Close Encounters of an Advanced Kind: Lessons Learned and New Approaches in Collision Risk Assessment and Mitigation

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ABSTRACT

To enhance its management of space debris alerts and space situational awareness, the Canadian Space Agency (CSA) Satellite Operations team has recently subscribed to Advanced Screening services from the United States Strategic Command (US-STRATCOMM), which widens the screening volume for Canadian space assets. While the resulting additional data is extremely valuable, it does bring with it new challenges and interesting features that were not characteristic of Basic Services. For example, long encounter times, which were mostly expected in the geostationary (GEO) regime, are now more common in the LEO regime. In addition, repeat encounters - the same two objects seeing each other over multiple orbits – is a more common occurrence under Advanced Screening and measures to understand and potentially mitigate the full situation are needed. Finally, the sheer volume of conjunction data messages produced requires new techniques to ensure that important situations are flagged and distributed efficiently to the operations team, without having to sift through many low priority encounters. The paper describes these situations and how CSA's Conjunction Risk Assessment and Mitigation System (CRAMS) was upgraded to efficiently manage its fleet on Advanced Screening.

1. INTRODUCTION TO CRAMS

With over twenty years of experience operating satellites, the Canadian Space Agency (CSA)'s Satellite Operations team has a long history with close approach warnings and plays a leadership role in helping to ensure that the risk to Canada's space operations from space debris is sufficiently understood and mitigated when necessary. Working with high-quality Conjunction Data Messages (CDMs) provided by the United States Strategic Command (US-STRATCOMM), the CSA's Collision Risk Assessment and Mitigation System (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.

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

- Login to Space-Track 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 the see the history and evolution of the event. An example of the summary sheet is shown in Figure 1.

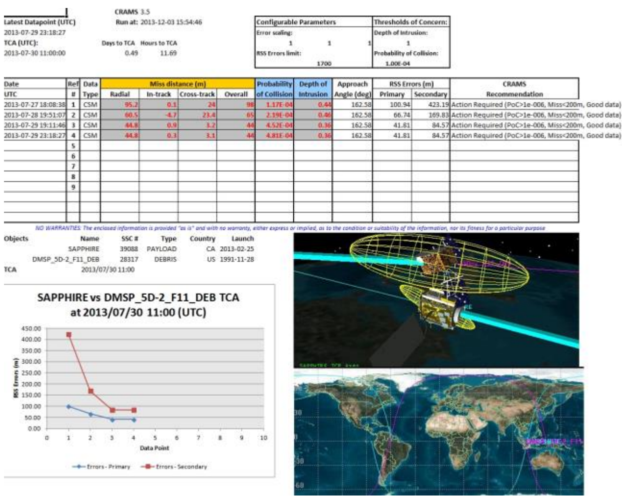

Figure 1 CRAMS Excel Output – Summary Sheet

Proc. 7th European Conference on Space Debris, Darmstadt, Germany, 18–21 April 2017, published by the ESA Space Debris Office
Ed. T. Flohrer & F. Schmitz, (http://spacedebris2017.sdo.esoc.esa.int, June 2017)

The CDM-specific tabs 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. Probability calculations implemented in CRAMS are based on numerical methods elaborated in [1], [2] and [3]. An example of the data and plots delivered with the CRAMS Excel output is shown in Figure 2.

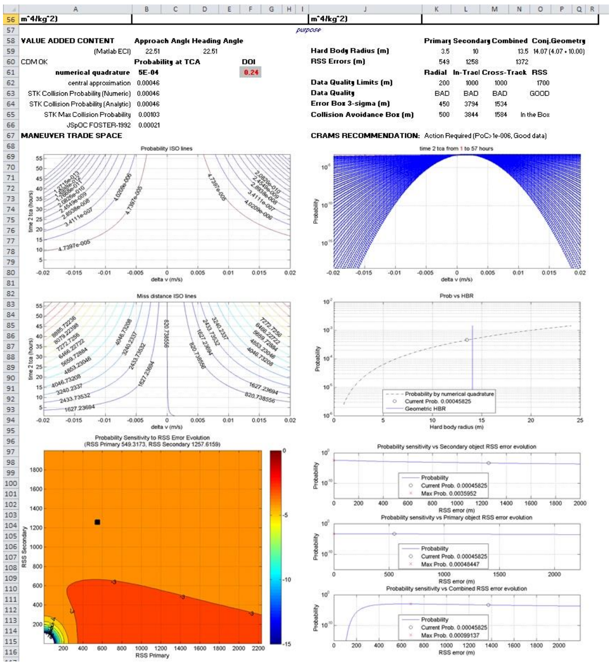

Figure 2 CRAMS Excel Output – CDM Sheet

1.1 CRAMS Maneuver Trade Space

One of the key outputs of CRAMS is the maneuver trade space. It is designed to help the operator make the best decision possible to deal with the encounter (when necessary). Even for low-probability encounters, the trade space can be helpful to determine what maneuvers to *avoid* to ensure the situation does not worsen. There are two types of maneuver trade space graphs provided in the CRAMS Excel spreadsheet: one showing the miss distances and another showing the probability. In both cases, the X-axis represents potential maneuvers (delta-V) and the Y-axis represents time-before-TCA in hours.

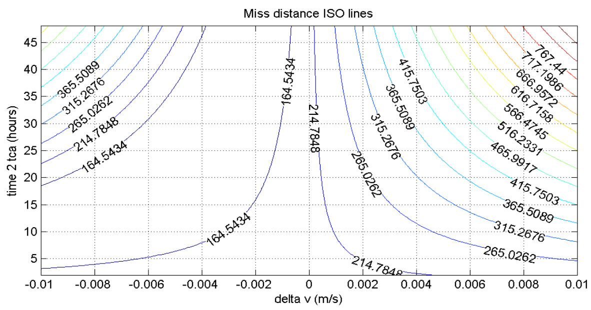

Figure 3 Maneuver Trade Space – Miss Distance

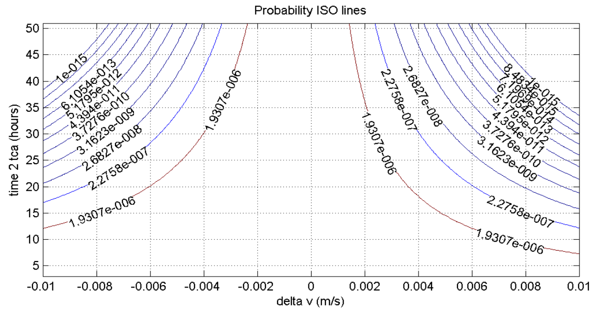

Figure 4 CRAMS Maneuver Trade Space – Probability

Based on methods elaborated in [4], CRAMS produces a set of maneuver trade space plots for each CDM received for satellites it supports. The range of delta-V to analyze is configurable on a per-satellite basis to allow the plot to be scaled to include any applicable routine orbit maintenance maneuver sizes. The delta-V range is automatically expanded to a configurable maximum if none of the maneuver options sufficiently reduce the probability of collision. To be considered sufficient, the tradespace should produce at least some solutions where the probability of collision is less than 1e-9. The default time-range analysed is from the CDM creation date until the time of closest approach, so trade space plots for early CDMs show a larger range of time on the Y axis than the plots for newer CDMs created closer to the time of closest approach.

In addition, new features were introduced recently to allow users to request CRAMS to deliver an updated trade space using a different range of delta-V and time-to-TCA parameters, thus enabling the ability to “zoom in” to areas in the tradespace that are considered or “zoom out” to see the impact of larger maneuvers.

1.2 CRAMS Probability Sensitivity Plots

Per [1], [2] and [3], it is well established that probability of collision depends on multiple factors including the error estimate associated with the measurements and the hard-body-radius of the objects involved. The CRAMS sensitivity analysis plots allow an operator to see how the probability would evolve with new measurements that would reduce the error estimates (covariances) or if more/less conservative estimates were used for the hard-body-radius of the objects involved. This is particularly useful to help decide whether it is better to act now or wait for better data.

The probability sensitivity plot is represented as a “heat map”, with the root-sum-square (RSS) errors of the primary object on the X-axis and of the secondary object on the Y-axis. The colours represent the range of probabilities, with red representing probability > 1e-3, orange representing probability > 1e-4, etc. In the example in Figure 5, it can be seen that if the errors on the secondary object were to be significantly reduced (by later measurements), it should significantly reduce the probability of collision. Thus, depending on whether there is enough time to wait for additional data, one might consider waiting for additional data before deciding to make a collision avoidance maneuver.

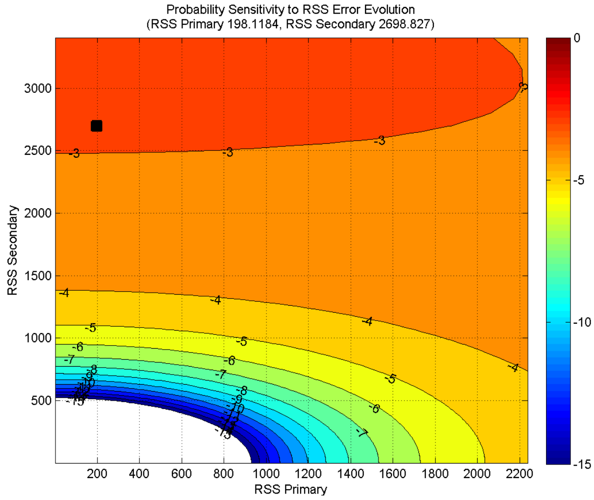

Figure 5 CRAMS Probability Sensitivity to RSS errors

The probability sensitivity to hard-body-radius is also a unique feature of CRAMS. Although the size of the primary object is usually well-known to its operator, the same cannot be said for the size of the secondary object. As a result, there is some uncertainty on the combined hard-body-radius (HBR) of the two objects involved in the encounter. CRAMS includes a Probability vs HBR plot which allows operators to see the impact of varying assumptions on the combined size of the objects.

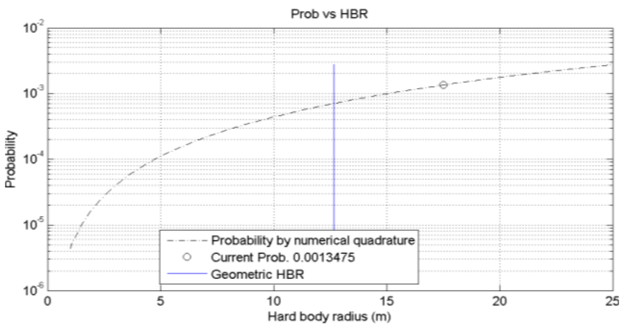

Figure 6 CRAMS Probability Sensitivity to HBR

Although the CDM includes a field "AREA_PC" for both the primary and secondary objects, it cannot be assumed that this represents the precise size of the secondary object. In many cases, this represents the measured radar-cross-section. In other cases, (for unknown or classified objects) the field may indicate 0.0 or be empty. CRAMS applies the following heuristic for the size of the object:

If an operator-provided HBR is available, use that. Otherwise, if AREA_PC available,

$$HardBodyRadius = 4\sqrt{\text{AREA\_PC}} \quad (1)$$

This conservative heuristic is based on assuming that the satellite has a 4:1:1 side ratio and that it is in a gravity-gradient stabilized attitude with the smaller side observable to radar. To further increase conservatism, if the calculated HBR is less than 1m, the HBR is set to 1m and if no size inputs are available, the HBR is set to 10m. The actual HBR used in CRAMS probability calculations is provided in the CDM sheet (Figure 2).

Using these heuristics for object sizing, the CRAMS default probability calculation may be conservative, but the operator can use the probability sensitivity plot to evaluate a more realistic situation. In borderline cases, this analysis could make the difference between choosing to maneuver or choosing not to maneuver.

It is worth noting that this object sizing heuristic differs from JSpOC defaults [5]. This difference in size assumptions usually explains any difference in probability reported by CRAMS and reported by JSpOC. In any case, as seen in Figure 2, the CRAMS reports always include the JSpOC-provided probability (when available) which serves as a useful cross-reference on the encounter situation. Additionality, evaluating the probability of collision under varying HBR assumptions is another application of the HBR sensitivity plot.

1.3 CRAMS Application to GEO satellites

Initially created to support CSA's fleet of satellites in low-Earth orbit (LEO), CRAMS now serves over 50 satellites in both the LEO and the geostationary (GEO) regimes, for Canadian and international operators. The addition of GEO satellites brought new types of encounters to be considered – notably long-duration encounters – which then led to several enhancements in CRAMS to ensure a high level of analysis for this family of satellite operators.

A new linearity test was introduced to warn users about situations where non-linear 3D probability techniques would be more than applicable than the default approach, which assumes that the curvilinear relative motion between the two objects can be approximated by rectilinear motion due to the short encounter time. The test, derived from [3], can be summarized as:

$$\frac{t}{T_c} = \frac{\frac{17}{V_r}\sqrt{\left(\sigma_x{}^2 + \sigma_y{}^2 + \sigma_z{}^2\right)}}{2\pi\sqrt{\frac{r^3}{\mu}}} \leq 2\% \quad (2)$$

Where t is the transit time as a function of the inertial relative velocity (V_r) and the one-sigma error obtained from the diagonal entries of the combined covariance matrix (σ), and where T_c is the corresponding circular orbit period as a function of the primary object's orbital radius r and the standard gravitational parameter μ. If the time to traverse the encounter frame, expressed as a percentage of the orbital period, is less than or equal to 2 percent, then it is a short encounter and the assumption of rectilinear motion is valid. Otherwise, it is a long encounter and the 3D probability techniques may be warranted.

In the current version of CRAMS, close approach encounters that do not meet the linearity test criteria are flagged with a warning indicating that the CDM represents a long encounter time and that further analysis may be warranted. The team is evaluating the possibility of implementing non-linear probability techniques as a future enhancement. This could potentially be done by using the ballistic and solar radiation coefficients, available in the current CDM, to generate an ephemeris for both objects. Alternately, US-STRATCOMM has expressed an openness to expand data sharing in support of spaceflight safety by making available the ephemeris files and/or catalog data for both objects, which would further simplify and enhance the automated implementation of non-linear probability techniques.

While initially developed to provide effective support for GEO satellites, the linearity test because useful for LEO situations once CSA started processing advanced screening CDMs from US-STRATCOMM. This is discussed in the next section.

2. IMPACTS OF ADVANCED SCREENING

In 2016, following changes to US-STRATCOMM data sharing policies, CSA transitioned to Advanced Screening services, which widen the screening volume and increase the notification period for subscribed operational satellites, leading to a major increase in the number of CDMs produced for subscribed satellites.

The larger volume of data has its advantages and drawbacks. The major advantage of larger screening volumes and more CDMs is the potential for a much heightened level of space situational awareness. Used properly, this data could be facilitate operators in ensuring the prevention of collisions in space and enhance spaceflight safety for all space actors.

The "drawback" was primarily the need to upgrade CRAMS to ensure that it could handle a significant increase in workload while also ensuring that satellite operators do not receive so much information that the important messages are lost within an avalanche of less important information. New criteria were established to determine which alerts would be passed onto operators and which would be noted and archived without disturbing operations. In this way, CRAMS would continue to provide value-added reports to operators without overloading them with excessive data. These new reporting criteria are discussed in more detail in Section 2.4.

Another advantage of Advanced Screening – coupled with a large number of satellites supported by CRAMS - was that a number of interesting and perhaps unexpected phenomena could be observed in close encounters, such as:

- Long encounters in the LEO regime
- Repeating encounters in the LEO regime.

These are discussed in the next sections.

2.1 Long Encounters in the LEO regime

One impact from the transition to Advanced Screening was that long encounters were observed in LEO, attributable not only to low relative velocity (as seen in the GEO regime) but also to the presence of large errors or a combination of these factors. These cases highlight the value of the rectilinear motion approximation validity test added in CRAMS to detect these situations. Taking another look at equation (2), it is perhaps understandable that the transit time is a function of relative velocity and of the applicable errors. Advanced screening brings with it much more data, but it is not all of high quality. Therefore, it becomes all the more important to consider data quality when reviewing a particular conjunction situation.

Since the implementation of the test in CRAMS, long encounter situations were observed in 328 of almost 7000 CDMs processed for LEO satellites between March 2016 and April 2017. However, only 57 of those events continued to report long encounter situations within 72 hours of the time of closest approach, consistent with the understanding that longer propagation times lead to larger errors. Of these 57 cases where long encounters were determined for close approach events less than 72 hours in the future, only 5 had one-sigma errors on both objects less than 1.7km, the threshold used in CRAMS to delineate good quality and bad quality data. In these situations, low relative velocity between the objects becomes a factor in creating the long encounter scenario.

Low relative velocity between satellites in LEO could be produced when multiple satellites are deployed from the same launch vehicle. The deployed satellites will share similar orbits and thus close approaches between the objects in early operations could materialize as long encounters. Indeed, this was observed with some satellites supported by CRAMS, as the satellite had a series of separate long-encounter close approaches with satellites that had been deployed on the same launch. These cases would have benefitted from non-linear techniques to more realistically assess the probability of collision. Further analysis could be performed on the situations to evaluate the difference between non-linear and linear probability techniques for these cases and make recommendations for conjunction analysis for multiple satellite deployment scenarios.

2.2 Repeating Encounters in LEO

Another interesting phenomenon that presented itself as a result of Advanced Screening was the concept of multiple (or repeating) encounters. This phenomenon, traditionally associated with the GEO regime, was also found to be present in the LEO regime.

New event periodicity checking features were incorporated to identify these situations to ensure that operators have the information necessary to make the right operational decision quickly based on the judicious analysis of evolving data.

Out of roughly 4000 CDMs processed between October 2016 (when repeat encounter identification was updated into CRAMS) and March 2017, 935 events were flagged with repeating encounters. Of these, about 2/3 were in the GEO regime, while 364 were identified in the LEO regime.

The occurrence of repeat encounters in LEO can be explained by the wider screening volumes applied in Advanced Screening. This can allow two space objects to be within applicable screening volumes of each other over subsequent orbits. An illustration of a repeat encounter scenario based on an actual set of CDMs processed by CRAMS is given in Figure 7.

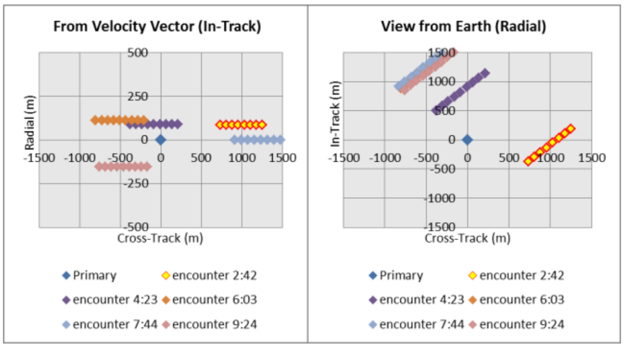

Figure 7 LEO Repeating Encounter Example

In this case, the pair of space objects has five close approaches that meet the advanced screening criteria and thus five CDMs are generated for each data update from US-STRATCOMM. Of these CDMs, at this particular update, the encounter at 4:23 has the smallest miss distance. In this case, the situation did not warrant a collision avoidance maneuver. However, if it had, it would have been important to consider all the close approaches and ensure that any collision avoidance maneuver mitigates all the risk and does not simply displace the risk from one time to another.

In principle, one could create a single tradespace that considers all of the encounters between the objects, rather than consider each encounter separately. This is being considered for future CRAMS releases. In the meantime, all the encounters are delivered within the same Excel spreadsheet, which includes the maneuver tradespace graphs (Figures 3 and 4) available for each encounter, with clear indications about repeating encounters. Operators can then essentially overlay the maneuver tradespace graphs to identify the most viable maneuver option to mitigate all encounters.

Being able to evaluate more than one close approach situation within a single data product (the CRAMS Excel spreadsheet) is a powerful feature that CSA and our partner operational teams are only beginning to get accustomed to and exploit. It is anticipated that as we grow our experience with repeat encounters, we will make further enhancements in the presentation of the full scenario in CRAMS and the efficient mitigation of the overall risk.

2.3 Covariance Matrix Validation Test

On rare occasions, CRAMS encountered CDMs where the probability calculations could not be completed due to numerical errors. In order to produce valid results in our probability computations, the error covariance matrices for both primary and secondary bodies extracted from the CDM must satisfy two properties—they must be symmetric and positive semidefinite. While this is almost always the case, it was found to be prudent to check both of these properties. As a result, a covariance matrix validation test was implemented in CRAMS.

When an invalid covariance matrix is detected, there are two options: the client can be alerted that the covariance matrix is invalid and further processing halted; or, the client can be warned that the covariance matrix was invalid but within tolerance for correction and further processing continued with a corrected matrix. Having a tolerance for correction is operationally preferred so as to avoid rejecting otherwise valid CDMs due to small numerical errors in the data. The next paragraphs discuss the covariance matrix test and correction techniques.

Symmetry is the first property of a covariance matrix to be verified by a simple three step process. First a corrected matrix , the average of the given matrix with its transpose, is generated. Then the difference of this corrected matrix and the given matrix is computed. And finally the ratio of the Frobenius norm of the difference to the Frobenius norm of the given matrix is examined. If zero, then the original covariance matrix was symmetric. If less than a chosen tolerance, say 1e-12, then we can proceed with the corrected matrix, which is now symmetric, and warn the client about the correction. Only if the tolerance ratio is exceeded will the processing be stopped and the client be alerted.

We check that a symmetric covariance matrix is positive semidefinite in a similar way. First we look at the spectral decomposition of the matrix (already corrected for symmetry if required) and generate a corrected matrix by reconstructing it from only the positive eigenvalues and their eigenvectors. In the process of reconstructing the matrix we can also count the number of negative eigenvalues. Now the computation of the difference matrix and the ratio of the Frobenius norms proceeds as for the symmetry check. Comparing these results to two tolerance parameters—the permissible number of negative eigenvalues and the tolerance on the ratio of the norms— allows us to either proceed with a corrected matrix and a warning, or to stop processing and alert the client.

It is interesting to note that CRAMS recently stopped processing a CDM and alerted the client to an invalid secondary covariance matrix. On examining the scenario, it was evident that, although symmetric, the secondary covariance matrix had 1 negative eigenvalue (our tolerance was for up to 2), but the ratio of norms was about 5e-10, whereas our tolerance was set at 1e-12. Reducing this tolerance for correction to, say, 1e-09, would have allowed the covariance matrix to be corrected and for probability calculations to proceed. It is certainly a desired future activity to open a dialog with US-STRATCOMM to determine where to set the tolerance for correction - what is the limit for an acceptable level of error in the covariance matrix?

2.4 Enhanced CRAMS reporting criteria

The first and most obvious impact of Advanced Screening, which enabled all the preceding observations and analysis, was the larger number of CDMs to be processed. In the past, CRAMS would dutifully report all published CDMs to the relevant operations team, always including the complete Excel spreadsheet discussed in Section 1 to the appropriate mission team. As the volume of CDMs increased with Advanced Screening, it was quickly discovered that sending out the analysis for all CDMs was not only impractical but also potentially dangerous. Since the vast majority of reported events under Advanced Screening were not actionable, it was easy for operators to fall into complacency, ignoring CRAMS messages and routinely deleting them from their email inbox. Within a sea of low priority events, it would be easy to miss a high probability, actionable event. As a result, recognizing that spaceflight safety depended on ensuring that important messages are not ignored by the operator, the CRAMS team set out to develop its own “reportable” criteria. This criteria reviews the information in the CDM and determines whether the event should be processed in priority and delivered by email to the operator (i.e., standard CRAMS operations), or alternately should be processed in the background by CRAMS and archived quietly, without notifying operators. Following conclusion with the relevant operational teams subscribed to CRAMS alerts, the following criteria was agreed upon for CRAMS report distribution.

LEO default	**GEO Default**
Radial Miss < 200m &	Radial Miss < 20km &
Overall Miss < 1km &	In-Track Miss < 20km &
Time-to-TCA < 72 hours	Cross-Track Miss < 20km

Table 1 CRAMS Report Distribution Criteria (default)

These criteria are based on US-STRATCOMM’s August 2016 spaceflight safety handbook [6], using the Basic Reporting Criteria for LEO and the Advanced Screening Volume for GEO. For LEO satellites on Advanced Screening, this significantly reduced the amount of CRAMS reports delivered, with priority given to the most credible threats. As with all CRAMS configuration parameters, these criteria can be modified on a mission-specific basis. So some missions who prefer longer lead times for alerts have configured a Time-to-TCA limit of 5 days rather than 3 days.

As of CRAMS 3.9, this report distribution criteria will be updated such that any encounter with a computed probability of collision greater than 1e-04 will be reported, regardless these criteria. This change/lesson learned stems from a few rare occurrences where a high probability close approach was filtered out (not immediately reported) due to either the radial miss distance criteria or the Time-to-TCA criteria not being met yet. It became clear that high probability of collision situations should always be reported.

Following the implementation of the CRAMS report distribution criteria, CRAMS generates a much more restrained volume of email and continues to provide the level of service that long-time subscribers have come to expect from it, that is providing the relevant information in a timely fashion. In the background, CSA servers continue to process lower priority conjunction data messages with the potential to use them for routine orbit maintenance / ephemeris screening.

3. FUTURE DIRECTIONS

Advanced Screening, coupled with the upgrades discussed in the previous section, has enabled a higher level of space situational awareness for the CSA operations team and is contributing to enhanced spaceflight safety.

Nevertheless, operators are now only receiving a fraction of the conjunction data messages being processed by CRAMS, with the majority of these messages being processed then archived on account of not meeting the new “reportable” criteria. In the present context, archived reports are consulted when reviewing monthly trends and statistics, as well as to identify problematic conjunction data messages (for example, where a covariance matrix is not positive semi-definite). There is much more that can be done with these reports.

For example, the current practice for most operators proposing a collision avoidance maneuver in response to an actionable alert is to send an ephemeris file including the maneuver to US-STRATCOMM for screening. This is done to ensure that the planned maneuver does not result in any new close approaches and does not worsen the situation. This practice will likely continue, but the availability of additional information in CRAMS could facilitate a “first pass” ephemeris review by CRAMS before submitting a maneuver plan to US-STRATCOMM. Given the multiple options for collision avoidance maneuvers and the relatively limited time window in which to respond to upcoming events (not to mention the unpredictable workload at any given point in time), reducing the number of iterations going back-and-forth with US-STRATCOMM on different options is expected to be valuable.

This approach of screening ephemeris within CRAMS is not limited to collision avoidance maneuvers. Routine orbit maintenance could also be screened against available information and provide information about potential close approaches that were not reportable under the original orbit but would be reportable under the new orbit. This feature would be particularly valuable for CSA’s upcoming RADARSAT Constellation Mission (RCM) which has very tight orbital control requirements and is expected to make very frequent orbit maintenance maneuvers. The regular maneuvers could make it difficult for the Space Surveillance Network tracking sensors to keep close track of the three satellites in the RCM constellation and therefore routine provision of ephemerides is planned. That being said, operational procedures will need to be adapted to ensure that routine orbit maintenance and collision avoidance processes are closely coupled and well-integrated. CSA has initiated studies in this area and will be adapting the CRAMS infrastructure to better integrate routine ephemeris analysis and all ancillary data about nearby space objects (including catalog information, as available) to ensure that collision risks are robustly mitigated to the largest extent possible.

4. CONCLUSION

CSA’s Conjunction Risk Assessment and Mitigation System (CRAMS) continues to serve the satellite operations community within Canada and abroad with robust analysis of conjunction data messages made available by US-STRATCOMM. Following the upgrade to Advanced Screening services for Canadian space assets, a number of upgrades were needed to ensure a continued high level of support to operators while ensuring that unique new situations arising from Advanced Screening are clearly and concisely presented to operators to facilitate their decision-making.

Process and technology improvements will continue to march together as CSA prepares for its newest satellite fleet – the RADARSAT Constellation Mission – which will present new challenges and opportunities for operational space situational awareness and spaceflight safety.

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