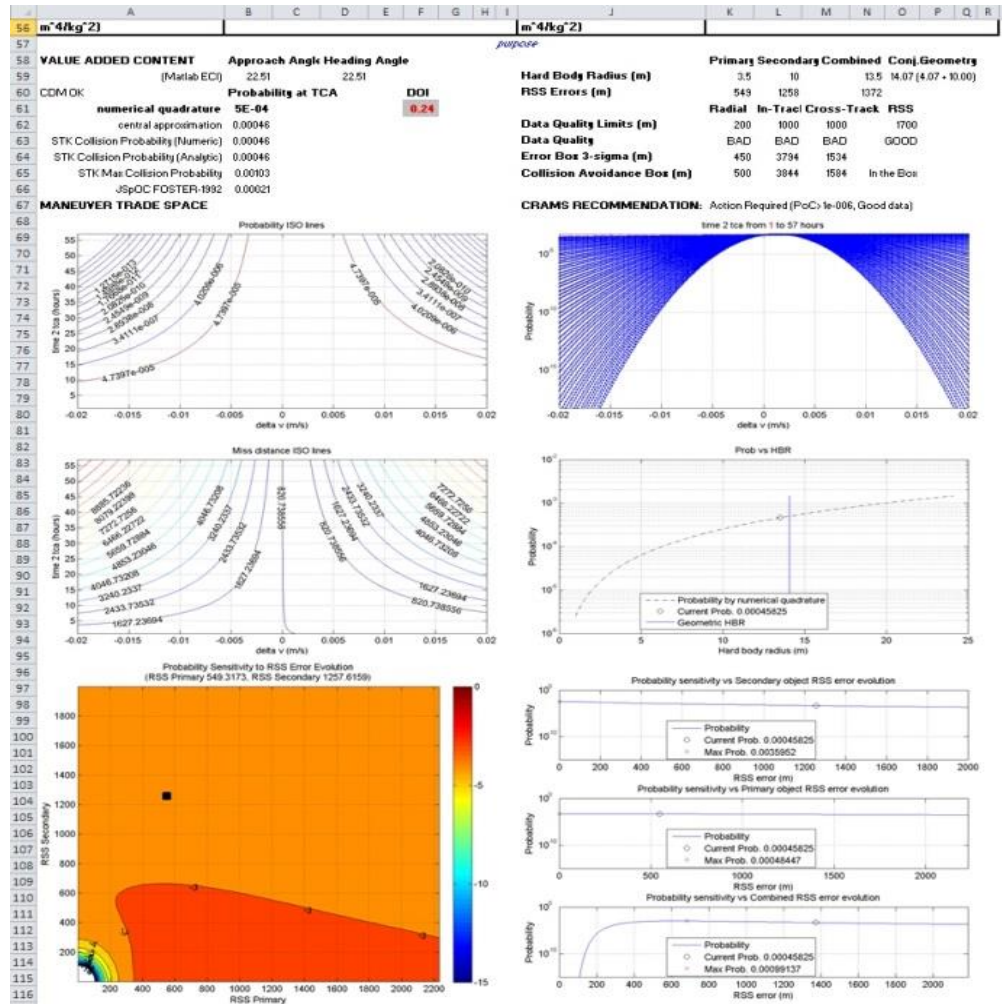


Fig. 2. CRAMS CDM sheet showing value-added content, including maneuver trade space and sensitivity plots

Probability calculations implemented in CRAMS are based on numerical methods elaborated in [1], [2] and [3]. More details on the CRAMS maneuver trade space and other graphics are provided in [4] and [5].

2.2 Adaptations driven by the RADARSAT Constellation Mission (RCM)

The 2019 launch of Canada’s flagship RADARSAT Constellation Mission (RCM) presented new challenges in conjunction assessment due to frequent routine orbit maintenance maneuvers necessary to maintain the constellation’s required orbital configuration. New features were added to better manage RCM’s unique requirements, and ensure that conjunction reports remain timely and relevant in light of the evolving orbital environment.

The most important category of new features added to CRAMS for RCM support relates to ephemeris processing. Since RCM performs regular orbit maintenance maneuvers to maintain its missions ground track requirements, it was important to ensure that all conjunction screening was performed taking into consideration those maneuvers. Consequently, a new ephemeris management feature was introduced for CRAMS. Some of the key features of CRAMS ephemeris management include:

- Ability to autonomously and securely download mission-specific ephemeris from mission data system
- Transformation of ephemeris from mission-specific data formats to standard Orbital Ephemeris Message (OEM) format supported by Space-Track.org
- Ability to autonomously upload OEM mission ephemeris to Space-Track.org for screening by the United States 18th Space Defense Squadron (18SDS)

Provision of RCM ephemeris created new categories of CDMs for CRAMS processing. Overall, CRAMS now sees three kinds of CDMs for RCM, based on the type of screening performed:

- SP-vs-SP CDMs, which are based entirely on the high-fidelity Special Perturbations (SP) catalog maintained by 18SDS, without knowledge of upcoming RCM maneuvers
- Ephemeris-vs-SP CDMs, where the RCM ephemeris is screened against the 18SDS catalog
- Ephemeris-vs-Ephemeris CDMs, where the RCM ephemeris is screened against the ephemeris provided by another operator.

Additional discussion on the different categories of CDMs is provided below.

2.3 Lessons Learned from RCM Conjunction Analysis

It has been interesting to compare the different CDM categories, and the comparison does reveal important information about the evolution of the space environment. In practice, it has been found that the SP-vs-SP CDMs, the best source of conjunction information for years, has now become the least relevant CDM we can receive from 18SDS. The reason is straightforward: for satellites that perform routine orbit maintenance maneuvers, it is absolutely necessary to consider the planned maneuvers in the screenings, since clearly the miss distances and probability of collisions change due to the trajectory changes. At the moment, the only way to perform a conjunction screening that includes satellite maneuvers is through ephemeris-based screening.

A second unexpected factor also drives down the ability to use SP-vs-SP CDMs for RCM conjunction analysis: the regular appearance of very poor covariance matrices for the primary object (i.e., the RCM satellite) shortly after a maneuver. When errors are too high, it is difficult to have confidence in the situation and the decision to perform a collision avoidance maneuver cannot be safely made. Figure 3 shows an example of a CRAMS summary sheet for an RCM close approach, where some data points come from SP-vs-SP screening and others come from ephemeris-based screening. The ephemeris-based CDM is also called a CDM_e in CRAMS terminology for ease of distinction. The RSS Errors columns is a root-sum-square of the covariance matrix for the CDM. The orange-highlighted fields, appearing for CDM_e rows, indicate that the covariance/error estimate comes from the ephemeris file. The yellow-highlighted fields, which uniquely appear in SP-vs-SP CDMs, indicating unacceptably high errors. Deeper investigation on the CDM sheets revealed that the extreme values are simply the “default” covariance matrix, which means that the orbit determination processes for RCM satellites in the presence of maneuvers could not be completed successfully. Further investigation is required by the 18SDS to identify the root cause of such issues, but for CSA Satellite Operations, the conclusion is that such CDMs should not be relied upon, particularly if ephemeris-based CDMs are available for use.

Creation Date	Ref #	Data Type	Miss distance (m)				Probability of Collision	Depth of Intrusion	Approach Angle (deg)	RSS Errors (m)		
			Radial	In-track	Cross-track	Overall				Primary	Secondary	
#####	1	CDM	150	-306.2	1267.7	1312	4.71E-05	0.20	153.17	1595.17	10620.16	No Action Required (PoC>1e-005, > 72 hrs out, Bad data)
#####	2	CDM	141.4	-271.6	1132.3	1172	4.42E-15	0.00	153.17	110472561.29	9037.51	No Action Required (> 72 hrs out, Bad data - WARNING
#####	3	CDM	138.4	-255.2	1071.9	1110	4.42E-15	0.00	153.17	110472561.29	7185.09	No Action Required (Bad data - WARNING: 18SPCS DEF
#####	4	CDM	137.5	-246.7	1028.8	1066	4.42E-15	0.00	153.17	110472561.29	5796.73	No Action Required (Bad data - WARNING: 18SPCS DEF
#####	5	CDM	121.3	-190.3	800.9	832	4.42E-15	0.00	153.17	110472561.29	5432.44	No Action Required (Bad data - WARNING: 18SPCS DEF
#####	6	CDM	52.9	132.7	-553.6	571	4.42E-15	0.00	153.17	110472561.29	3556.43	No Action Required (Bad data - WARNING: 18SPCS DEF
#####	7	CDM _e	-3.5	252.8	-1046	1076	8.06E-05	0.22	153.17	663.78	3556.44	Action Required (PoC>1e-005, Bad data)
#####	8	CDM	87.6	-20.8	64.3	110	2.32E-04	0.29	153.17	243.60	2216.46	Action Required (PoC>1e-005, Miss<200m, Bad data)
#####	9	CDM _e	43.1	68.1	-273	284	2.62E-04	0.17	153.17	663.78	2216.46	Action Required (PoC>1e-005, Bad data)
#####	10	CDM	99.3	-57.5	225.5	253	4.42E-15	0.00	153.17	110472561.29	1466.81	Action No Longer Required (Bad data - WARNING: 18SF
#####	11	CDM _e	49.1	36.8	-171	181	4.01E-04	0.20	153.17	663.78	1466.81	Action Required (PoC>1e-005, Miss<200m, Good data)
#####	12	CDM	87.7	-20	69.5	113	4.42E-15	0.00	153.17	110472561.29	1166.63	Action Required (Miss<200m, Bad data - WARNING: 18
#####	13	CDM _e	41.2	64.4	-264.6	275	2.83E-04	0.23	153.17	222.08	1166.63	Action Required (PoC>1e-005, Good data)
#####	14	CDM _e	15.8	192.5	-814.7	837	9.37E-10	0.78	153.17	241.29	741.43	Action No Longer Required (Good data)
#####	15	CDM	93.6	-49.1	199.9	226	5.94E-04	0.42	153.17	52.50	741.42	Action Required (PoC>1e-005, Good data)
#####	16	CDM _e	15.8	195.1	-814.1	837	6.72E-10	0.78	153.17	241.29	741.43	Action No Longer Required (Good data)
#####	17	CDM	96	-42.8	189.7	216	4.42E-15	0.00	153.17	110472561.29	444.81	No Action Required (Bad data - WARNING: 18SPCS DEF
#####	18	CDM _e	14.7	199.8	-845.4	868	1.24E-19	1.29	153.17	241.29	444.82	No Action Required (Good data)
#####	19	CDM	89.9	-28.9	131.4	161	4.42E-15	0.00	153.17	110472561.29	384.11	No Action Required (CDM created after TCA)
NO WARRANTY: The enclosed information is provided "as is" with no warranty, either express or implied, as to the condition or suitability of the information, its fitness for a particular purpose, or that its use will yield a specific result												

Fig. 3. CRAMS summary sheet for an RCM event showing different types of RSS error, including ephemeris-based covariance (orange highlight) and SP-based covariance, both bad (yellow) and good (no highlight)

Increasingly, CRAMS is also seeing CDMs based on Ephemeris-vs-Ephemeris screening. This is a result of more operators uploading their ephemeris to Space-Track for screening, typically also in a routine and automated fashion. So when two operational and maneuverable satellites are involved in a close approach, and both operators have uploaded their ephemeris, an Ephemeris-vs-Ephemeris CDM can be produced. In discussions with other satellite

operators with maneuvering satellites, this is considered best possible CDM for a given scenario, since we can ensure that any planned satellite maneuvers are taken into the account. Mega-constellation operators often use low-thrust electrical propulsion and also have requirements to maintain certain phasing between their satellites. As a result, similar to RCM, they also perform routine maneuvers. A CDM that does not have knowledge of such maneuvers might be giving incorrect information and cannot be used to determine whether an avoidance maneuver is warranted or not.

2.4 CRAMS Statistics

The fact that CRAMS supports almost 100 satellites and has been operating for over 10 years allows the generation of interesting statistics on the evolution of space environment. Fig. 4 shows the evolution of the secondary objects that are affecting Canadian space assets in low-Earth orbit from 2017 to 2022. Key findings are that mega-constellations are taking an increasing presence in the conjunction events and that debris from anti-satellite tests continue to be a major contribution to conjunction events. It is also interesting to note continued presence of “unknown” objects, which are objects which are difficult to attribute precisely.

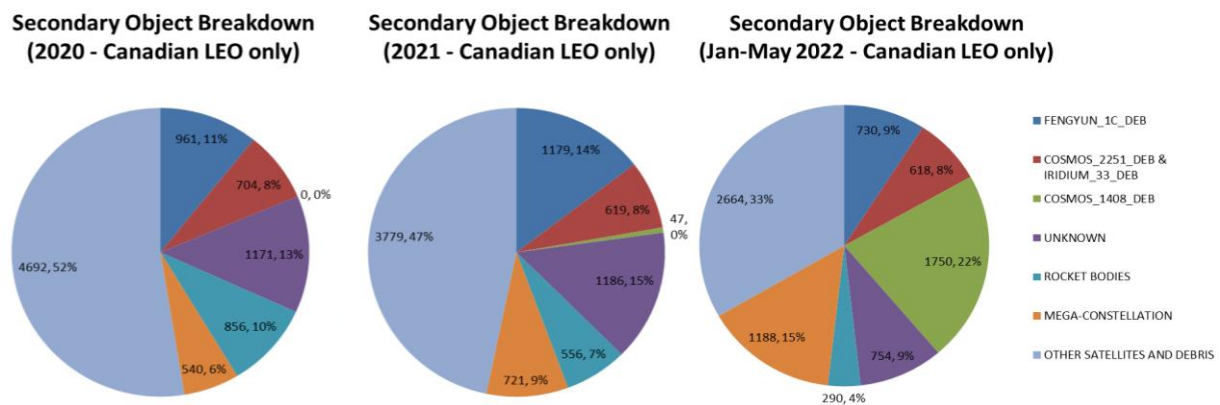


Fig. 1 Evolution of secondary objects facing Canadian LEO satellites (credit CSA)

Specific to Canada’s flagship RADARSAT Constellation Mission (RCM), launched in 2019 and operating at 600km altitude, the three satellites have seen more than 30,000 conjunction data messages (via CRAMS reports) associated to about 5,500 close approach events. From these events, about 65 events were actionable according to CRAMS’ criteria and less than 10 led to a dedicated avoidance maneuver.

3. Near-Earth Object Surveillance Satellite (NEOSSat)

3.1 Overview of NEOSSat

NEOSSat is a Canadian space telescope launched on February 25, 2013, as a partnership between the Canadian Space Agency (CSA) and Defence Research & Development Canada (DRDC). Built in Canada by Microsat Systems Canada Inc (MSCI), NEOSSat performs a dual mission of space astronomy, covering near-Earth asteroids, comets and also now exoplanets, as well as resident space object space surveillance research and development. NEOSSat shared its launch with another Canadian space surveillance satellite Sapphire (Fig. 4), owned and operated by the Canada’s Department of National Defence (DND). SAPPHIRE is a dedicated contributing sensor to the United States Space Surveillance Network (SSN). Both satellites operate at 780km altitude in a sun-synchronous orbit. A more detailed summary of NEOSSat is available in [5]

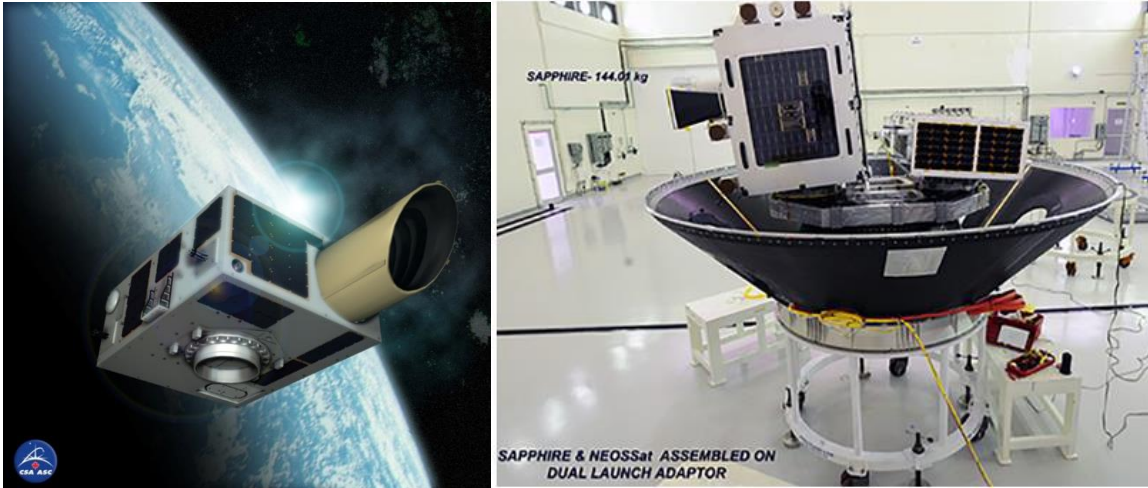


Fig. 4 Artist's rendition of NEOSSat on-orbit (left) and NEOSSat & Sapphire launch configuration (credit CSA)

3.2 Use of NEOSSat to enhance conjunction analysis

The NEOSSat space surveillance mission was originally to track objects in high-Earth orbit, including geostationary orbit. Since then, supported by the satellite's highly agile and robust attitude control system flight software, the team has been able to demonstrate tracking capabilities from Cis Lunar orbits down to low-Earth orbit (LEO). Tracking objects in low-Earth orbit from a LEO satellite is particularly complex due to the high relative velocities between the objects.

Like any other satellite, especially in LEO, NEOSSat faces its own share of CDMs featuring warnings about close approaches with space debris. Although NEOSSat does not have propulsion allowing it to avoid on-orbit collisions, NEOSSat's LEO-to-LEO observation capabilities allow it to take images of the secondary objects with which it has a close approach. Conveniently, pointing the telescope baffle towards the secondary object also presents the smallest surface cross-section to the secondary object, which provides a small reduction in risk, since probability of collision is also linked to the object size. Since 2018, as detailed in [7] and [8], NEOSSat has routinely attempted imaging on close approaches that are identified by conjunction warning systems, including CRAMS. Since orbits are cyclical, the images need not only be taken at the time-of-closest-approach (TCA), but can also be taken in the orbits before. This has the benefit of potentially better characterizing the risk, as the images can be used to provide estimates on the trajectory of the secondary object and consequently on the risks.

An example of NEOSSat's ability to perform LEO-to-LEO conjunction imaging is shown in Fig. 5, which shows the conjunction between NEOSSat and the Spot-2 satellite in 2018 [7]. Although the miss distance is relatively large in this particular case, the images can be dramatic and help illustrate the on-orbit risks faced by satellites. A series of images from the same event is shown in Fig. 6. Careful selection of the exposure durations can help reduce overexposure and blooming, but the object brightens through the encounter and thus there is a tradeoff between acquiring at long-range distances and short-range distances. Astrometric solutions from each frame can be used to validate the CDM data and this type of research is now being performed, as detailed in [7] and [8].

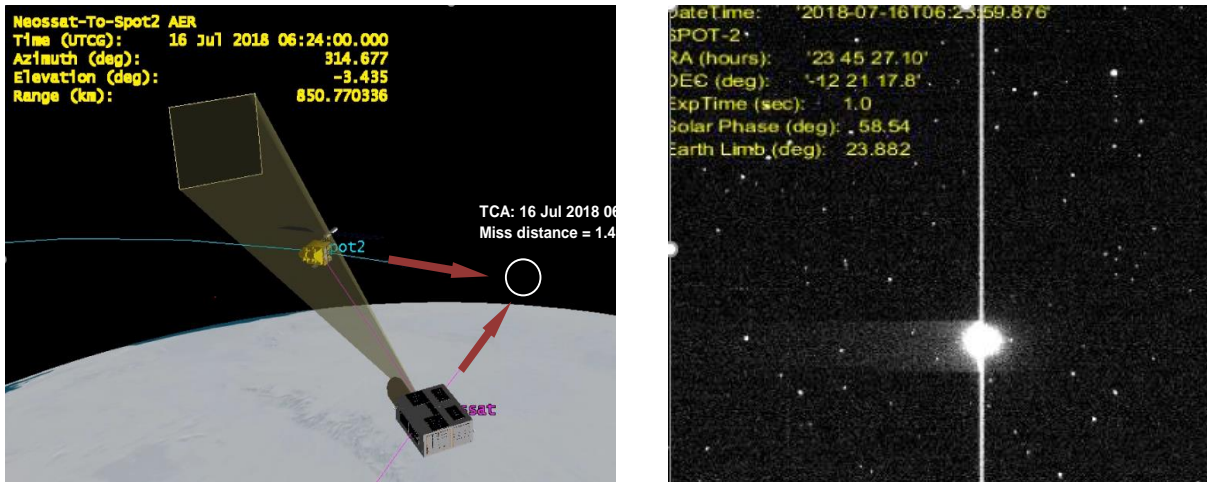


Fig.5. (Left) NEOSSat conjunction geometry with Spot-2. (Right): Single frame of Spot-2 as observed by NEOSSat (Credit: DRDC [6])

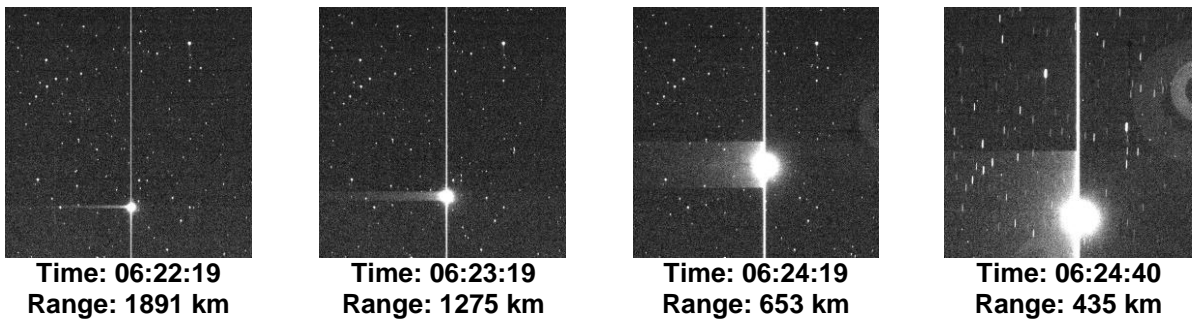


Fig. 6. NEOSSat observations of the Spot-2 satellite conjunction on 16 July 2018. (Credit: DRDC [6])

Recently, NEOSSat successfully imaged a small secondary object that came within 20m of it. The CRAMS report for the event showed a risk of collision (probability of collision $> 1E-4$), with a predicted miss distance ranging between 20m and 30m. While the imaging data from this event is still being analysed, NEOSSat imaging was able to confirm that the accuracy of the CDM predictions in this case.

4. Conclusions

Canadian Conjunction analysis capabilities and services have evolved considerably since the first conjunction message received by CSA Satellite Operations in 2002. Today, CSA's Conjunction Risk Assessment and Mitigation System (CRAMS) is supporting almost 100 satellites, for operators in Canada and beyond. While CRAMS' primary function is to support satellite operator decision making, it also provides Canada with a capability to understand the evolution of the space environment and risks faced by satellite operators. Canada also operates an agile space telescope, NEOSSat, which can assist in the conjunction data validation and visualization. NEOSSat's ability to characterize on-orbit conjunctions "in real-time", for itself and for other objects in a variety of orbits, will continue to be an exciting capability for further development.

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